[Optimizing Automotive Electrical Distribution Systems Design and Development by Reducing Design Iterations]

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Submitted to the System Design and Management Program on [April 23, 2015] in Partial fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management.

Abstract

The design and development (D&D) of electrical distribution systems (EDS) is a practice that has been performed in the automotive industry for more than100 years. The amount of technology infusion in vehicles within this history impacts the design and development of electrical distribution systems in an exponential manner. The electrical architecture of a vehicle increases in complexity with every new product launched into the market. The number of interactions and interdependencies between design and development activities, and across functional groups, has been increasing as a consequence of the constant innovation in the vehicle electrical architecture. These interdependencies and interactions with design and development tasks and cross functional groups generate potential design iterations and rework loops that have direct impacts on the cost, scope and schedule of automotive projects.

This research has a fundamental purpose, the review of the electrical distribution systems design and development process inside an automotive OEM through the use of (1) traditional and modern project management tools, (2) surveys and interviews inside the OEM EDS organization, and (3) a review of product development literature, in order to identify recommendations to reduce unplanned design iterations and rework generated by the nonlinear nature of automotive product development. While the analyses, summary and recommendations are specific to EDS product development, it is hoped that the use of both traditional and modern project management tools described in this thesis can serve as a model for those in other industries.

Thesis Advisor: Dr. James M. Lyneis

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This has been quite of a journey. The opportunity to study at Massachusetts Institute of Technology (MIT) has been one of the greatest experiences of my life and I will always be thankful to those who walked beside me during this journey. Specially, I want to express my sincere gratitude to:

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List of Acronyms

AA1	Appearance approval 1
APQP	Advance Product Quality Plan
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CP	Critical Path
CPA	Commercial Program Agreement
DIA	Denver International Airport
D&D	Design and Development
DFMEA	Design Failure Mode and Effects Analysis
DPA	Digital Pre-Assembly
DSM	Design Structure Matrix
DT	Device Transmittal
DVP	Design Verification Plan
EDS	Electrical Distribution Systems
EESE	Electrical and Electronics Systems Engineering
ESOW	Engineering Statement of Work
FAA	Final appearance approval
FC	Feasibility Checkpoint
FDJ	Final Data Judgment
FMA	Failure Mode Avoidance
FT&L	Facilities, Tooling and Launch
GPDS	Global Product Development System
HMI	Human Machine Interface
IVS	In Vehicle Software
OEM	Original Equipment Manufacturer
M-1	Prototype Build (Under body)
M-1 DC	M1 Development Completion
M-1 DJ	M1 Data Judgment
MIT	Massachusetts Institute of Technology
MP1	Mass Production 1
MR	Management Review
NTEI	New Tooled End Item
NVH	Nosie, Vibration and Harshness
PA	Program Start
PALS	Product Attribute Leadership Strategy
PAT	Program Attribute Team
PD	Product Development
PD 0	Platform Design 0
PD 1	Platform Design 1
PD 2	Platform Design 2
PDB	Power Distribution Box
PDL	Product Development letter
PDP	Perfect Drawing Plan
PMT	Program Module Team
PPAP	Production Part Approval Process
PS	Program Start

PSC	Program Strategy Confirmed
PTC	Program Target Compatibility
RFQ	Request For Quote
R&D	Research and Development
SDM	System Design and Management
SDS	System Design Specification
SOBA	Supplier on Board Agreement
TDR	Technical Design Review
THD 0	Top Hat design 0
THD 1	Top Hat Design 1
THD 2	Top Hat Design 2
UNV	Under Body Verification
UPV	Upper Body Verification
VEV	Vehicle Evaluation and Verification
VP	Vehicle Prototype
VPP	Vehicle program Plan
WBS	Work Breakdown Structure
X-1	Prototype Build (Engine)

Chapter 1: Introduction

1.1 Motivation

The design and development (D&D) of electrical distribution systems (EDS) is a practice that has been performed in the automotive industry for more than100 years. The amount of technology infusion in vehicles within this history impacts the design and development of electrical distribution systems in an exponential manner. The electrical architecture of a vehicle increases in complexity with every new product launched into the market. The number of interactions and interdependencies between design and development activities and across functional groups has been increasing as a consequence of the constant innovation in the vehicle electrical architecture. These interdependencies and interactions with design and development tasks and cross functional groups generate potential iteration and rework loops that have direct impacts on the cost, scope and schedule of projects.

I have been involved in the Electrical distribution systems (EDS) design and development for almost 8 years, working for two automotive Original Equipment Manufacturers (OEM). I have had the chance to experience what an engineering team faces in meeting project cost, scope and schedule challenges when working on highly innovative products that need to be delivered to market in a short period of time to remain competitive and meet customer expectations. It is not as unusual as one would think for automotive projects to overrun their schedule, scope and cost; this reduces the profits of the company developing the project and potentially loses market share by launching products late.

The need to constantly review and improve the product development system along project management best practices inside an automotive OEM is critical to ensure the work being done is high quality, and to avoid costly rework during the launch of a vehicle or recalls and warranty claims during the product life cycle. This is important to remain competitive in an Industry that is in constant change based on customer needs, requirements and expectations.

The opportunity to study at the Massachusetts Institute of Technology (MIT), pursuing my degree for a Master of Engineering and Management in the System Design and Management (SDM), has given me the opportunity to learn about best-in-class product development models. I have been able to analyze in detail the latest system project management methodologies that allow a company to deal with the increase in interactions and dependencies between cross-functional groups, and reduce the risk of rework and design iterations. These new methodologies have the potential to deliver products with high quality within a short period in time.

This thesis has been created as a personal decision to use all the concepts and knowledge gained during my studies at MIT to look at the current EDS product development process and system project management practices inside an automotive OEM. In doing so, I hope to identify areas of improvement in processes, tools, and people to reduce the risk of iterations and rework that could impact the overall success of an engineering project.

1.2 Thesis Objective

The objective of this study is to analyze the current processes and human interactions for the EDS D&D system inside an automotive OEM to identify through the usage of system project management practices and best-in-class product development models potential system changes that could help the OEM to more effectively accomplish project targets such as scope, schedule, and cost.

1.3 Research Objectives

The following research objectives have been generated to guide the development of this thesis:

-Identify the activities to be done during the Electrical Distribution System design and development. What is the critical path of the "as is" EDS design and development process?

-Identify interactions and interdependencies between tasks and cross-functional groups, and use a Design Structure Matrix to map, couple, and decouple tasks. Which are the main clusters of coupled tasks?

-Conduct a survey of EDS design and development engineers and engineering supervisors to identify, based on their experience, which activities are the most challenging to complete on time and with high quality during the design and development cycle.

-Cross reference the voice of the customer (EDS D&D engineers) with DSM results to identify clusters with high potential for optimization.

-Introduce new communication strategies, task sequences, and a set of recommendations to reduce potential design iterations and rework, based on the literature of best-in-class product development models and the usage of system project management practices.

-Generate a systems dynamic model of an EDS project case study to analyze the impact of technical, managerial and human factors in the completion of a project. How are the parameters of cost, scope and schedule impacted by the input of external and internal factors?

- Generate a systems dynamics model using the case study as a base to test the magnitude of improvement from the new communication strategies, task sequence, and set of recommendations proposed.

1.4 Research Methods

The methodology in this thesis was developed to support the research objectives listed in section 1.3. To accomplish this, two separate branches of research were required. The first one focused on research inside the OEM to understand the current EDS D&D System. The second one focused on product development models and system project management literature outside the OEM.

For the research inside the company I utilized the Generic Product Development system at the OEM to analyze tasks, task duration, dependencies, owners and milestones covering the entire product development cycle; these can be described using four main phases: Define, Design, Validate and Launch.

For research outside the company I utilized best-in-class product development models inside and outside the automotive industry to compare against the current EDS D&D system in the OEM. In addition, I researched system project management methodologies available to help identify and reduce iteration loops.

After doing this research inside and outside the company, a Work Breakdown Structure (WBS) was generated using the OEM Generic product development system. This filters the tasks that the Product Development (PD) team leads and the main tasks that provide input to the product development team.

After generating a generic PD WBS, the specific EDS tasks and deliverables were identified using help from EDS tech specialists inside the OEM. Perfect drawing plans, technical design reviews, deliverables, and EDS checklists were reviewed to ensure all the tasks required for EDS D&D were identified. After this, the specific EDS WBS was generated by crosschecking the EDS data against the generic PD WBS.

The critical path (CP) for the EDS WBS was calculated in an effort to uncover areas of the entire EDS D&D that cause a bottle neck in the process, and to focus the efforts of this thesis to solve such situations.

An EDS D&D process survey was issued to 45 EDS engineers and engineering supervisors working for the OEM in four different regions: the USA, Mexico, Germany and China. The survey was used to gather engineer needs and opinions in regards to the current EDS D&D system, and to use such information, along with the CP, to decide the final section of the PD cycle where the rest of the analysis on this thesis should focus.

After defining the section of the PD cycle, a condensed list of EDS Tasks was generated in order to create a Design structure Matrix (DSM) to map the clusters of coupled tasks that could be the sources of iterations and rework.

A case study of a design refresh vehicle program inside the OEM was used to create a system dynamics model to simulate the behavior presented in the case study using technical, managerial and human factors as endogenous and exogenous inputs affecting the main project targets of cost, scope and schedule.

Changes to model inputs and parameters were then developed to represent the direct impacts of the policy changes, illustrating the set of recommendations generated through analysis of the EDS D&D system and the lessons learned from the literature outside the OEM. Simulations of the model confirm that the recommendations could improve overall project targets such as cost, scope and schedule, identify and reduce design iterations and rework, and approximate the magnitude of the expected improvement.

Figure 1 shows a graphic representation of the thesis research approach

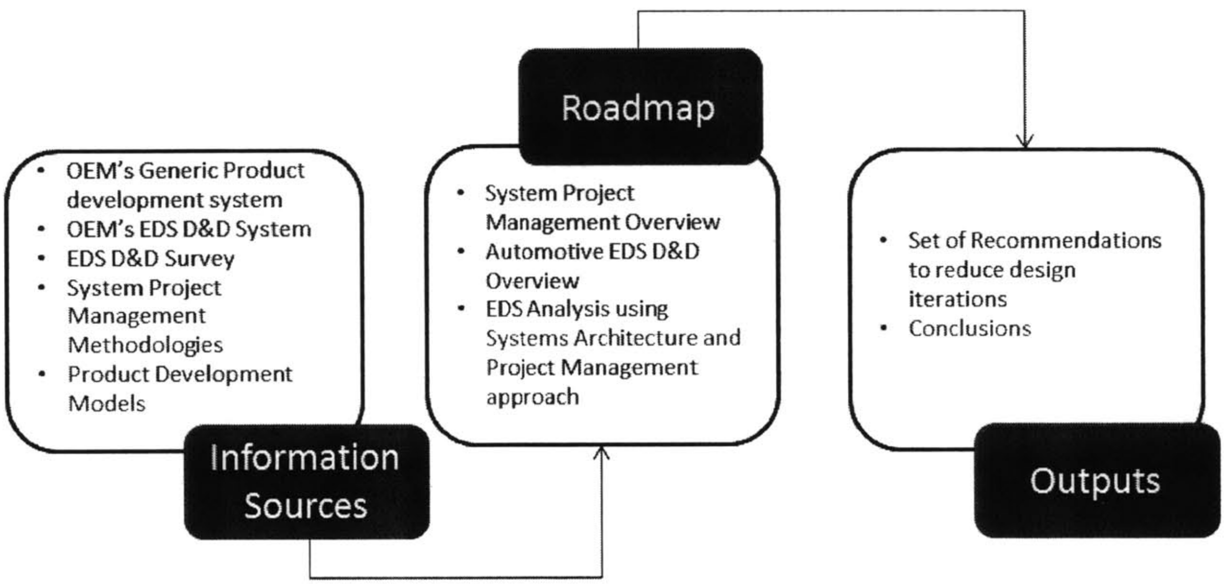

Figure 1: Thesis Research approach

1.5 Thesis structure

As a reference, the outline of each chapter developed in this thesis is below. The structure of the chapters has been selected to provide a logical progression through the research approach and to support the research objectives and methods.

Chapter 2 System Project Management

A general overview of the system project management literature is provided, covering critical concepts, history, evolution, characteristics and phases. Examples of successes and failures in project management are also provided in this chapter, along with an overview of modern project management tools such as DSM and System Dynamics capable of understanding design coupling, the causes of design iteration and their impacts on project targets.

Chapter 3 Automotive EDS Design and development overview

A general overview of the Automotive EDS design and development process inside the OEM of study is provided during this chapter. Product development best-in-class practices are also explained in this chapter and a description of the case study used to develop the system dynamics model for the EDS analysis in Chapter 4 is provided.

Chapter 4 EDS Analysis

The usage of traditional project management tools such as work break down structure and critical path method to analyze the EDS design and development process are illustrated in this chapter. The usage of the modern project management tool DSM to identify unplanned iterations, coupled tasks, tasks dependencies, cross-functional groups interaction and EDS optimal tasks sequence to avoid rework and design iterations is presented in this chapter. A post mortem analysis of the case study described in Chapter 3 and testing of a set of recommendations that could improve the EDS team performance will be presented using the modern project management tool system dynamics.

Chapter 5 Conclusions and recommendations

Conclusions and recommendations to avoid design iterations and rework in the EDS design and development process are provided based on literature reviewed, surveys performed and utilization of project management tools.

Chapter 2: System Project Management

2.1 Traditional project management

Humanity has been involved in projects from the beginning of civilization, but there is no evidence of formal project management until the beginning of the 19th century. The following sections present an overview of the core concepts of system project management, history of project management and its evolution to match the growing complexity of modern sociotechnical projects.

2.1.1 Concept, History and Evolution

This section provides the three critical concepts this author used as the base of the study performed on system project management methodologies and the roots and evolution of program management.

A **system** can be defined as a set of physical or virtual components/parts whose interrelationships enable a desired function that is greater than that of its individual parts. (de Weck & Lyneis, 2014)

A **project** can be defined as a set of tasks that are related to each other; each task has a specific objective with defined start and end date, resource consumption and funding limitation. (de Weck & Lyneis, 2014)

Project management is the application of knowledge, tools and techniques that facilitate the achievement of project objectives within time, cost and scope by utilizing resources efficiently and carefully dealing with risks and opportunities.(PMI, 2008)

The human race has been involved in projects since the beginning of civilization, examples being the Egyptian Pyramids, the Great Wall of China, the Great Cathedrals of Europe, the aqueducts of the Roman Empire and the Tower of Babel. Most of these projects were characterized by the usage of limited technology and thousands of workers. Most of these projects were created with the simple objective of glorifying gods or as symbols of respect to emperors or kings. There is no evidence of particular project management methodologies being used during the construction of these projects.(Gauthier & Ika, 2012)

Formal project management started more than100 years ago with the industrial revolution and has its roots in the work of industrialists such as Gantt, Taylor and Fayol. Project management emerged as a response to the need to define, manage and improve the work in complex undertakings. (Moser & Wood, 2014)
Industrial work performed up to the middle of the 19th century was fairly linear and the main focus of project management was to ensure each task was described from an initial through a final state, resources were allocated according to the logic of the process and dependencies

between tasks were provided for the entire work process. Project management responsibility was usually held by a subject-matter expert that provided the task flow to the workers at the assembly or production line without the need for particular input from workers in process delimitation. This type of project organization is considered a "mindless system (mechanical model)," where work is routinized and controlled, like clockwork, by a central authority. (G. Morgan, 1997) The objective in the mechanical model was to monitor tasks to ensure they were completed on time and the overall assembly line produced as much product as possible; employee satisfaction, motivation or professional growth were not part of the objectives of the project.

Many of the latest project management methodologies emerged during World War II and the Cold War. The fact that projects have increased in complexity in the latest decades has shifted the linearity approach of the 19^{th} century to a broader approach, where interactions between entities, iterations of work and social aspects of the projects have to be included as part of the design and management of projects to ensure different possible outcomes are considered and risk is managed properly to avoid surprises. This type of project model was named by Ackoff as "the sociocultural model" where planning is decentralized and the organization is considered a multi-minded system where members have ownership of project activities and cultural aspects (communication, interaction, shared values, artifacts, deeply-held beliefs and assumptions) of the project are important to deliver project targets of cost, scope and schedule. (Ackoff & Roven, 2003)

Although we can see from history how project management methodologies have evolved to align with multi-minded systems and the importance of social aspects of the project, there are some industries in the modern world–including the automotive industry–that have been facing difficulties in evolving their project management approach to align with the new nature of complex systems, where planning, keeping track of progress and implementing project control policies is not enough to ensure success.

Best-in-class project management tools are capable of understanding work iterations, identifying clusters of coupled tasks, mapping interactions among project stakeholders and providing forecasts or a set of possible project outcomes in terms of cost, scope and schedule according to the dynamics of the project. This is important for the project manager to avoid surprises during the project life cycle and create a strategy, since the planning stage of the project must deal with risk and uncertainty.

Section 2.3 provides an overview of two best-in-class project management tools – Design Structure Matrix (DSM) and System Dynamics – to effectively understand iterations and nonlinearity in project processes. These tools allow the analysis of possible project outcomes based on original project targets, initial parameters assigned to the project team – (resources, time, sequence of work, newness of the project, productivity and fraction of error) – and the impacts that unplanned iterations, infeasible plans and managerial decisions have on the overall project performance.

Chapter 4 provides an application example of such project management tools based on the Electrical Distribution Systems (EDS) design and development process of an automotive OEM and a case study of a recent design and development project of a minor refresh of a Sport Utility Vehicle (SUV).

2.1.2 Project parameters of success: Cost, Scope and Schedule (Iron Triangle)

The literature reviewed suggests that project performance is constrained over three main dimensions: cost, scope and schedule. These three dimensions integrate the concept of "Iron Triangle". This geometric figure illustrates how a project is constrained by these three parameters and the importance of each of them when taking decisions or providing direction in complex projects.

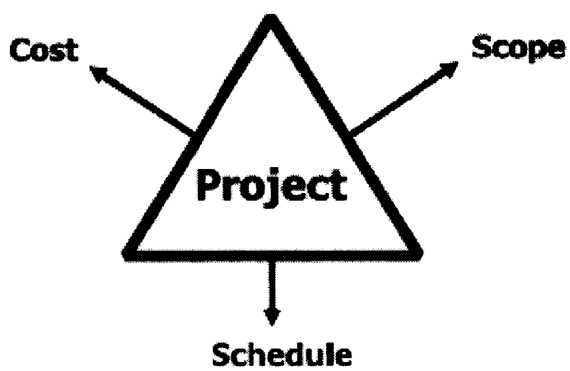

Figure 2: Iron Triangle of Project Management (de Weck & Lyneis, 2014)

The Project Management Body of Knowledge in his 5th edition expands the number of dimensions in which a project is constrained:

- Scope
- Quality
- Schedule
- Budget
- Resources
- Risk

This thesis will consider the dimension of product quality as being part of the scope of the project. Resources are mainly tracked by the project cost and the risk is embedded in the relationship between the dimensions in the iron triangle. The relationship among the iron triangle factors is such that if any one factor changes, there is a risk that at least one other factor is likely to be affected.

Modern complex projects have been struggling with meeting initial iron triangle targets due to the risk embedded in the project process, characterized by the nonlinear nature of tasks flow and, the interactions between humans and the set of tools available to complete each of the tasks that are part of the project. The usage of project management methods and tools provides a way to deal with the risk embedded in complex projects and facilitates the achievement of initial project targets. Project management methodologies can also provide a performance forecast in order to generate awareness inside an organization before a project starts, in regards to potential outcomes and difficulties the project team could face along the way.

29.1.3 **Project management phases**

Project management is exercised in different ways, depending on the project section being analyzed. Figure 3 illustrates the main objectives of program management in a generic project.

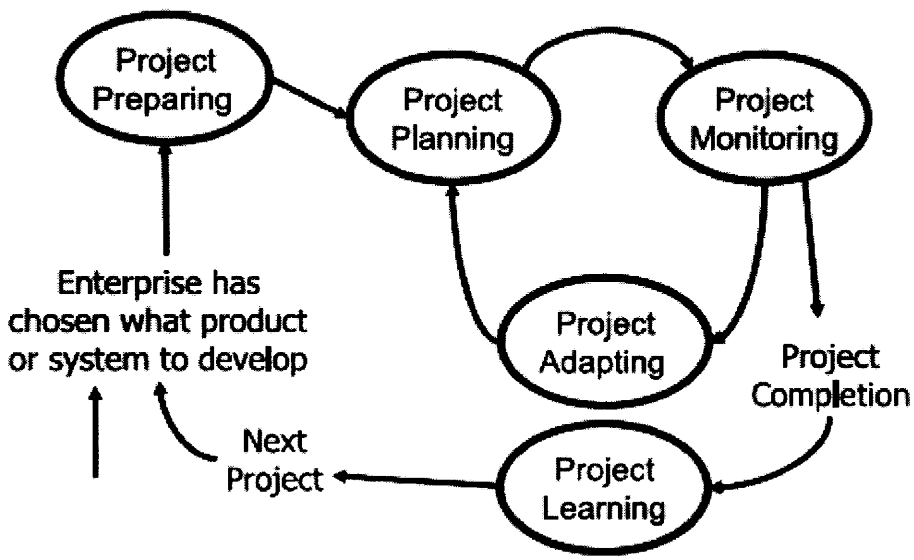

Figure 3: Program management objectives within a Generic Project (de Weck & Lyneis, 2014)

The following is a brief description of the program management functions inside a generic project provided by Olivier De Weck during the ESD.36 System project management class:

Project Preparing: During this phase, the main activities that are accomplished are:

- Project targets definition
- Program Manager Designation
- Resources allocation
- Review of lessons learned from previous projects

Although project preparing is used at the early stages of the project, this phase should be used in other phases as well, such as the beginning of milestones or when the scope of the project is updated and new activities and task subset have to be performed.

Project Planning: During this stage, all efforts are focused on the project kick off. The project should be approved by this stage based on the work done during the preparation phase and the activities to be performed are:

- Creation of the work breakdown structure (WBS)
- Project Critical Path calculation
- Subdivision of project deliverables by milestones
- Staffing plan and facilities allocation

Project Monitoring: During this stage, progress, cost, schedule and scope are constantly reviewed to ensure the project is moving along as projected during the preparing and planning phases. The main activities performed during this phase are:

- Allocation of tasks, activities and responsibilities
- Assessments of technical progress
- Cost status reports
- Project issues analysis and resolution
- Review of deliverables at major project milestones.

Project Adaptation: During this phase, actions have to be implemented immediately when the project has deviated from the original plan. The impact on the project iron triangle has to be analyzed every time actions or decisions have to be implemented to get the project back on track. The activities performed during this phase are:

- Staff addition or removal
- Rescope or descope of technical objectives
- Tasks addition or removal
- Project schedule revalidation

At this stage, some of the actions to be performed require iteration in some of the activities described under the planning and monitoring phases to ensure the overall project targets are accomplished.

Project Learning: During this stage, the overall project outcome is analyzed and lessons learned from the project have to be captured and cascaded to future projects in order to generate continuous improvements and generational learning. The main activities performed during this phase are: Project outcome (product or service) Hand off, iron triangle final status review, lessons learned input into a knowledge database and formal storage of project documents and tools for future projects.

2.2 Complexity in Modern projects

Modern projects are complex in two fundamental dimensions: technical complexity and organizational complexity. Technical complexity is generated by the lack of linearity in project workflow, the coupling of tasks or cross functional groups in the decomposition and integration of several layers of work (e.g. big projects such as product development projects which will be reviewed in section 2.2.1), the number of interfaces and the interaction of several subsystems to enable the emergence of system functionality such as reliability, serviceability, maintainability, security and usability. Organizational complexity is generated by the size of the workforce that has to be involved in the project, the location of resources across the globe, the number of stakeholders that have to be considered to ensure project success and the interaction and communication between such stakeholders to align cost, scope and schedule targets.

2.2.1 Nonlinearity, Coupling and Interaction (Technical complexity)

Product development projects are very complex, due to having so many functional groups working in parallel to accomplish a unique goal: deliver a product with high quality in a short period of time. Marketing, Finance, Purchasing, Manufacturing, Engineering, Suppliers and R&D are some of the stakeholders that have inputs and outputs in the overall product development system. The task flow is iterative by nature due to the fact of having to align requirements and validate function at component, sub-system, system and product level. Having similar design freeze dates for several components of a product generates a need for iteration in the product development system, especially in parts where design depends heavily on input from other components to enable proper function.

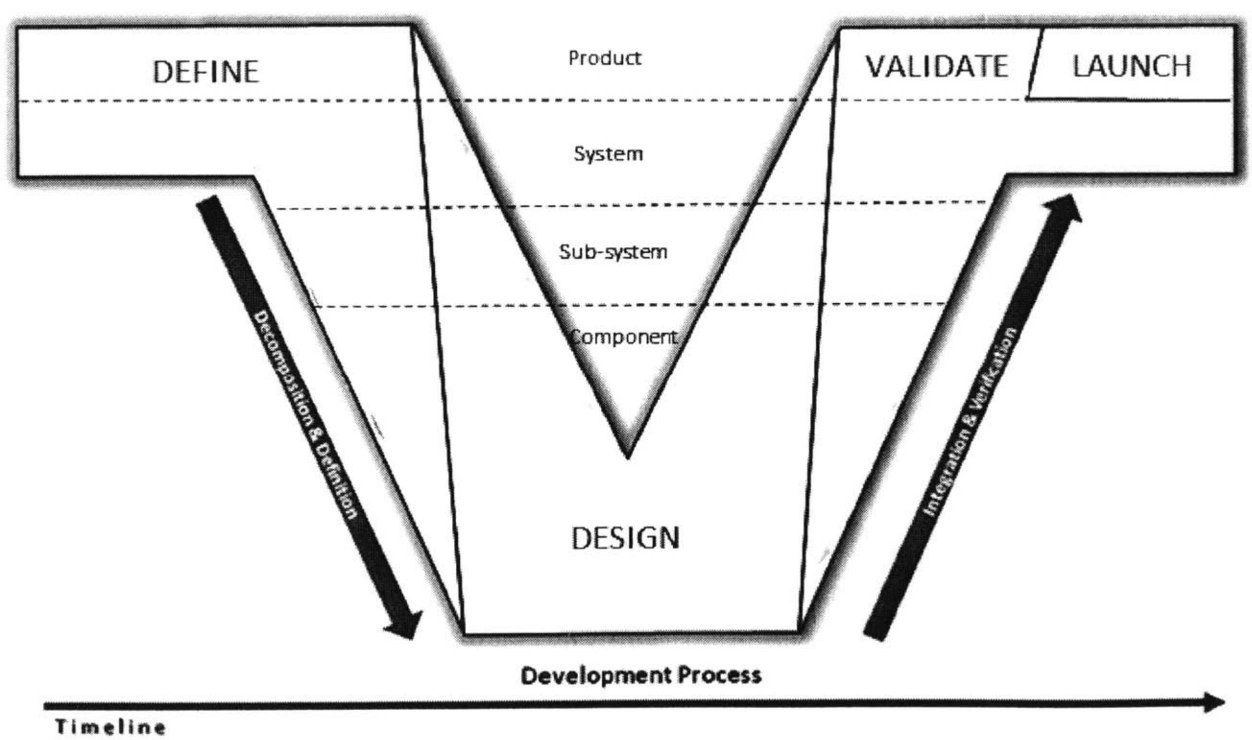

Figure 4: Systems Engineering V-Model (Modified from INCOSE 2012)

Figure 4 illustrates the System Engineering V-Model commonly used in the automotive industry along with the main automotive product development phases that for this thesis are considered to be: Define, Design, Validate and Launch. The nonlinearity, coupling of tasks and cross-functional interaction occur at every level of the V-Model in the decomposition and integration sides and along all the product development phases.

Technical complexity in product development projects requires effective use of project management tools that consider work iterations and cross functional interactions along the system engineering V-Model. This provides a set of possible project outcomes based on project team performance, initial project targets and the effects of managerial decisions along the project lifecycle. This leads to strategies for dealing with risk and uncertainty. Traditional project management tools are widely used in product development. However, these tools plan and manage the project as a linear development effort, when decomposition and integration of components, subsystems and systems along the process clearly show a nonlinear behavior. As a result, while plans using traditional project management tools seem to have a consistent strategy to reach project targets, in practice they are infeasible. This thesis acknowledges not just the importance of project management tools to improve product development process but the importance of applying project management tools aligned with project technical complexity type.

2.2.2 Managing multifunctional, international projects (Organizational complexity)

The battle in the customer-driven automotive industry to capture market share and increase profit has shifted in recent years from manufacturing capabilities to product development excellence. Customers are increasing their demand for customized products; this has led to a market micro-segmentation that has critical implications for product development and the overall profit of companies where low production volumes for many products–instead of mass production of standard products–is a consequence. In order to meet customer expectations and still make projects profitable, efforts at standardization of component, sub-system and system across products has been done as well as usage of product platforms to communize architectures and big systems, such as the powertrain or chassis. Yet, one of the key efforts being pursued by OEMs nowadays towards cost efficiency is the outsourcing of workforce to low-wage countries such as Mexico, China and Brazil. Customer base expansion and technology and knowledge acquisition are also benefits of doing this. The main workforce being outsourced is manufacturing and engineering, which has great impact on the overall product development system though the define, design, validate and launch phases.

This latest tendency to outsource engineering and manufacturing workforce introduces new challenges in the accomplishment of project iron triangle objectives. These challenges are related to the organizational complexity of a project. Different languages, time zone, cultures and perception, technical skills, regional regulations and currency exchange rates are just some of the main organizational challenges of managing international or global projects.

Greater efforts in communication and coordination have to be implemented when working in projects with high organizational complexity. The usage of proper project management tools is critical to ensure the additional risk introduced through cross-regional interactions is being managed, possible project outcomes are analyzed and actions taken to ensure project target completion.

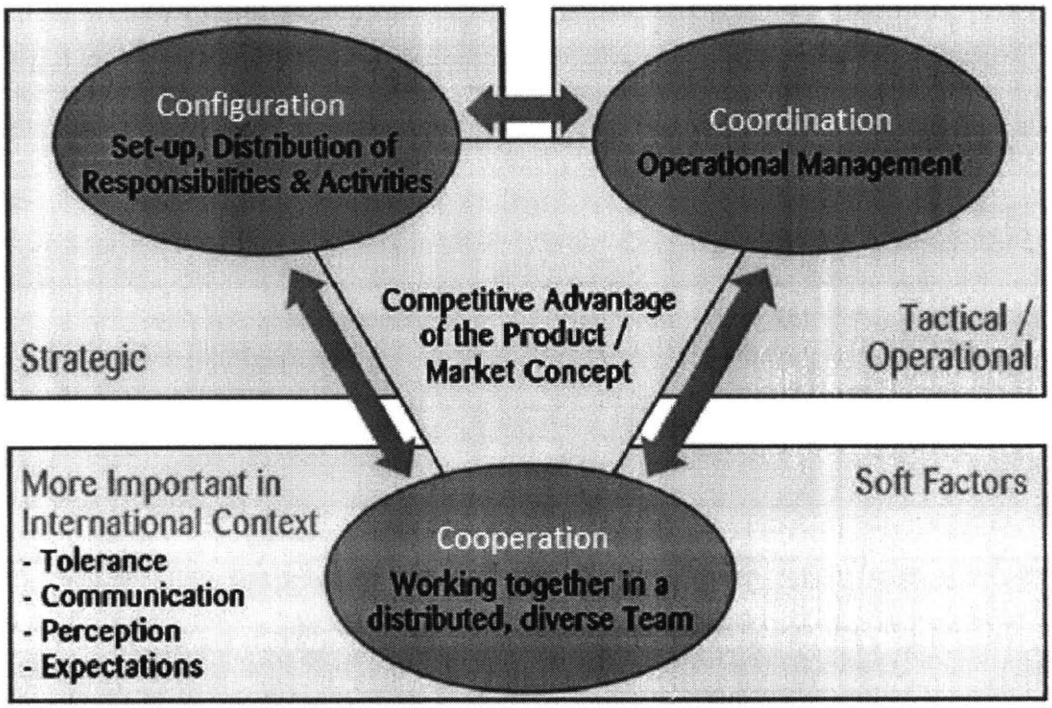

Figure 5: Framework for International Project Management (Source: Lectures from ESD.36)

Figure 5 shows the framework for international PM. Configuration at the early stages of the project is critical to ensure the project vision is clear, scope has been defined and the unified project goal understood by the global team.
Coordination and cooperation have to be monitored and improved along project development to ensure the challenges of international projects are overcome and the organization can truly obtain the benefits of lower cost, customer base expansion and technology and knowledge acquisition.

The organizational structure of projects has evolved to align with the complexity of modern projects. The following is the main classification of organizational structure described by Thomas J Allen in his book "The organization and Architecture of Innovation".

- Departmental or Functional Organization
- Project or Dedicated Organization
- Matrix Organization

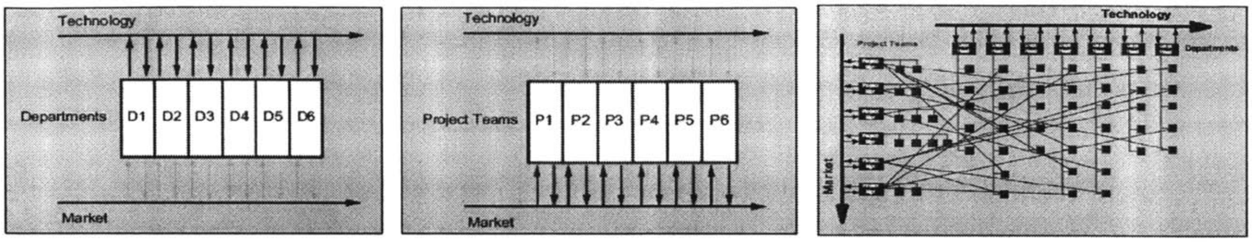

Figure 6: (a) Departmental org, (b) Project org, (c) Matrix org. Modified from (Allen & Henn, 2007)

Figure 6 shows a graphical representation of the three organizational structures commonly adopted in modern projects. The departmental organization groups staff by their specialties and provides the benefit of having strong contact with technology development; but it has weak interaction with the market. In this type of organization, the workers are just on loan to a specific project being developed and the project manager has low authority over the team members (who report directly to the management of their own department). The cross-functional communication under this structure becomes a challenge because people work in silos usually spread among different regions. Although this type of organization is not frequent in modern projects, it can still be useful in projects where uncertainty and risk are low, duration and scope are small and the company has become expert in delivering within the iron triangle targets.

The project or dedicated organization groups staff by product or service to develop, causing strong contacts with the market but weak links to technology development. The workers report directly to the project manager and communicate more with people inside the same project rather than with people of their same specialty. This helps communication and coordination efforts towards project completion; however, it dilutes the knowledge each engineer has within the cutting-edge technologies of his or her own specialty. This causes some problems in assigning team members finishing one project to another where different technologies are used.

The Matrix organization emerged in the aerospace industry around the mid-20th century as a hybrid of functional and dedicated organizations in an effort to keep the benefits of each structure and remove disadvantages. In this type of organization, workers remain in their departments but report directly to two bosses, the project manager and the functional manager. The links to technology and market are strong under this structure, avoiding dilution of expertise in specialties and improving contact with the development of products or services. The project manager usually has authority over tasking and budget, while the functional manager has it over resource allocation and promotions. Although this structure has proven its effectiveness, one of the main challenges under this type of organization is the battle for resources, corporate authority and budget between project and functional management and the need of the team members to accommodate the requirements of each manager.

2.2.3 PD Projects main challenges

As noted above, product development projects are complex in technical and organizational dimensions, number of tasks to perform, non-linear nature of task flow, simultaneous design freeze of components, subsystems and systems, dependency between components of the product, spread location of team members, organizational culture differences between regions and the interaction of cross functional groups to ensure success. These are some of the characteristics that make product development so challenging. Any minor change in the original project plan could put at risk the accomplishment of the project's iron triangle targets.

The following is a list of the most common challenges the organization creating the product faces:

- Customer requirements changes
- Regulatory requirements mismatch between markets
- New technologies adoption
- Understaffing
- Component, subsystem or system budget overrun
- Component, subsystem or system not meeting design specifications
- Unplanned design iterations
- Unplanned assembly line iterations
- Product test and validation unplanned iterations
- Poor communication between project stakeholders
- Project schedule delay
- Attrition
- Product complexity or levels of customization
- Suppliers' availability and sustainability
- Simultaneous product launches across the globe

The usage of proper project management tools to improve configuration, coordination and collaboration is critical to analyze all possible project outcomes and take actions to effectively manage risk and ensure compliance with the project iron triangle targets.

In Chapter 4 of this thesis, I will provide an application example of how project management tools such as Design Structure Matrix and System Dynamics can be used to analyze product development process inside an automotive OEM to uncover task sequence, task dependencies, communication and project parameters that should be monitored in order to avoid facing problems such as unplanned iterations, budget overrun, poor communication between project stakeholders and staffing levels.

2.2.4 Example of success & failure in Managing projects

The Manhattan Project

The Manhattan project was a research and development project led by the United States with the support of Canada and the United Kingdom. The main objective of the project was to develop the first atomic bombs. (Lenfle, 2008)

The project started officially in 1942, led by the US Army Corps of Engineers and required the involvement of several universities and civil organizations. The overall project integrated over 150,000 employees working on facilities spread all over the United States. These were created for uranium treatment, plutonium breed and atomic bomb design.

Besides the technical challenges of the project, the Manhattan project operated under tight security; indeed, secrecy was critical to ensure project success and avoid leakage of technical information to enemy nations. Even though the project had an enormous staff, only a few knew the overall project goal.

The overall project management of the project's cost, scope and schedule was led by US General Leslie R. Groves and the technical management of the project was led by Dr. Robert Oppenheimer. The project cost around US$2 billion dollars (about US$26 billion in 2014 dollars) and its duration was approximately three years. It led to the surrender of Japan and the end of WWII after the atomic bombing at Hiroshima and Nagasaki. (Schwalbe, 2009)

The preparing and planning phases of project management were led by Groves and Oppenheimer. Figure 7 shows the high level planning of the Manhattan project. It is important to mention that due to the high levels of uncertainty with the technology, usage of parallel approaches for material usage and bomb design during the planning, monitoring and adaptation phases was crucial to deal with risk and uncertainty.

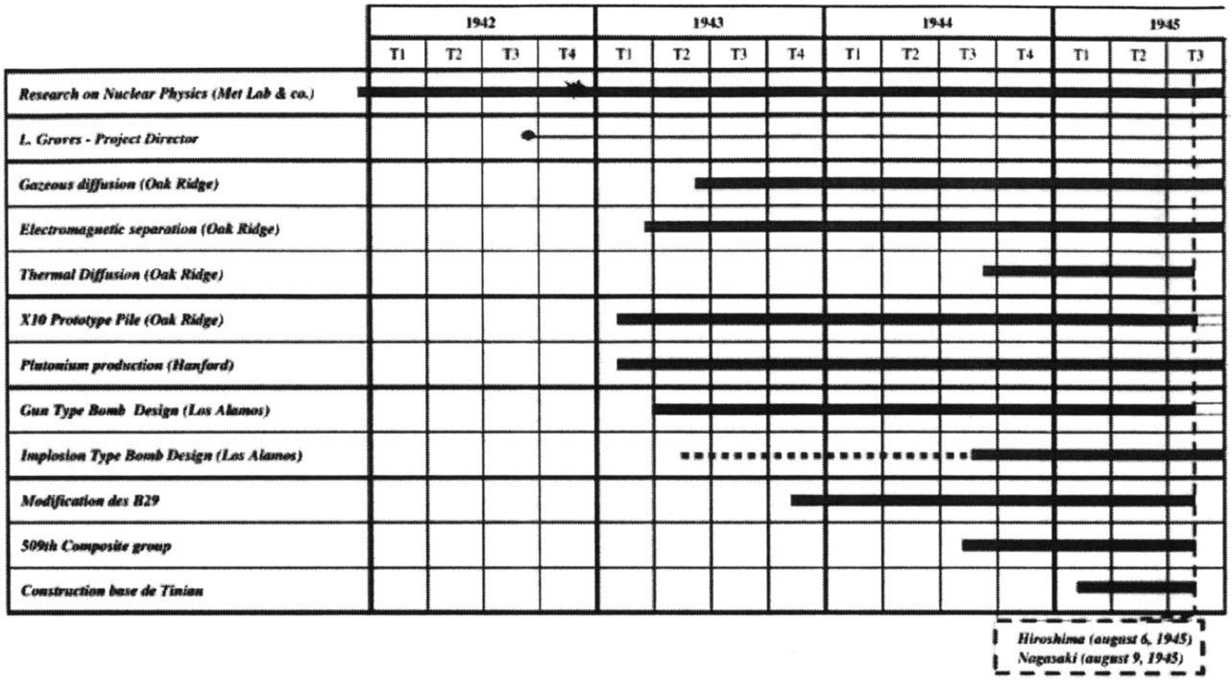

Figure 7: Manhattan Project Planning (Lenfle, 2008)

The Manhattan project is a clear example of success which could not have been achieved without the usage of project management tools and methodologies to meet iron triangle targets. The understanding of project complexity during the preparing and planning phases enabled the team to assign feasible targets of cost, schedule and scope. The integration of critical stakeholders and the high technical skills of the project team allowed quick issue resolution along the monitoring and adaptation phases. The importance of sponsorship and support from authorities – in this case the US Presidents Franklin Roosevelt and Harry Truman – overseeing the project was critical to ensure progress and completion of major milestones.

The US military has been one of the lead users of project management methodologies and their long history of success has been an inspiration and motivation in industry project management practices.

The project learning phase was very successful, since the Manhattan project marked the start of the nuclear age and several breakthrough discoveries in nuclear energy have occurred based on the lessons learned from it.

Denver International Airport (DIA) Automated baggage system

In 1989, the city of Denver decided to start an ambitious project to construct a new state-of-the-art airport in response to the need to increase airport capacity. The new airport would position the city as one the most important transportation hubs in the US, covering a land area of 140

Km^2 and having the capacity to handle more than 50 million passengers per year. (de Neufville, 1994)

One of the key features considered for the airport was an automated baggage system that would allow aircraft turnaround time of approximately 30 minutes. This would increase operations efficiency.(de Neufville, 1994)

The baggage system was integrated by 17 miles of track, 5 miles of conveyor belts, 3,500 carts, and 14 million feet of wiring, a network of more than 100 PC's for carts control, 5,000 electric motors, 2,700 photo cells, 400 radio receivers and 59 laser arrays. (Calleam Consulting Ltd., 2008)

The project was completed 16 months late, with delay costs of approximately $500 million and with a final product distant from the original 1989 specs. The maintenance costs of the baggage system upon operation were around US$1 million dollars per month, which at the end exceeded the cost of the manual baggage handling system that was eventually adopted 10 years later. Figure 8 shows a picture of the conveyor belts that were part of the automated baggage system.

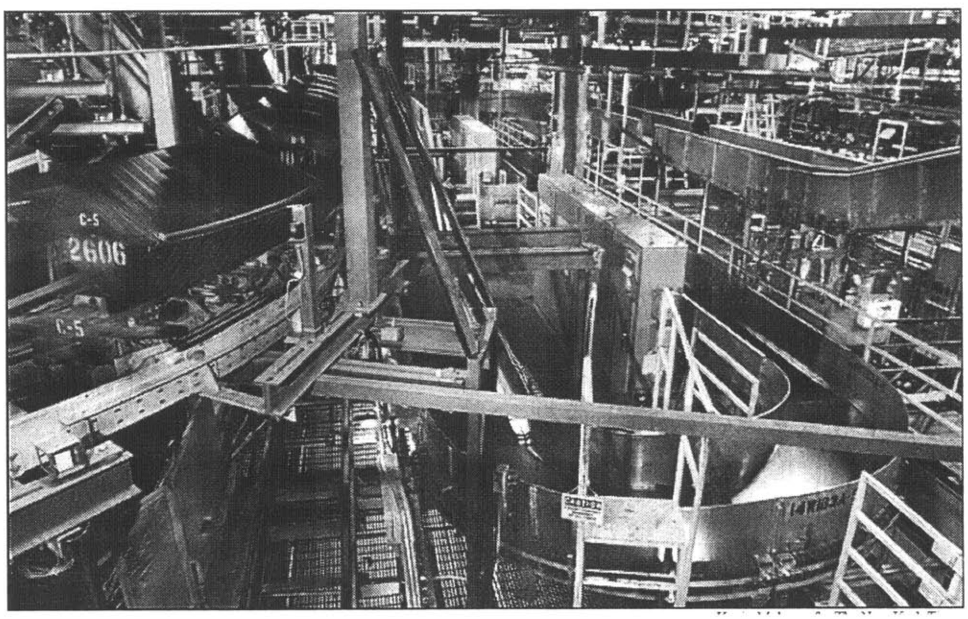

Figure 8: Conveyor Belts of the DIA Automated Baggage System (Moloney, 2005)

The problems for the automated baggage system started in the very beginning–during the preparing and planning project management phases–by underestimating project complexity and committing to a schedule impossible to meet. Critical stakeholders for the system such as the airlines and the contractor company in charge of the creation of the airport facilities were not integrated during the project preparing and planning which caused late requests during the development of the system to meet stakeholders' needs. The lack of technical skills of the management team in regards to this type of system impacted the monitoring and adapting phases, where poor communication with suppliers, airlines and government produced slow responses to deviations from the project plan and cost and schedule commitments were impossible to achieve. The lack of risk management actions along the project, mainly because of the project's tight schedule, restricted the team from analyzing in detail the possible outcomes of the project based on constant design changes and their impact on cost, scope and schedule.

The Denver International Airport automated baggage system is a clear example of failure which could have been avoided by an efficient development of the activities to be performed during the different project management phases.

2.3 Best Practice Tools for addressing Complex Projects

Traditional project management tools such as Gant, WBS and CPM are well suited for linear systems where project progress moves downstream in the list of tasks to perform and there is no feedback or changes that could impact upstream tasks. However, as explained in section 2.1, the nature of systems has evolved from mindless to multi-minded and sociotechnical, where nonlinearity and the interaction of several functions is commonly producing iterations and feedback to upstream tasks that were initially considered complete but, based on downstream results, in fact needed to be reassessed and redone. This section provides an overview of two best-in-class project management tools – Design Structure Matrix (DSM) and System Dynamics – to effectively understand iterations and nonlinearity in project processes and analyze possible project outcomes based on original project targets, initial parameters – resources, time, sequence of work, newness of the project, productivity and fraction of error – assigned to the project team and impacts that unplanned iterations, infeasible plans and managerial decisions have on overall project performance.

2.3.1 Design Structure Matrix

Design Structure Matrix is a network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture. (Eppinger & Browning, 2012)
It is primarily used in engineering management but DSM is well suited to applications in complex systems of any kind. DSM consists of a square NxN matrix that helps to map interactions among the elements of the system. Figure 8 (b) shows an example of a 12x12 design structure matrix representing the task sequence and dependencies of Figure 9 (a).One of the fundamental benefits of DSM, in comparison to other network modeling methods is the graphical nature of the matrix display format. Figure 9 (b) is easier to understand than the spaghetti representation on Figure 9 (a) and still DSM captures the same amount of information of tasks sequence and dependencies.

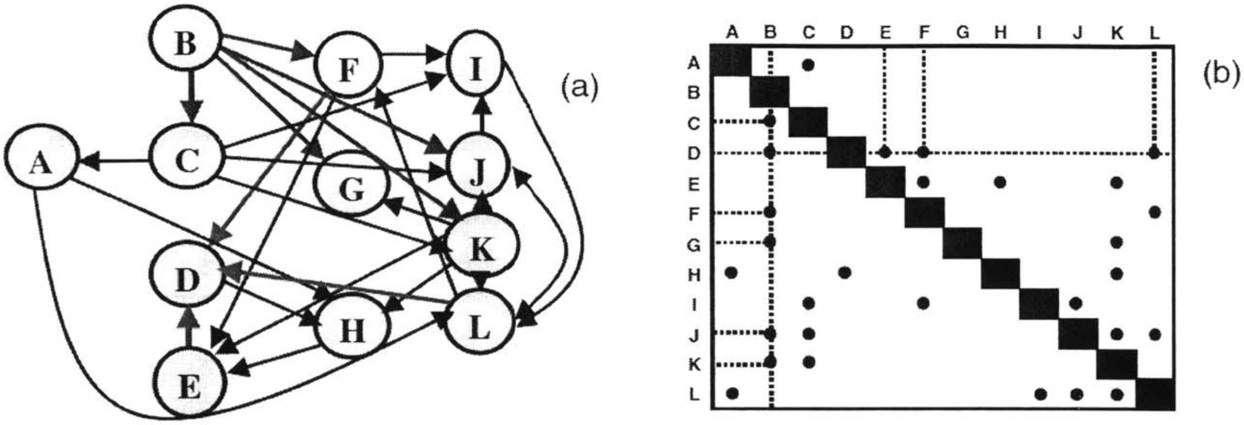

Figure 9: (a) Task sequence and dependencies, (b) DSM representation. Modified from (Yassine & Braha, 2003)

Figure 9 (b) is called a binary DSM, since the off-diagonal marks represent only the presence or absence of interaction between on-diagonal elements. The binary DSM representation can be extended by representing the importance, strength or impact of each interaction by using numbers, symbols, shadings or colors for the off-diagonal marks. This variety of DSM is called numerical DSM.(Eppinger & Browning, 2012)

DSM can follow two conventions: Inputs in Rows (IR) or Inputs in Columns (IC). Figure 9 (b) follows the IR convention where the marks in each row are inputs to the elements in the diagonal while the marks in the column are the outputs that these elements in the diagonal provide to others in the system. Figure 10 provides a graphic representation of the IR convention. It is important to mention that the work done using DSM described in Chapter 4 of this thesis follows the IR convention.

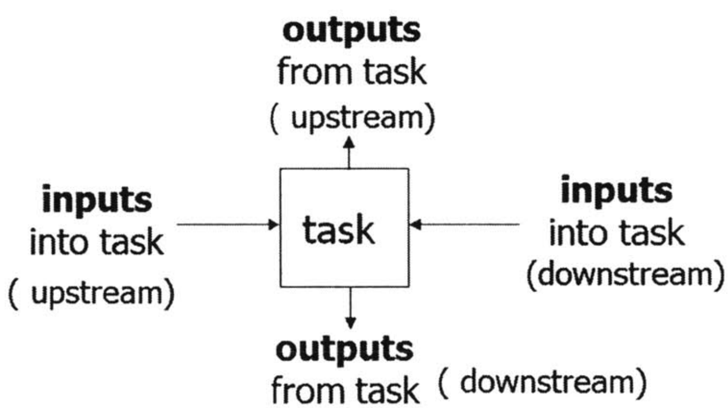

Figure 10: Inputs in the Rows (IR) convention. Source: ESD.36 Lectures

2.3.1.1 Types of DSM

There are four types of DSM models that can be classified into three main categories, as shown in Figure 11. Under the static architecture category, the DSM models represent elements that exist simultaneously. Products and organizations are types of applications for this static architecture category. For temporal flow category, DSM models represent elements that may be actuated over time. Processes, activity-based process models and parameter-based models are types of applications for this temporal flow category. The third category is called multidomain and the DSM models under this category represent more than one type of DSM (product, organization and/or organization) in a single matrix. (Eppinger & Browning, 2012)

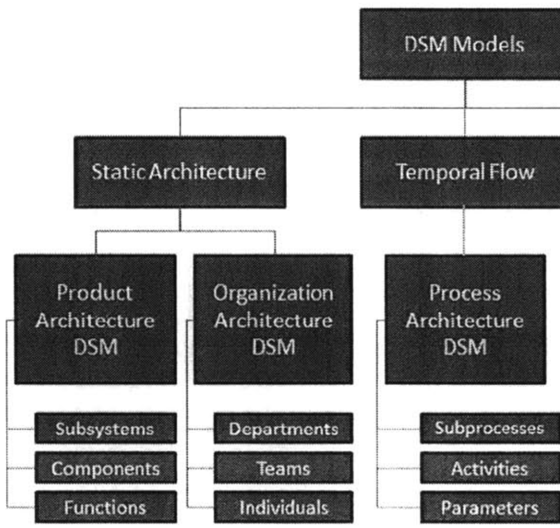

Figure 11: Types of DSM. Modified (Eppinger & Browning, 2012)

Design structure matrices can be partitioned or rearranged using different analytical methods, the most common being clustering and sequencing. Clustering analysis is commonly used for DSM models under the static architecture category where the interaction marks are largely symmetric along the diagonal. Sequencing analysis is commonly used for DSM under the temporal flow category, where the elements of the system begin and end at different times. The main purpose of DSM partition using clustering or sequencing methods is to reduce the number of iterations in the system by reducing the amount of off-diagonal marks above the diagonal in the IR convention. (Eppinger & Browning, 2012)

2.3.2 System Dynamics

System Dynamics is a computer simulation methodology used to enhance learning in complex systems, based on the theory of nonlinear dynamics and feedback control originally developed by Jay W. Forrester at MIT. (Sterman, 2000)

Complex systems are characterized by the number of tasks to perform, non-linearity nature of the task flow, simultaneous validation of components, subsystems and systems, dependency between components or subsystems, spread location of team members, organizational culture differences between regions and the interaction of cross-functional groups to ensure success. Examples of complex systems include the stock market, social insects and ant colonies, biospheres and ecosystems, brains and immune systems, product development and manufacturing businesses and any human group-based endeavor in a cultural and social system -- such as political parties or communities.

2.3.2.1 System Dynamics in Project Management

The usage of system dynamics in project management has been successful due to the complexity embedded in the nature of projects where the set of tasks to be completed show a nonlinear behavior, causing challenges in complying with original project targets. The usage of system dynamics can help to understand how changes along the project in scope, performance of project team, technology familiarity, staffing levels, work process and side effects of managerial responses during monitoring and adaptation phases of project management affect project cost, scope and schedule. The usage of system dynamics in project management has generated a branch of methodology called "project dynamics". Project dynamics is the usage of fundamental system dynamics structures to analyze, forecast and learn from current, past or future projects and to understand how iron triangle parameters are affected along the project lifecycle based on the endogenous and exogenous characteristics of the project.

2.3.2.2 Fundamental Structures to Analyze Project Dynamics

According to Lyneis & Ford, 2007 there are four fundamental structures used to model project dynamics:

- Project Features
- Rework Cycle
- Project Control
- Ripple and knock-on effects

Project Features

This structure is created to simulate the work process of the project by representing tasks or work packages with certain sequences aligned with the actual project being used as the base for the model. The tasks to be performed during a project typically start in a stock of original work to do and flow according to the project development process and tasks sequence to a stock of work done. The application of resources to complete project tasks is another feature that is included in this structure and is not limited to the addition of resources at the beginning of the project. However, it can be modeled to change dynamically based on the gap between project performance and project targets.

The rework cycle

This is the fundamental structure for project modeling using system dynamics. The basic premise is that during the process of moving tasks from the stock of work to do to the stock of work done, only a work fraction is performed correctly. The work done incorrectly flows to a stock called "undiscovered rework", this undiscovered rework has to be discovered by downstream activities in the project and is reflected in more effort required to fix the errors and complete tasks that were considered completed during previous stages of the project. This difference between work done and work done correctly is the main reason for the misalignment between project manager perceptions of project progress versus actual project progress.
It is important to mention that once undiscovered rework is discovered it becomes part of the stock called "rework to do" and again there is still only a fraction of such rework that is done correctly and the rest generates more undiscovered rework that requires an increase in effort to discover rework and fix errors again. These increases in effort affect the cost, scope and schedule of the project, since this error generation is usually neither considered during the preparing and planning phases of the project nor estimated properly.

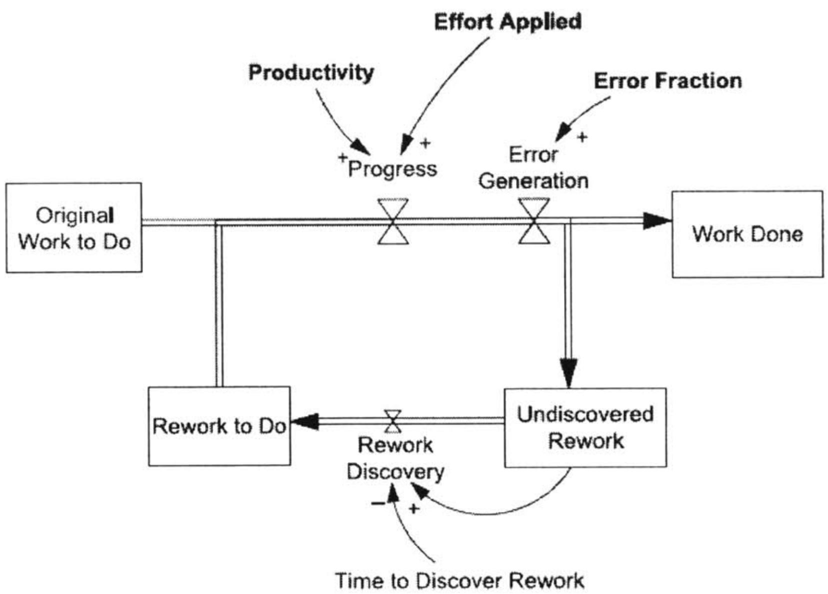

Figure 12: The rework cycle (Lyneis & Ford, 2007)

Figure 12 shows the generic structure of the rework cycle. The behavior generated by this structure is aligned with the behavior observed in complex projects where productivity and fraction of work correct and complete based on error fraction are not 100% from the beginning of the project, based on the limited amount of information the team has when working with new technologies or innovative products, the experience of the team members, the time provided to complete the project and the estimation of resources required. Productivity and Error fraction change along the project lifecycle based on the actions taken by the project management team to close the gap between project performance and project targets.

Project Control

This structure is focused on the actions taken by the project management team – managerial responses – to close gaps between project performance and project targets. Performance and targets are usually measured in terms of the iron triangle parameters of cost, scope and schedule. Between the common actions taken to close project gaps and meet project targets are the usage of overtime (work more), speed (work faster), deadline slippage and the addition of resources. Figure 13 shows the feedback loops that each of these actions generates and how they impact the parameters in the rework cycle structure. The willingness to let deadlines slip impacts the intensity of the managerial decisions for working more, working faster or adding people. It is important to mention that each of these managerial decisions impose costs which limit their size and speed of implementation towards closing the gap between performance and targets.

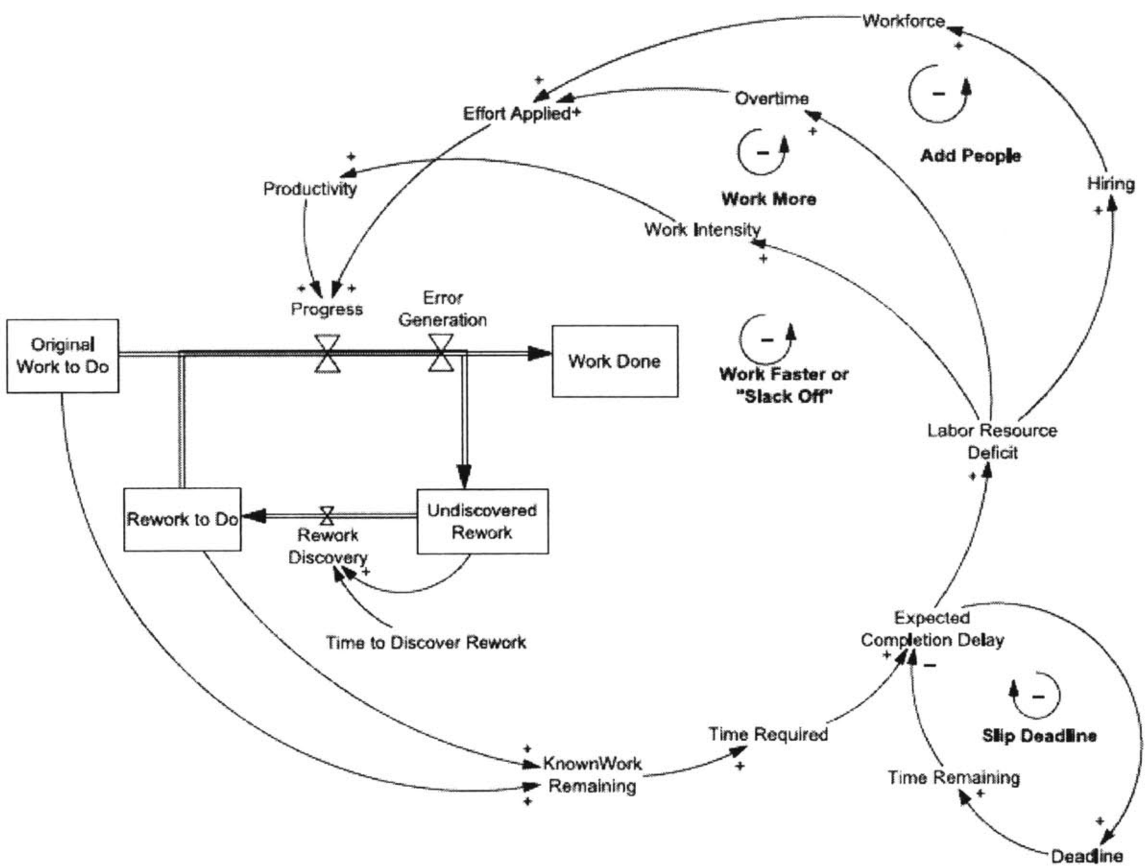

Figure 13: Project Control Structure (Lyneis & Ford, 2007)

Ripple and Knock on Effects

Managerial decisions implemented in the project control structure in efforts to close the gap between performance and targets generate unintended side effects, resulting in policy resistance. These side effects produce feedback that can be classified as primary, secondary and tertiary. The primary feedback are the impacts of project control on rework – through error fraction – and productivity and are called ripple effects. The common ripple effects are: experience dilution, communication difficulties, fatigue and haste makes waste.

Experience dilution is an effect of adding resources to the project in efforts to control it. The additional staff have varying skill levels and are not fully familiar with the project, so there is a learning curve that affects the error fraction. The productivity is affected in the sense of having experienced project team members investing time training the new hires and reducing the time they spend working on project-related tasks.

Communication difficulties are an effect of increasing the size of the team by adding resources, which increases the error fraction and reduces productivity.

Fatigue is an effect of working overtime, which leads to an increase in error fraction and lower productivity. It is important to mention that the effects of fatigue on team performance depend on time (error fraction and productivity). Haste makes waste is an effect of work intensity, which basically can be explained as cutting corners in the development process; this leads to increase in error fraction. Figure 14 shows the feedback loops generated by the ripple effects of managerial decisions implemented for project control.

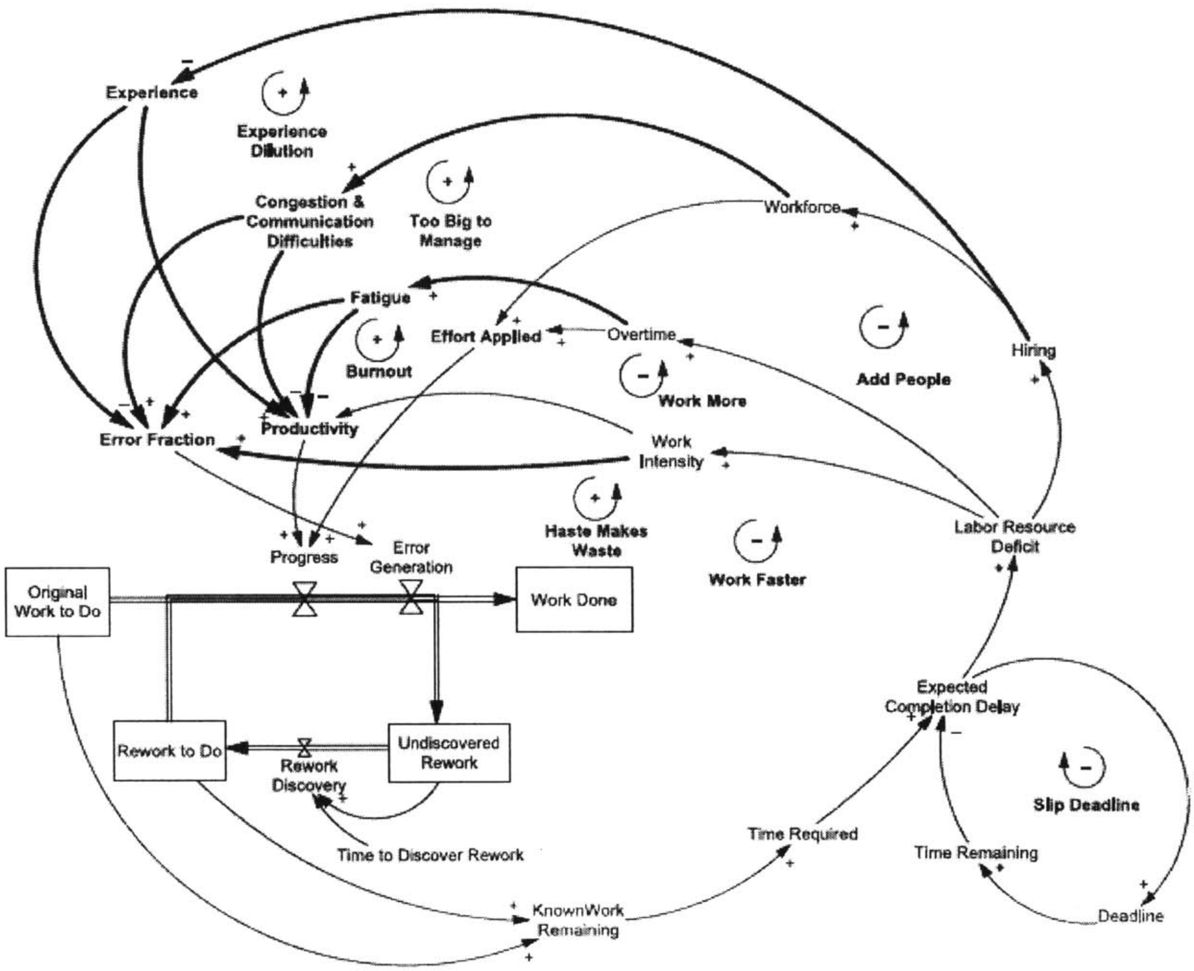

Figure 14: Ripple effects feedback loops (Lyneis & Ford, 2007)

Secondary and tertiary knock-on effects (feedback) are generated by ripple effects. Some of these knock-on effects are a consequence of the physical process of the project work and others are a consequence of human response to project conditions. The most common knock-on effects are:

- Out of sequence work
- Errors build errors
- Errors creating more work
- Hopelessness.

Figure 15 show the feedback loops generated by the knock-on effects of ripple effects.

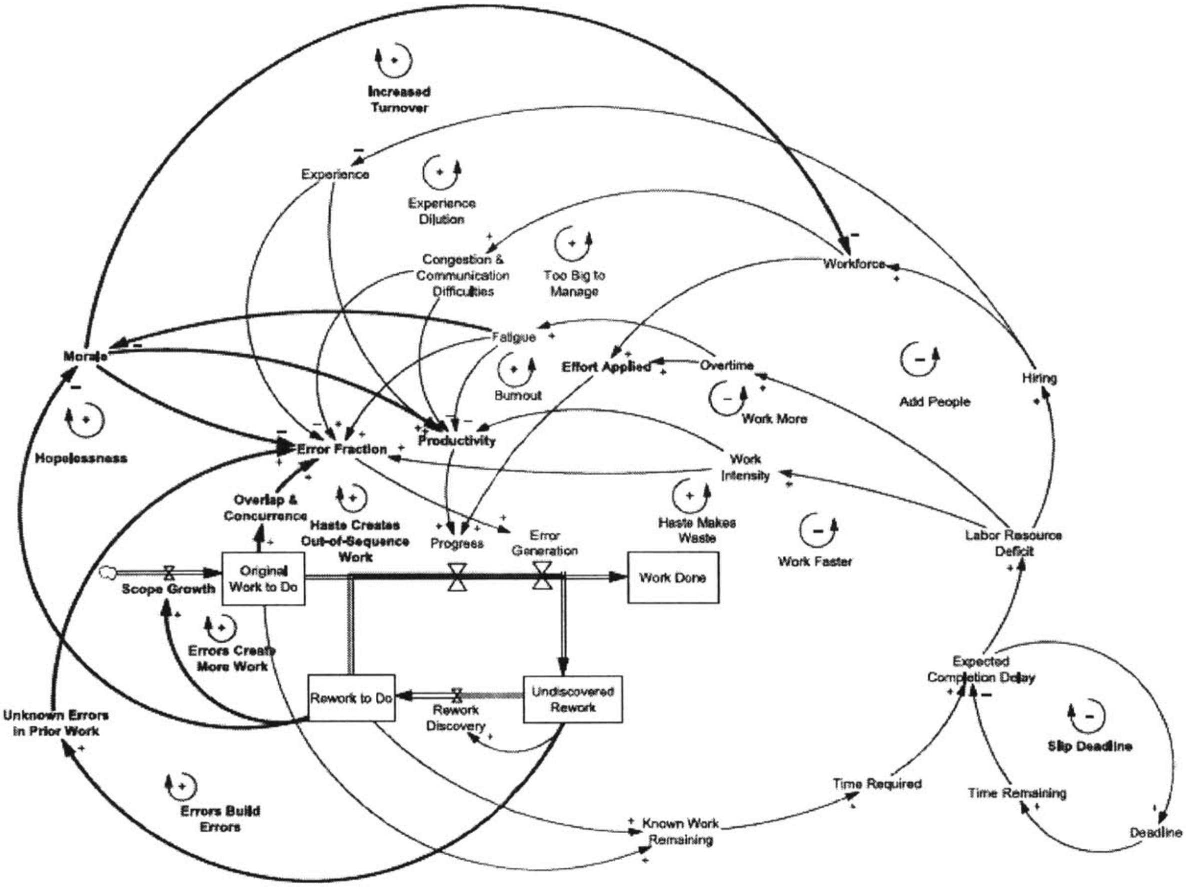

Figure 15: Knock-on effects feedback loops (Lyneis & Ford, 2007)

Out-of-sequence work is a consequence of haste makes waste by completing tasks in parallel when the original project's work flow was developed as a sequential string of tasks due to the dependencies between tasks. This knock-on effect decreases productivity and increases the error fraction.

Errors build errors is a consequence of the quality of the tasks done upstream compounding quality problems in tasks done downstream by the undiscovered rework embedded in the upstream work. This knock-on effect increases the error fraction.

Errors creating more work is a consequence of quality errors in tasks done upstream and the need to correct them before moving further down in the project workflow; this increases the overall effort devoted to error fixings. This knock on effect increases the amount of work to do.

Hopelessness is a consequence of fatigue generated through overtime and is related to low morale levels and increases in turnover. This knock-on effect increases the error fraction and decreases productivity.

Chapter 3: Automotive EDS Design and Development Overview

3.1 Phases: Define, Design, Validate and Launch

The EDS design and development process to be described in this chapter is based on this author's experience working for a North American OEM over the last five years, surveys performed by EDS engineers and engineering supervisors working for the OEM around the world and the analysis of the OEM's EDS product development process.

The process will be classified under four major phases: Define, Design, Validate and Launch. It is important to mention that these phases are sequential and even though the OEM's product development system integrates more segmentation in regards to the design and development process, the usage of this generic classification helps to maintain proprietary information while illustrating the essence of the process.

Define: During the define phase, the EDS team is estimated for the program. The EDS staff at this point is small, usually integrated by a senior EDS engineer and an EDS technical specialist; the ramp-up for the EDS staff comes during the design phase. In the define phase, the EDS team works closely with product planning, marketing, finance, cost estimators, design studio, R&D, other design and development teams –exterior trim, interior trim, powertrain, chassis, climate control- and manufacturing to collect initial assumptions of the new product to develop. These include volumes forecasted, level of change for the new product in comparison with a surrogate vehicle, surrogate vehicle design and cost, initial concepts for new technologies to be adopted, manufacturing plant (to assemble the new vehicle), list of electrical features to be included in the new vehicle program, initial packaging of new electrical modules, markets to be covered by the new vehicle and competitor benchmarks. The main activity the EDS team performs during this phase is the quotation of the new features to be included in the program based on the requirements from manufacturing, design studio, marketing, finance and other design and development teams. The EDS supplier selection is also part of the define phase; this is done at this point due to the need for the supplier to prepare the necessary production capacity –tooling, workforce, facilities- for the new program to be developed. At the define phase, product planning is the lead and, along with finance, monitors cost, scope and schedule through the review of system and subsystem information in several milestones. This is to ensure the estimates provided by EDS and the rest of the design and development teams are aligned with the original targets. It is important to mention that during this phase, there are high levels of uncertainty in regards to the cost of cutting-edge technologies to be introduced for the first time in the OEM, so risk management is fundamental to avoid inaccurate quotes for the new product. The EDS team has heavy support from R&D to get as much detail as possible for new technologies, ensuring there is enough information to provide an accurate cost estimate. The review of lessons learned from other vehicle programs (outside the OEM or outside the industry) implementing similar features is another approach that helps to deal with uncertainty. As we can see from the explanation provided for the define phase, the way project management is exercised during this stage of the process is through preparing and planning the lists of tasks to perform, targets to accomplish, technical content, identification of manufacturing facilities, supplier selection, allocation of resources and review of lessons learned.

Design: During the design phase, the EDS team gets fully staffed and focused on collecting design requirements at subsystem and component levels and transforming such requirements into wiring harness data:

- Electrical schematics
- Circuit content
- Wiring harness partition
- Design quality controls –DFMEA-
- Manufacturing quality controls –PFMEA-
- 2D prints and 3D data.

The EDS team works closely with manufacturing, suppliers, CAE Engineers, systems integration team, service and other design and development teams such as interior and exterior trim, climate control, chassis and powertrain.
The EDS design and development at this point splits into two sections based on the OEM's product development system, the design and development of platform content and the design and development of top-hat content. Platform content covers all electrical distribution systems responsible for proper functioning of vehicle systems: powertrain, safety, exterior lighting, chassis, power distribution and power supply. Top-hat content covers all electrical distribution systems responsible for proper functioning of vehicle systems inside the vehicle, such as climate control, multimedia, power convenience electronics, interior lighting, communications and entertainment.
One of the first activities the EDS team has to perform, along with the systems integration team –which is responsible for integration of all electrical and electronic content in the vehicle—is collection of electronic modules characteristics and requirements, such as number of signals to be used, along with power and ground, type of interface at the module side, circuit pin out at the module interface, voltage operation rate and temperature operation rate. Based on this electrical modules information, logical schematics of the vehicle are generated covering all inputs and outputs between power supply, power distribution, ground, communication and logic and the requirements in regards to fuses and relays to enable proper functioning of the systems. Along with logical schematics of the vehicle, the EDS team has to work on the creation of 3D data based on the assumptions cascaded from the define phase and the proposed physical vehicle location of the electronic modules obtained from the module owner. The 3D data contains major mechanical components such as clips, connectors, grommets, circuit coverings and plastic protectors that enable EDS to be routed along the vehicle and connected to specific electrical devices. The 3D data has to consider the partition of EDS in major zones of the vehicle to align with major vehicle sections, such as the engine compartment, the front end and rear end structures, the cockpit module, closures, chassis and roof and allow the assembly of the EDS at

the vehicle assembly line and provide an EDS segmentation that enables the easy serviceability of the car.
The 3D data for the EDS of the vehicle goes through several iterations along the design phase, due to EDS dependence on most of the design of other components in the vehicle. Since the design freeze for most of the components and subsystems in the vehicle is similar –except by powertrain which is completed long before the rest of the vehicle subsystems – these iterations can occur until the very last part of the design phase causing, a lot of rework on EDS design efforts.

Once the logical schematics are obtained and there is a fair level of alignment between 3D data and design intent, harness topology is generated which describes the location of EDS along the vehicle, considering EDS segmentation and the location of electrical devices. Computer Aided Engineering (CAE) is also performed at this stage to define the proper wire sizes and fuses according to restrictions in length based on 3D and the location of circuits along the vehicle based on logical schematics and topology.

The physical schematics of the vehicle are then generated based on input from 3D data, CAE and logical schematics. The physical schematics contain the specific information of wire size, wire length and EDS segmentation and interfaces between EDS segments. The physical schematics also contain each connector number based on electrical modules characteristics, connector code, circuit name and color; these are selected based on OEM design requirements for wire usage and location. CAE has to then be performed on physical schematics to validate design decisions taken in regards to wire length, size, fuse allocation, ground and power strategies.

Based on 3D data and physical schematics, 2D prints are generated for EDS segments or wiring harness families. These prints contain different configurations of mechanical components:

- Coverings
- Connectors
- Circuit bundles
- Clips
- Grommets and terminals
- Circuit content
- Circuits name, size, color, length and location

These depend on the feature-offering catalog for the vehicle. Each configuration is termed wiring harness level and provides a unique set of mechanical components and circuit content that work properly only when installed in a vehicle containing the same feature content. The 2D prints contain all necessary information to build a physical wiring harness.

Once 2D prints are generated, activities are performed to ensure the physical harness will meet the design specifications and not cause any issues at the moment of manufacture. The

electrical compatibility review is one of the fundamental activities that have to be performed, consisting of a crosscheck of information between electric modules characteristics and requirements, logical schematics, physical schematics, circuit configuration according to the feature-offering catalog and 2D print.
This compatibility review should be performed to ensure all documentation and information used to build the physical harness is aligned with design intent. Design for manufacturing review is also performed during this time, to ensure the harnesses can be manufactured under required specifications and harness manufacturer capabilities.

Along the design phase, there are activities performed constantly though each design milestone to ensure quality of the data generated. Some of these activities are:

- DFMEA
- PFMEA
- Lessons learn review
- Identification of special characteristics critical for quality.

At the end of the design phase, 2D prints and 3D data are frozen and released to the supplier in order to start manufacturing EDS parts for the validation phase.

Validation: During the validation phase, the EDS team works closely with manufacturing, vehicle engineering validation, vehicle integration, suppliers, systems integration, service and other design and development teams. In the validation phase the EDS team supports the electrical functional tests that are performed without any vehicle components apart from electrical components. The electrical components are connected to the wiring harnesses and ground and power are provided. In this functional test, the validation of proper subsystems function is reviewed to ensure the electrical system of the vehicle matches the design intent and avoid further issues when assembling entire vehicles in the production or static line. Once the functional test starts, the set of validated harnesses and electrical components are transferred to either the pilot plant or production plant of the OEM to start assembly of prototypes to validate overall vehicle performance. During prototype builds, the manufacturing team confirms that the assembly sequence of components does not represent any problem at static or production lines and the fit and finish of the parts are validated. In addition, the EDS team has to monitor the assembly of vehicles, provide guidance to the operators at the assembly line and gather feedback to ensure assembly can be done without concerns once vehicle mass production ramp-up begins during the launch phase.
Once vehicles are fully assembled and issues presented during the functional test or prototype build are resolved, the vehicles are submitted to different types of tests to ensure targets have been achieved. The main tests performed are:

- Noise vibration and harness tests
- Durability tests
- Routing quality assessments

- Fit and finish quality audits
- Calibration and electrical checks

The importance of performing a robust design phase is reflected in the validation phase; any design issue discovered during the validation phase is more expensive to fix and has serious repercussions in the schedule and scope of the project. The fact that the validation phase is so close to the actual release of the vehicle through the launch phase introduces a lot of limitations as far as time to resolve any design issues and the cost to fix such issues. If the validation phase is not properly completed, it could result in warranty claims and recalls once the vehicle is in customer hands. Several milestones have to be passed at vehicle level performance and targets to enable the project to move forward to the launch phase.

Launch: During the launch phase, we have production ramp up, permission to proceed with sales and logistics and distribution of the product to defined markets. The EDS team works closely with manufacturing, service and Plant Vehicle Team (PVT), who take the lead in EDS design maintenance –quality and cost improvements- once the vehicle is released.
The EDS team takes the role of support and guidance to the PVT team, who then start a process of continuous improvement in the EDS design and coordination of small changes that could provide a bigger value to the customer. The importance of a proper validation phase takes importance at this launch phase, since any issue not detected during the validation phase could cause potential warranty claims or product recalls that could affect the value offered to the customer and the overall product impact on the market.

3.2 EDS D&D Pillars: People, Process, Training & Development and Flawless execution

The EDS organization at the OEM has built its mission and vision toward the successful completion of work with high quality and on-time, on top of four fundamental pillars that are explained below.

People: The EDS organization acknowledges the importance of talent inside the organization towards company deliverables. Therefore, efforts are constantly made to bring inside the organization people with high technical, communication, team-work and decision-making skills and who otherwise are capable of adapting quickly to OEM design and development systems. In this way, the organization benefits from the experience these people brings from other OEMs, suppliers or related industries.
Detailed interviews are performed during recruiting to ensure that best-in-class engineers are brought into the organization. They enhance the quality of the design implemented in all vehicle programs and this, in turn, results in higher value to the customer. The retention of key talent is a priority at an OEM always generating new opportunities and challenges; in a virtuous cycle, these opportunities and challenges motivate engineers and raise their professional growth. The OEM's interaction with universities around the world has led to a variety of opportunities for the engineers inside the organization to join educational programs supported by the OEM towards

the improvement of Product Development. The establishment of international assignments where engineers can interact with their counterparts in other regions and be exposed to an accelerated learning process is an important action the organization takes towards talent acquisition and retention.

Process: The EDS organization acknowledges the importance of a robust design and development process towards company targets and deliverables. Although there is an established global product development system in the OEM, there are several working-level activities that are unique to the EDS organization and that can be analyzed to define the best practices to accomplish tasks with quality and on time. There is a group of EDS technical specialists inside the organization that is in constant communication with sources inside and outside the company to implement best-in-class processes that help the organization to improve the EDS design and development process. There are initiatives to involve EDS engineers in the improvement of the EDS D&D process as well. These initiatives are quite value-adding, since they involve the lead user of the process –EDS engineers- who have profound knowledge of the activities to perform; they are able to identify uncovered needs through the EDS D&D process. There are also forums of open discussion –tech clubs- led by tech specialist teams where the EDS community can share major lessons learned from specific projects. The forum also helps engineers obtain feedback and guidance in regards to roadblocks or issues happening in their projects.

Training and development: The EDS organization is constantly making efforts to ensure engineers can exploit their strengths and close gaps in their knowledge bases. There is an individual technical development plan document that is filled by the engineer and the management team to identify the technical level of each engineer and the necessary training that has to be taken during the calendar year to close the aforementioned gaps and improve their technical profiles; this is required to become a better EDS engineer. This document is revised twice a year and the management team is responsible for scrutinizing the progress made by the engineer; the management team plans and monitors the necessary activities and educational programs required for the engineer to achieve professional growth within the organization.
As mentioned in the People pillar explanation the organization keeps strong relationships with universities around the world to send EDS engineers to educational programs focused on the improvement of product development. These educational programs help:

- Expand engineers' visions to encompass different types of industries and processes
- Design effective product architectures
- Approach complex systems
- Manage efficiently

The international assignments expose engineers to a variety of technical environments to accelerate learning in the OEM design and development process; the organization does this for the training and development of its engineers.

Flawless execution: This pillar depends heavily on the people, process and training and development pillars. It is related to the accomplishment of key engineering milestones with quality and promptness; this holds for each of the projects with which the organization is involved. The organization acknowledges that in order to be competitive in the automotive industry, the scope of new projects increases overtime and the allocated time to complete such projects decreases. Therefore, flawless execution is fundamental when working in environments with tight cost, scope and schedule. Yet, flawless execution is just one of many characteristics the organization has to nurture, such as getting talented engineers, offering challenges that help them keep learning and improving, and providing a training and development platform capable of measuring technical skills, leadership skills and communication skills progress along each engineer's professional career inside the OEM.

3.3 Communication, Tools and Organization

In order to better understand the analysis performed during chapter 4 of this thesis a brief overview of the OEM communication, tools and organization structure is provided in this section.

Communication

As discussed in Chapter 2, modern projects are complex sociotechnical systems and product development is a clear example of that. Product development excellence is now central to competitive advantage in the automotive industry; this contrast with previous strategies that focused on manufacturing and sales capabilities. In these efforts, the industry has taken different strategies to generate continuous improvements. These includes introduction of product platforms to enable commonality, Design modularity and outsourcing of engineering and manufacturing to low-cost labor countries. All these actions introduce new interfaces inside the product development system and communication, as reviewed in section 2.2.2. They are the keys to truly designing optimal strategies for product development excellence. The automotive industry trend towards global products has led to the global spread of the product development team, working across different time zones, languages, organizational cultures, levels of technical skill and local regulations and requirements. Communication then becomes a challenge based on these factors. The EDS organization prefers communication face-to-face, where there is less chance of information transfer degradation. However, this type of communication is not always possible due to the distributed location of the team. Efforts toward face-to-face communication have increased for the validation and launch phases of the product development cycle, due to the need for immediate resolution of any issues discovered therein. For the define and design phases, communication is mostly handled by telephone or e-mail, which brings a certain information challenge, especially when the team members speak different languages and have different technical skills. The usage of remote conference systems is very common in the EDS department to involve multiple stakeholders in the transfer of critical information and alignment of next steps towards problem resolution. The standardization of working level processes at this point becomes critical to enable better communication among the team members, regardless of the differences generated by the global team distribution. The

EDS process has to become the strongest communication tool in the organization to truly optimize product design and development globalization.

Tools

The EDS organization acknowledges the importance of proper tools to help with the design and development process. The organization focuses its efforts on developing tools that reduce the time required to perform tasks and that help to minimize iterations or rework downstream. Computer Aided tools such as 3D CAD, CAE and 2D CAD have been implemented in the design and development process to validate designs through simulation and avoid the need to create a large number of physical prototypes to validate process decisions. It is important to mention that the creation of prototypes is expensive in the automotive industry, so the implementation of these tools moves part of the validation process back to the early stages of the design. One of the lead users of such computer aided tools is the aerospace industry, where the number of prototypes planned is close to zero. Therefore, the usage of computer aid tools represents a big part of their design and validation process. The level of integration of these computer-aided tools is still an area for improvement in the EDS organization, since the engineers still have a lot of manual input and manipulation of data. The aerospace industry has the highest level of integration of these tools in its design and development process, making the analysis performed more reliable.

The usage of robustness tools, such as DFMEA, PFMEA, Six Sigma, P-Diagrams and Special Characteristics Identification play a fundamental role in the design and development process. However the correct usage of these tools requires proper training for the engineering staff and special monitoring of updates from milestone to milestone.

The OEM has developed several databases for cross-functional communication. These databases are designed to:

- Review design specifications and, design requirements
- Release parts in the OEM's system for order and supply
- Manage issues discovered during parts of the design and development process
- Manage issues discovered during prototype builds and production trials
- Communicate design changes to the wiring harness supplier
- Communicate electronic modules characteristics
- Release 2D and 3D data to suppliers and cross-functional groups inside the OEM
- Communicate and resolve validation problems, such as durability and quality audits

For project management and progress tracking, the OEM has two main tools: Integrator and Design verification systems where score cards are captured based on the progress the team has achieved against the original plan and deliverables. These score cards are reviewed at major design and development milestones to ensure the team is performing as expected or implement actions towards the closure of gaps.

Organization Structure

As discussed in section 2.2.2, there are several organizational structures that could be implemented in an organization, according to the complexity of a project. The EDS organization uses a matrix structure having a functional manager for the entire EDS department and a number of project managers based on the number of projects being developed. Even though the literature describes several challenges when working under a matrix structure, the EDS organization has overcome such challenges by giving more authority to the functional manager. The functional manager is in charge of resources allocation, tasking, budgeting and promotions authority. However, in regards to promotions, the project manager input is fundamental. The project manager acts as more of a coordinator for all the electric and electronic design engineering teams and keeps track of iron triangle parameters over the life cycle of the project. Strong communication and coordination is required between both managers to ensure the actions to be taken are aligned with the project's best interests. By having this type of organizational structure, EDS engineers keep in contact with the latest EDS achievements accomplished across projects; this is because the link to the department is strong. Moreover, they remain fully aware of project-specific assumptions and requirements. The fact that there is no obsolescence in knowledge or technology dilution by spending time working on a specific project makes the allocation of the EDS engineers to new projects easier. However, one of the key problems captured by the survey and the interviews performed for this thesis show that the definition of roles and responsibilities between the project and the department managers has to be done from the beginning of the project and standard across projects in order to avoid communication problems.

3.4 EDS D&D main challenges

The survey performed on the EDS community to learn about the EDS process and to uncover needs of the engineering team has helped to capture some of the main challenges the EDS organization faces when working on new projects. These challenges are very similar to the generic project challenges described in section 2.2.3. The complete survey and results can be reviewed in Appendix A. The following is a list and explanation of these challenges.

Understaffing: The lack of proper tools to forecast the amount of work required to develop a new project, including unplanned iterations and difficulties in designing global products inside the EDS organization is one of the key challenges. The approval of staff for a new project is done at the early stages of the define phase, where there are a lot of engineering assumptions and high levels of risk and uncertainty.

Unplanned Iterations: The quality of the work done upstream impacts the number of errors the team will discover in downstream activities. The quality of work depends on the engineer's knowledge of the design process and the discipline to follow such process. The nonlinear nature of the process creates feedback loops and changes to upstream tasks.

These feedback loops are not considered at the initial planning and preparation of the project, which causes a lot of problems in meeting deliverables along the project lifecycle.

Changes in requirements: Constant changes to the product feature catalog and the late introduction of technologies into the project generates design iterations and reduces the time the EDS team has to complete the set of activities under design and development and reduces the opportunity to double check the work done.

Aggressive milestones: The constant reduction of design and development time in the automotive industry to gain competitive advantage by releasing products more complex in less time can generate problems for the EDS team in meeting program milestones. These problems become more critical due to the underestimation of project complexity, inaccurate staffing level decisions and the lack of guidance through the design process.

Dependency in other cross-functional groups: The EDS design and development process has many inputs from cross-functional groups, especially during the design phase. Any input being delivered late or without the necessary quality generates problems in downstream tasks and introduces undiscovered rework that will require effort from the team to identify and fix during the validation phase.

Communication with cross-functional groups: The organizational complexity described in section 2.2.2 is one of the main causes of communication problems. It is fundamental to standardize working-level tools and documents to use them as the universal language of the organization. Efforts have to be made to enable clear information transfer communication, such as face to face meetings.

Time to check work done: The lack of time to check the quality of the design activities performed by the EDS team is generated by the introduction of aggressive milestones, lack of tools that could reduce the time to complete tasks, lack of knowledge of the design process, unplanned iterations, late information from cross-functional groups, poor communication and constant changes in requirements.

Budget compliance: The lack of proper project management tools to account for unplanned iterations and, estimate project complexity and staffing levels usually cause challenges in meeting project cost targets. Effective risk management techniques have to be implemented in order to deal with uncertainty and the limited engineering information the team has at the define phase.

3.5 Best-in-class Product development methodologies

The purpose of this section is to analyze best-in-class product development practices that have been implemented in the industry and use this information in Chapter 5, along with the results obtained during Chapter 4, to provide a set of recommendations to the EDS D&D organization at the OEM to reduce design iterations and potential for rework during the validation and launch phases. The value of reducing iterations and rework is reflected in the maintenance and improvement of value to the customer and the strength of the brand in the market (as indicated by higher market share and an expansion of its global customer base).

3.5.1 Set Based Concurrent Engineering

Set based concurrent engineering is a design methodology where several design alternatives are considered and developed in parallel at a specific period of time during the design phase and at some level of detail in order to analyze the potential of each alternative to solve a design issue or address a need in the design and development process. (J. M. Morgan & Liker, 2006) This methodology helps to reduce design iterations commonly generated when following a design process called "iterative point-based design"(J. M. Morgan & Liker, 2006). In the iterative point-based design, the decision to proceed with a selected alternative to address a problem is premature and without analyzing a full range of possibilities. Iterative point-based design is commonly caused by the pressure to resolve problems immediately to avoid delays in the project, but this approach actually increases the risk of project delays due to further modifications or updates to the original solution downstream to accommodate the needs of the project stakeholders. Figure 16 shows a graphical representation of each design methodology. The structure of the iterative point based design is constantly correcting the original solution to accommodate the needs of all groups affected by the change, while the set-based methodology carries a set of possible solutions along the design process to integrate the needs of the project stakeholders and select a final alternative superior to the rest.

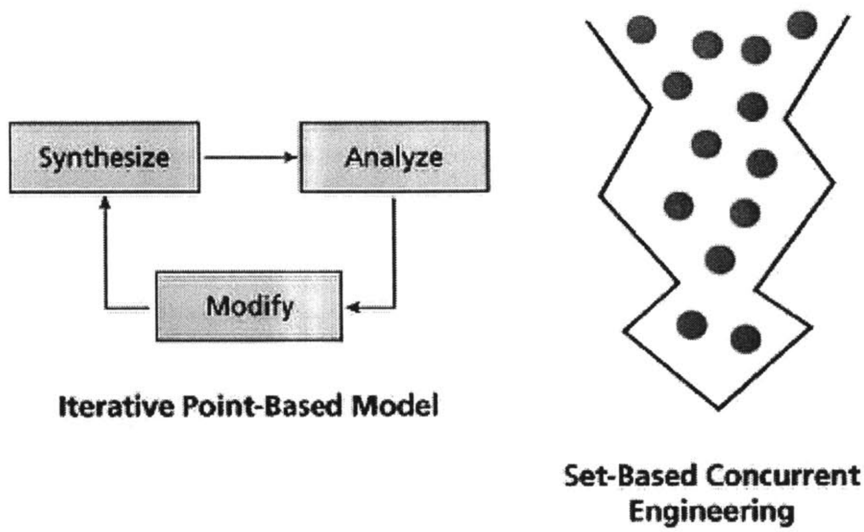

Figure 16: Design methodologies (J. M. Morgan & Liker, 2006)

The main principle of using set-based concurrent engineering is prioritizing compatibility of design between subsystems and components in the product –interfaces- rather than focusing primarily on the completion of individual designs. It is important to keep the usage of the methodology, especially under tight deadlines. Pressure to comply with deliverables and deadlines usually leads to iterative point-based solutions that allow the engineering team to achieve project milestones, only to produce a larger delay in downstream deliverables and milestones. Support from upper management in using concurrent engineering is fundamental, since it may lead to a slow decision making process that could generate complaints in regards to progress from the stakeholders involved in the problem being analyzed. Yet, the team needs to keep in mind the net benefits in convergence towards creating an optimal solution through this methodology and the disadvantages in regards to rework generation using it. Figure 17 shows the convergence to optimal solutions using iterative point-based design and set-based concurrent engineering design.

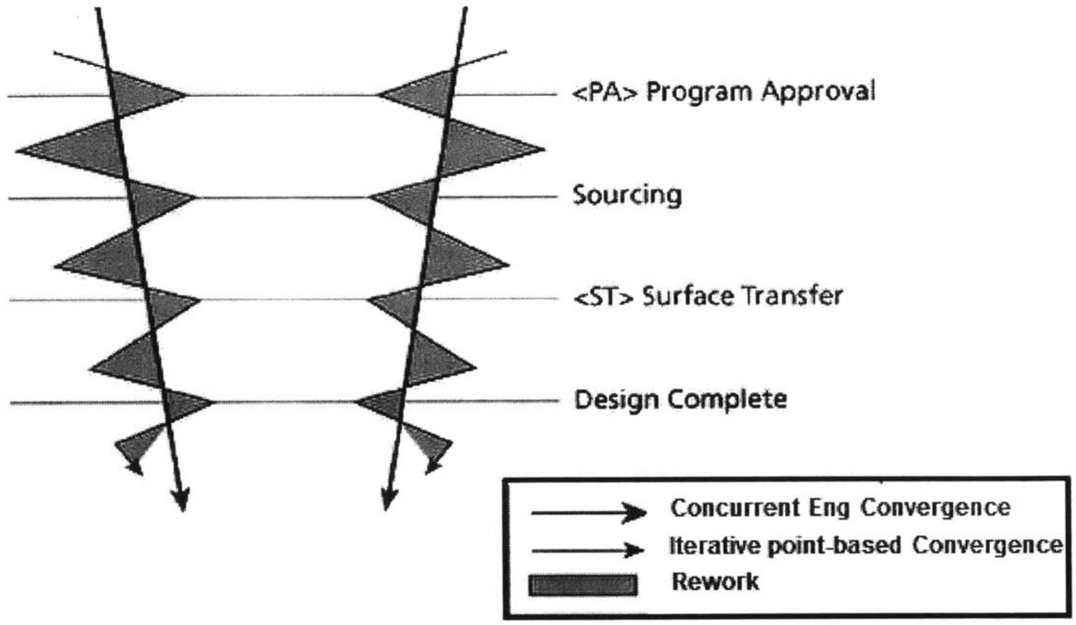

Figure 17: Design Methodologies Convergence and Rework Modified from (J. M. Morgan & Liker, 2006)

It is important to mention that the process from the OEM analyzed for this thesis uses concurrent engineering during the define phase to choose the set of systems and subsystems to be integrated in the new vehicle under development. The literature describes the major benefits from concurrent engineering being gained by its usage during the design phase of the project, especially during working-level activities. In order to implement concurrent engineering within working-level activities, it is mandatory to standardize tools, methods and processes across the organization.

3.5.2 **Modular Development Teams**

As discussed above, most product development companies have shifted their attention from efficiencies in manufacturing to product development excellence. Even so, one key factor in determining the grade of improvement in design and development is manufacturing ease. In order to accomplish this, there is one best practice – modular development teams- in the industry that should be analyzed for further implementation in the OEM.

Modular development teams are cross-functional groups that integrate the design and development team and manufacturing specialists from the define stage. These manufacturing specialists, called “simultaneous engineers” are assigned not just for the entire assembly plant where the new product is going to be assembled to provide high-level assumptions in regards to complexity capacity and the current assembly sequence and available tools, but for defined pieces of the assembly process such as stamping, painting, trim, chassis and powertrain assembly and end of line testing.(J. M. Morgan & Liker, 2006)

The modular team meets on a bi-weekly basis in order to monitor design decisions being taken along the define and design phases of the project and the simultaneous engineer has to sign off on every design action to be implemented.

This type of modular development strategy enables the design and development team to integrate manufacturing team needs, from early stages of product design, in order to reduce the amount of feedback –design iterations- to be received during the validation phase when prototype building begins. The simultaneous engineers are relocated to the design technical centers during the define and design phases of the project and report not just to their functional manager but the project manager and design functional manager as well. The main responsibility of the simultaneous engineers is to identify potential problems in the assembly and manufacture of the vehicle due to new designs being introduced. They have to take potential problems back to the assembly plant and provide solutions that could help to keep the design strategy for the project without major impact on assembly strategy.

These modular development teams help to reduce the antagonism commonly present between design and production organizations – an antagonism aggravated when the design team does not communicate design decisions and the production team finds out about these decisions very late in the design phase or at the beginning of the validation phase, where flexibility in the manufacturing process is limited. This results in the design team having to find alternative concepts to work around the manufacturing processes already established.

Another exercise that helps to increase the productivity of the module development team is the assignment of design and development engineers as residents in the manufacturing plant where the new vehicle is going to be assembled. This relocation has to be made before the new project starts, either in the define phase or the early stages of the define phase. The design engineers spend between two to three months analyzing and studying the capabilities and process sequence at the assembly line, interacting with assembly line operators to capture latent needs that could be addressed when the new vehicle starts the design and validation phases. The design and development engineer becomes a practitioner of the design for manufacturing methodology and can strengthen the links of communication with the production team.

3.5.3 Learning and Continuous improvements

"The ability to learn faster than your competitors may be the only truly sustainable competitive advantage" (DE GEUS 1988)

The ability to learn, transfer knowledge and manage information is critical to ensure product development projects success. Knowledge and information are the stock and trade of product development. (J. M. Morgan & Liker, 2006)

Single-loop learning and double-loop learning: There are two types of learning: single-loop learning and double-loop learning. Single-loop learning occurs when problems or errors are identified and actions are implemented to return the system back to the status quo. Double-loop learning occurs when the actual requirements from which the system has been deviated are challenged and questioned to understand their true value and validity. (Argyris, 1998)

Explicit knowledge and tacit knowledge. These are the two main knowledge types, explicit knowledge or know-what is defined as easily codified and transferred without significant loss of meaning. Tacit knowledge or know-how is complex, difficult to codify and the success of transfer such knowledge depends heavily on the relationship between participants. (Kogut & Zander, 1992)

Most companies involved in product development are very efficient in enabling single-loop learning and transferring explicit knowledge. However, the literature reviewed for best-in-class product development models - such as the Toyota product development system - suggests that the key to enabling continuous improvements resides in the capability of the organization to master the generation of double-loop learning and the transfer of tacit knowledge across the team involved in the product development. In order to achieve this, the standardization of processes enabling work has to be implemented across all levels of the organization; without standardization of processes, any efforts towards double-loop learning and transfer of "know how" will have minor impacts on the overall project.

Once standardization of processes is implemented and cross-functional groups "speak the same language", a change needs to happen in how failures are perceived in the company. This is related to the culture inside the organization and the capabilities of an organization to unlearn old practices. A study performed by James Morgan in his Book "Toyota Product development System: Integrating People, Process and Technology" shows how Japanese culture approaches failure as an opportunity to learn and improve and encourages positive problem-solving behaviors. By contrast, Western culture sees problems as negative and unexpected and is more prone to accusations and blame in the face of failure. In the Western culture, project team members learn quickly to hide problems as long as possible while looking for a solution. This type of behavior affects the capability of an organization to introduce continuous improvements across projects.

The need to reflect about the work done and introduce continuous reviews of requirements and practices being utilized in a product development project have to be introduced as part of the product development process.

The organization has to consider in advance the main roadblocks that it will face during the development of a project and commit to reflection and continuous review discipline regardless of such roadblocks. The following is a list of the most common roadblocks that affect how efficient learning and continuous improvements can be implemented:

- Complex projects
- Time Pressure

- Organizational culture (how failures are perceived inside the organization)
- Lack of technical skills
- Lack of proper Communication channels
- High Workload
- Lack of commitment from cross functional groups

3.6 Importance of using project management concepts, tools and methodologies in EDS D&D

As mentioned in section 3.4, there are several challenges that the design and development teams face when working in complex technical and organizational projects. The need to use modern project management tools to deal with nonlinearity, the high number of interactions and dependencies between cross-functional groups and the distribution of teams across the globe is fundamental to providing a set of possible project outcomes in terms of iron triangle parameters to understand how managerial decisions taken along the define, design, validate and launch phases could help to manage risk and ensure project success. The usage of DSM and system dynamics can help to uncover unplanned iterations, coupled tasks, dependencies between tasks and cross-functional groups and understand the impact of technical, managerial and people factors in the completion of project in terms of the iron triangle parameters.
In order to use DSM, the OEM's EDS Design and development process was reviewed in sections 3.1, 3.2 & 3.3 and further details will be provided in Chapter 4. For the usage of system dynamics, this author will provide a brief overview of an EDS project completed by the OEM under analysis. This project will be used as a case study to provide an analysis of the design phase of the project using system dynamics and test the magnitude of improvement of a set of recommendations generated by a review of best-in-class product development literature, surveys performed in the EDS community and the usage of modern project management tools.

3.6.1 Case study overview

Sport Utility Vehicle (SUV) 2015MY Middle life cycle design refreshment

The information provided in this section comes from the survey of the EDS team that worked on this program, interviews with the project managers and the experience of this author as one of its EDS design and release engineers.

In 2011, the OEM decided to proceed with a design refreshment of a sport utility vehicle that had been on the market for more than four years. The company decided it was time to refresh the vehicle introducing new features and looks to keep customers interested in the product and avoid losing market share while the company prepared the launch of a new sport utility vehicle scheduled for 2018. The scale of change for this vehicle was considered of middle complexity having the following changes:

Exterior:

- Modified Front and Rear Fascias
- Modified Rear closure and Hood
- New Exterior lighting (Headlights, Tail lamps and fog lamps)
- New front grill
- Modified Sun Roof
- New noise, vibration and harshness shields for engine and transmission

Interior:

- New Instrumental Panel
- New center console
- Modified front seats
- New seatbelt retractors and buckles
-

Powertrain:

- Replacement of 5.4L engine with 3.5L
- New Engine transmission
- New fuel lines

Electrical:

- New Passive-entry and passive-start feature
- New blind spot detection feature
- New multimedia technology
- New audio systems
- New electrical release of 3rd row seats
- New body control module
- New battery and Alternator
- New rear view camera
- New interior lighting
- New side crash sensors

Climate control

- Modified heating and ventilating air conditioning modules
- New Air condition lines
- New Cooling module

The EDS design and development responsibility was assigned to the OEM's design technical center located in Mexico, based on the successful results that office provided during the release of a previous 2013 sedan vehicle and with the intention to prepare the Mexico EDS organization for future responsibility for design and development of new vehicle programs.

There are two main EDS design strategies inside the OEM. The first one is called "full service supplier", in which - besides the responsibility for manufacturing the physical wiring harnesses -, the selected supplier takes full responsibility for 2D and 3D data generation and maintenance while the rest of the activities described in section 3.1 are a shared responsibility between the OEM and the supplier.

The second design strategy is called "in-house", in which the OEM has full responsibility for the EDS design and development and the EDS supplier becomes a build-to-print agent, where its only responsibility is to manufacture the physical wiring harnesses according to the 2D prints and 3D data provided by the OEM. The selection of the design strategy for a new project takes place during the define phase and the decision is based upon the business case analysis of paying the supplier for engineering services under the full service supplier strategy, versus the expenditure the OEM would have to do to staff a new project with OEM engineers with the required skill set. For some projects, it is more attractive to follow the in-house strategy when resources to staff the project are available and such staff have the required set of skills or if there is enough time to hire, train and develop OEM engineers before the new project starts. However, for other programs it is more attractive to push some of the design responsibility to the supplier and avoid dealing with staffing, training and development of new OEM engineers, especially when those with the proper skill sets are busy working on other projects and the new project's timing does not allow spending time hiring and training engineers.

For this particular project, the design strategy followed was the full-service supplier. Based on the complexity of the project and the electrical changes, the EDS organization, in conjunction with the EDS supplier selected for this program, assigned the staff levels described below starting from the design phase:

- 7 EDS design and release engineers (3 from the OEM and 4 from the supplier)
- 2 Program Managers (One from the OEM and one from the supplier)
- 4 2D drafting engineers from the supplier
- 2 Systems engineers (One from the OEM and one from the supplier)
- 1 3D Designer from the supplier

As described in section 3.1, during the define phase of the project the EDS team is not fully staffed and for this particular project the EDS staff available were the two project managers and two design and release engineers, one from the OEM and one from the supplier. Starting with activities related to the define phase, the team identified potential risks for the completion of the project on time based on the forecasted staff levels due to the introduction of electrical features that were not 100% compatible with the electrical architecture of the vehicle. This is because, as described above, the vehicle being refreshed had been on the market for at least four years and since then the electrical features released inside the OEM had been developed for newer vehicle architectures.

This compatibility problem was not fully explained to the upper management of the program and the complexity of the project was somewhat underestimated. This underestimation of complexity became worse once the EDS team understood during the define phase –where major assumptions provided during the define phase became design detailed information- the major impact the new engine, transmission, AC lines, battery and starter would have on the EDS located in the engine compartment. The lack of flexibility in the manufacturing processes at the assembly line generated design iterations as well especially during the validation phase of the project when vehicle prototypes were assembled. This lack of flexibility was mainly caused by the assumptions made during the define phase in regards to the manufacturing of the new vehicle. Since major sections of the vehicle were not changing –chassis, trim, sheet metal- the manufacturing team expected to have an assembly and sequence processes similar to the one they had for the base vehicle over the last four years. However, the changes in the engine compartment and the introduction of new Instrumental Panel and Center console generated a lot of disruption in the original assembly process. Some of the processes were modified by the manufacturing team to contain the new vehicle content and design but the majority of changes to alleviate assembly problems came from the design team through iterations of work to accommodate manufacturing needs.

The gap between the actual complexity of the project and the original complexity estimated during the define phase resulted in high workload levels for the entire EDS team along the design, validate and launch phases. The EDS design and development process was followed as encouraged by the OEM. However, there were a lot of design iterations and rework generated by the lack of time to double check the work done, the aggressive timing for the vehicle milestones, the level of technical skills of the EDS team, the compatibility problems between vehicle architecture and new electrical features, the major re design of the engine compartment wiring, the lack of flexibility in the manufacturing process and the high levels of attrition on the supplier side.

The overall project was completed on time with the exception of one milestone during the validation phase. The delay was caused for reasons not related to the EDS work. However the engineering workload and the overtime approved during the entire program were dramatically high. The EDS management had to add four more EDS engineers – for a total of 20 engineers in the program- during the early stage of the validation phase to deal with all the undiscovered rework generated during the design phase and fix the errors prior to the start of the launch phase.

Chapter 4: EDS Analysis

This chapter describes the use of a number of tools and techniques to analyze the performance of EDS projects. First, two surveys of EDS engineers are conducted to gather data and information on project performance and issues. Then, traditional project management tools such as Work break down structure and Critical path are used to analyze the EDS design and development process, and to identify particular sections of the process where the task linearity proposed by the OEM's Generic product development system becomes nonlinear for EDS.
The identification of unplanned iterations, coupled tasks, tasks dependencies, cross functional groups interaction and EDS optimal tasks sequence is done using the modern project management tool Design structure matrix.
Finally, a post mortem analysis of the case study described in section 3.6.1 and the test of a set of recommendations that could improve the EDS team performance will be done by the usage of the modern project management tool system dynamics.

4.1 Data collection

In order to perform the analysis described above this author performed research inside the OEM by creating two surveys, one for the entire EDS team inside the OEM and one for the EDS team working on the SUV project described in section 3.6. The purpose of the EDS team survey was to gather information from the lead users of the EDS design and development process in regards to latent needs, difficulties in the process, interactions with cross functional group and information about the iron triangle parameters accomplishment. The survey of the SUV EDS team was generated to capture the background of the project, the difficulties the team faced, the causes of design iterations along the project, opinions in regards to the performance of the team and the information about iron triangle parameters accomplishment.
Besides the surveys, the OEM's generic product development system and the EDS design and development process were reviewed in detail to get a deep understanding of the tasks to perform, the task flow, the identification of critical stakeholders, the dependencies between tasks and the time allocated to each phase of the design and development process.

4.1.1 EDS Design team survey

The EDS design team survey was submitted to 45 EDS engineers working for the OEM in four main regions: North America, Europe, China and Mexico. The survey had 23 questions that helped to collect information in regards to the following aspects:

- Years of Experience as EDS engineer
- Number of programs in which the engineer participated inside the OEM
- Iron triangle parameter most difficult to accomplish in their experience inside the OEM
- Main reasons for the difficulty in accomplishing iron triangle parameters
- Main sources of design iterations in the EDS design and development process

- Main factors that affect the quality of the EDS design and development work
- EDS team dependencies with other teams inside the Electrical and Electronics system department (EESE)
- EDS team dependencies with other product design and development teams inside the OEM
- Information of past projects in regards to the percentage of design work redone after the design phase.
- Identification of the project phase more critical to ensure project success
- Identification of the project phase that takes more time to deliver
- Identification of the project phase that depends more on cross-functional information for completion
- Identification of activities by project phase that take more time to deliver
- Identification of activities by project phase that depend on cross-functional information for completion
- Brainstorming on actions to be implemented in the EDS organizations to improve the design and development process.

The full results of the EDS Team survey can be found in Appendix A. The main takeaways and conclusions from the survey are listed below:

- OEM EDS engineers average experience is 10-20 years

- The majority of engineers have worked in 2-4 programs complete programs
- Schedule (Vehicle and Engineering Milestones) is the more difficult program target to accomplish

- The main reason for the difficulty to achieve program schedule is the amount of unplanned design changes along the design process (PDL Changes, Program Targets, Non EDS components design changes and manufacturing requests)

  Critical comments from engineers:
  "PDL never stabilizes and FQV Coding contains many errors"
  "Marketing does not communicate and negotiate with EDS the feature offering"
  "Design never freezes at Milestone"
  "Staggered Launches in Global Programs"
  "Lack of information on time from outside departments"
  "The usage of new software to create 2D prints generates lots of problems"
  "Targets setting and change control cannot be done at <PA>"
  "Late supplier selection"
  "Lack of process and guidance during the development phase"

- The main source of design reworks is due to People/Organizational reasons (Inexperience, Communication, Collaboration)

- EDS Design quality is mainly affected by:

  -The dependence on other groups. Other groups not finishing their work on time increase the risk of lowering the quality on the EDS Design work.
  - Not having resources at proper time
  -Poor communication with cross functional groups
  -Management pressure to get things done
  -Lack of time to double check work done

- GPDS does not reflect clearly the amount of electrical changes in a new program.

- Robust EDS D&D depends on Systems Integration work and performance (Inside EESE Dependence)

- Robust EDS D&D depends on Program Management group work and performance (Outside EESE Dependence)

- On average between 20% & 30% of the design has to be re-done after FDJ.

- How to improve our EDS Design and Development?

  <u>Critical comments from engineers:</u>
  "Mandatory compatibility reviews/ ckt bingo"
  "We need a team devoted to coordinate changes"
  "More time between VP & TT to complete testing"
  "Pre TT Build should be mandatory for all programs to review the design in more detail with VO & Ergo"
  "Golden harness reviews by Ford mfg. and design should be mandatory prior to each build"
  "More time before FDJ to debug design"
  "Freeze dates for wiring changes. Introduce an EDS Milestone in GPDS"
  "Increase awareness from program regarding EDS Lead times, DFM and Launch readiness"
  "Avoid overlap between regions in global programs"
  "Quality workshops between EDS and rest of PD to ensure EDS inputs are understood properly"
  "Technical Design Reviews should be Go-No Go activities"
  "Add EDS staff since Pre-PS and have complete staff starting <UNV0>"
  "EDS should have a FDJ date at least one week after the rest of the design teams"
  "A separate change control forum for EDS"
  "Need to improve compatibility reviews process"

"Detailed DFMEA and proper updates at each milestone"
"A unique IT group dedicated to improve the tools used on EDS"

-Development until VP is the most important phase to ensure program success.
- The tasks that consume more time under the development phase are program oriented activities (Product catalog review, electrical compatibility reviews, Failure Mode analysis, System part release, etc.)

- The tasks under the development phase that depend more on cross functional groups are Computer aided design tasks (3D data creation, maintenance and virtual checks)

The results from the EDS team survey helped to narrow the scope of this thesis to focus efforts in solving the main problems described by the EDS community through this survey. The analysis to be presented in the following sections was delimited to cover only the design phase which the EDS community considers the phase with more rework and design iterations. The main iron triangle parameter to be analyzed for improvement will be schedule based on the feedback from the survey as the most challenging project parameter to comply.

4.1.2 OEM Generic Product Development system

In order to understand completely the needs from the EDS Community a deep dive into the OEM's generic product development system had to be done.
The generic product development system is the sequence of activities, deliverables, methods and tools used across the OEM organization to design and develop high quality products that cover customer needs and that can be delivered in competitive time and cost. This system covers all the four product development phases: Define, Design, Validate and Launch.
In order to define the correct project duration the OEM classifies its projects by changes scalability. A 3 digit scalability number is used to describe the degree of product change and the development timing for a vehicle program. Each digit represents one of the three main subsystems of the vehicle: powertrain, platform and top hat. Powertrain subsystem covers the engine and the transmission of the vehicle. Platform subsystem covers the underbody structure, chassis, interior structures, electrical architecture and safety features of the vehicle. Top hat subsystem covers the body shell, exterior lights, exterior trim, instrument panel, seats, electrical architecture and interior trim. Each digit can go from 6 (Completely new) to 1 (Carryover from previous vehicle). For a new product with new powertrain (6), new platform (6) and new top hat (6) the time to market using the generic product development system is 52 months. This project duration is reduced based on the scalability number for a specific project.
The system has more than 1000 deliverables, 14 milestones and 23 technical maturity points. Every deliverable completes at a milestone or maturity point. Each milestone or maturity point is closed when all the deliverables contained in it are completed.
The main cross functional groups interacting through the generic product development system are: engineering, manufacturing, purchasing, quality, sustainability, information technology, finance, human resources, legal, government relations, marketing and communications. Each of

these cross-functional groups leads specific deliverables and supports deliverables lead by other groups.

4.1.3 SUV 2015 mid cycle design refreshment EDS Team survey

The EDS SUV project team survey was submitted to eight EDS engineers working in the project during all the product development phases. The main purpose of this survey was to capture the experience from the engineers and to understand the main problems the team faced during the day to day activities and milestones. The survey had 12 questions that helped to collect information in regards to the following aspects:

- Team opinion in regards to project staffing levels
- Main EDS issues faced during the project
- Project phase with more design iterations and rework
- Iron triangle parameter most difficult to accomplish in the project
- Main reasons for the difficulty to accomplish Iron triangle parameters
- Main sources of design iterations in the project
- Main factors that affected the quality of the EDS design and development work
- Information in regards to the percentage of design work redone after the design phase.
- Brainstorm of actions that could be implemented in the EDS design and development process of the project to reduce design iterations and rework.

The full results of the EDS SUV project team survey can be found in Appendix B. The main takeaways and conclusions from the survey are listed below:

- Staffing level was adequate for the program but Roles and Responsibilities were not assigned properly

- Average staff level required (Between OEM and Supplier):

  Five Design and release engineers
  Two 3D CAD designers
  Three 2D drafting engineers

- The SUV EDS project team had issues mainly because of:

  Critical comments from engineers:
  "Complexity not reviewed in detail before FDJ"
  "Late PDL Changes"
  "Lack of DFM"
  "Lack of compatibility reviews"
  "Rotation of people"

"Lack of control on design changes and reworks"
"Wiring Bundle diameters increase"
"Poor communication with cross functional groups"

- The design phase where more rework was done was VP.

- The program target most difficult to accomplish in the project was schedule (Milestones, MRDs, Testing)

- The main reason for the difficulty to achieve program schedule was the amount of unplanned design changes along the design process (PDL Changes, Program Targets, Non EDS components design changes and manufacturing requests)

- The main source of design reworks was due to People/Organizational reasons (Inexperience, Communication, Collaboration)

- EDS Design quality was mainly affected by:

  -The dependence on other groups. Other groups not finishing their work on time increase the risk of lowering the quality on the EDS Design work
  -Introduction of new features into the program
  - Inexperience from the engineering team
  -Management pressure to get things done
  -Lack of time to double check work done

- In the SUV project the amount of design work that had to be re-done after FDJ was between 30% & 50%

- How to improve our EDS Design and Development?

  <u>Critical comments from engineers:</u>
  "More resources since the beginning"
  "Compatibility Reviews"
  "PDL Review and monitor complexity"
  "Better communication with other groups"
  "Better documentation of issues"
  "Push back changes that introduce risk"
  "More time between milestones"

The results from the EDS SUV project team survey are aligned with the results from the EDS Team survey which helps us to conclude that the SUV project falls into the normal project performance inside the OEM. The results from the survey helped to develop the SD Model presented in section 4.4.

4.2 EDS WBS & CPM

In order to analyze the EDS design and development process to identify sections of the design phase where iterations and rework are high, tools such as work breakdown structure and critical path method were used. These tools provided a tree-decomposition of project tasks where terminal elements were identified, dependencies between tasks were presented, and structure for an activity-oriented analysis was created.

4.2.1 Strategy followed for creation

In order to capture all the deliverables to be completed by the EDS team during the design phase the work breakdown for the generic product development system was done. This exercise considered only the deliverables where engineering is the lead and the deliverables that have direct input into the engineering led activities. Then the generic product development list of activities was complemented with the EDS unique activities obtained from the EDS technical design review process and the EDS perfect drawing plan. Each activity was identified with an ID number, a description of the task, immediate prerequisite tasks and expected duration. The deliverables were arranged in technological order where no task appears in the list until all its predecessors have been listed.

4.2.2 Results & Findings

The EDS WBS has 417 tasks covering all the platform and top hat deliverables and activities. These 417 activities contain all the EDS led activities plus the activities led by other engineering commodities that have a direct feed into the EDS deliverables.

The groups interacting with the EDS team are:

- Basic Design
- 2D Drafting
- Systems integration
- EDS Components
- Program Management
- Purchasing
- Body Exterior
- Body Interior
- Block Leaders (Digital Innovation)
- EESE CAE
- EDS Core
- Service
- Ergo
- Vehicle Operations
- Craftsmanship

- EMC
- Supplier
- Service STA
- Environmental and Safety Engineering

The main takeaways from the EDS work breakdown structure are:

- The generic product development system gives 3 months from the Platform design 2 phase completion to the first prototype build functional test parts arrival to the plant while some EDS Platform design 2 deliverables such as the design freeze and tooling kick off of harness components (i.e. plastic shields and grommets) have to be completed 7 months prior to the actual functional test during the first prototype build. This situation generates a lot of rework and design iterations since the design freeze for shields and grommets happen 4 months in advance to the actual platform design 2 phase finish date. During these 4 months there are a lot of design changes in the vehicle components interacting with the harness components and tooling modifications and last minute design changes have to be performed to align harness design with the latest vehicle components design completed at the end of Platform design 2 phase.

- Critical tasks in Platform design 2 are not feeding 100% the release of harness manufacturing prints for the first prototype build. Tasks such as 3D CAD, Virtual layout assessments, Electrical schematics, electrical compatibility reviews, Harness complexity and design requirements deviations are not fully completed when the harness 2D prints have to be prepared for the first prototype build. This situation introduces a lot of rework during the functional test performed at the beginning of the first prototype build. Design iterations increase due to the lack of maturity in the data used for the physical creation of the prototype harnesses.

- First prototype release overlaps with platform and top hat activities. This creates a peak in the workload of the EDS team since now the engineering time has to be allocated between three different clusters. This split of time could cause the team to start cutting corners and stop double checking work in order to meet deadlines. This situation can generate design iterations and rework on downstream tasks and the quality of the overall design work could be affected.

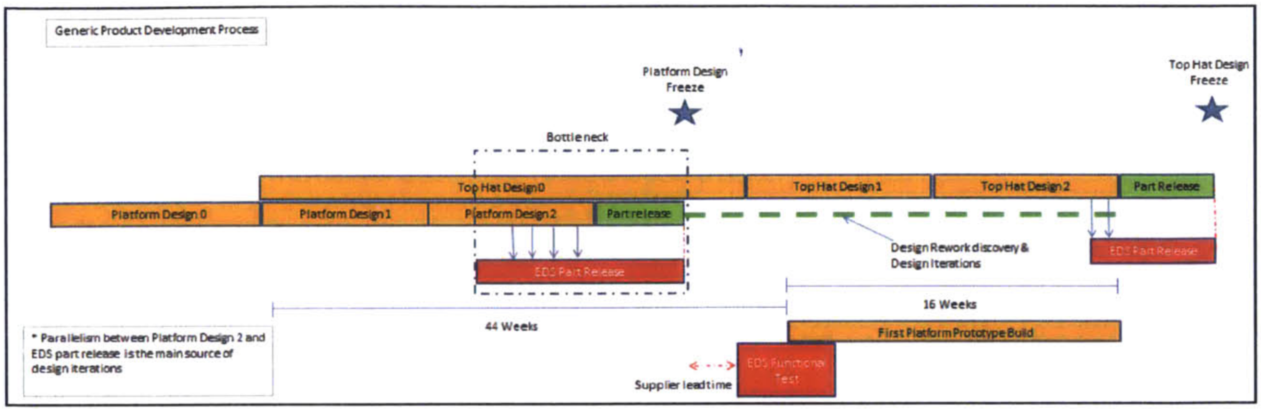

Figure 18 EDS design and development time line

Figure 18 shows the time line created based on the generic product development process, the EDS unique activities and the mapping of the EDS led activities and predecessors activities in a time sequence. We can see clearly that while the generic product development process part release (green squares) is shown as linear once Platform design 2 phase finishes and again when top hat design 2 phase finishes, the unique EDS part release is parallel with those design phases and is the main source of design iterations and rework.

The calculation of the critical path uncovered the bottle neck route of the process and helped to focus efforts in ensuring critical tasks are managed as a priority to avoid impacts on downstream tasks and to the overall project schedule.

Figure 19 shows the EDS tasks on the critical path. The majority of the tasks considered as critical are integrated in the platform design phases and the first prototype build. It is important to notice that even though the top hat design tasks are not shown as critical the quality and results from the platform design phases and the first prototype build affect directly the output of work during the top hat design phases, causing a snow ball effect when errors are built into the design during the platform phases and the first prototype build. If the number of design iterations that have to be done during or after the first prototype build are high then the probability of finishing on time and the quality of the top hat design activities becomes a challenge; tradeoffs between time and quality have to be made.

Task Name	Process Executor	Durat	Predecessors
Provisional List of Selected Systems for < Program Start >	Basic Design	33 days	
< Program Start > Sign off	Systems Integration	0 days	1
PMT Collection of System/Subsystem Level Benchmarking Data < PSC >	Basic Design	88 days	3
<Platform Design 0> Collect all Final DTs & Surrogate Parts DTs	Systems Integration	66 days	19FS+66 days
<Platform Design 0> ECAR Phases I & II	EDS Connectors	44 days	40
<Platform Design 1> Submit ECAR matrix w/ connectors and insertion forces to VO/ERGO	EDS Connectors	101 day	48FS-11 days
<Platform Design 2> Physical Schematics Status & Review	Systems Integration	43 days	75FS-25 days,90
<Platform Design 2> Final Compatibility Reviews Complete (Physical Schematics)	Systems Integration	11 days	110,148
<Platform Design 2> Update EDS Complexity Matrix (Wiring Giveaway Optimization [WGO] and Wire Harness Complexity Analysis [WHCA] Tools	EDS	11 days	95,110,113FS-5 days
<1st Proto Build Release> EDS System Design Freeze (Final PDL Received;Minor Logical Schematic & DT changes based on PDL are due)	EDS	5 days	95,110FS-38 days,90,40,136
<1st Proto Build Release> Generate Clean Prints & Releases / Notices at R Status (includes cutsheets)	EDS	55 days	170,172,173,174,90
<1st Proto Build Release> Interconnect Studies / Wire Harness Complexity Analysis (WHCA)	EDS	5 days	186FS-11 days,172,174,113,121,124
<1st Proto Build Release> Manufacturing Print to Physical Schematic Compatability Review	EDS	5 days	186FS-11 days,172,174,113,121,124
<1st Proto Build Release> Manufacturing Print Clarifications / DFMs	Supplier	22 days	186,187,188
<1st Proto Build Release> Build Readiness Review #3: Supplier Readiness	EDS	1 day	190,194,195,196,197,192,199
<1st Proto Build Release> Update Prints from CAE Test Results & DFMs	EDS	11 days	111,190,194
<1st Proto Build Release> Lead Prep Startup - cut wire & crimping	Supplier	11 days	198
<1st Proto Build Release> Build Harnesses	Supplier	11 days	201,202
<1st Proto Build Release> Ship Wire Assemblies	Supplier	11 days	204,205
<1st Proto Build Release> Parts available at the plant	Supplier	0 days	206
<1st Proto Build Release> Functional test results & Build Concerns report	EDS	66 days	169,207FS+11 days
<Top Hat Design 2> Initial Vehicle Specifications for Each Vehicle Prototype Build	Program Manageme	44 days	279,276,277FS-38 days,278FS-28 days
<Top Hat Design 2> Preliminary Vehicle Prototypes Test Plan	Systems Integration	22 days	279,319FS-17 days,276,277FS-11 days,275,130
<Top Hat Design 2> EDS Technical Design Review (TDR) & Report	EDS	1 day	300,301,302,303,304,305,306,307,308,309,310,3
< Top Hat Design 2 > / < Program Approval > Sign off	EDS	0 days	300,301,302,303,304,305,306,307,308,309,310,3
< Vehicle Prototype build> Final Harness Complexity Defined per WGO and AVBOM/WERS updated	EDS	11 days	323FS+11 days
< Vehicle Prototype build> Generate Clean Prints & Releases / Notices at R Status (includes cutsheets)	EDS	55 days	340,379,381,382,383
< Vehicle Prototype build> Manufacturing Print Clarifications / DFMs	Supplier	22 days	395,396,397
< Vehicle Prototype build> Build Readiness Review #3: Supplier Readiness	EDS	1 day	399,403,404,405,406,401,408
< Vehicle Prototype build> Update Prints from CAE Test Results & DFMs	EDS	11 days	340,399,403
< Vehicle Prototype build> Lead Prep Startup - cut wire & crimping	Supplier	11 days	407
< Vehicle Prototype build> Build Harnesses	Supplier	11 days	410,411
< Vehicle Prototype build> Ship Wire Assemblies	Supplier	11 days	413,414
< Vehicle Prototype build> Parts available at the plant	Supplier	0 days	415

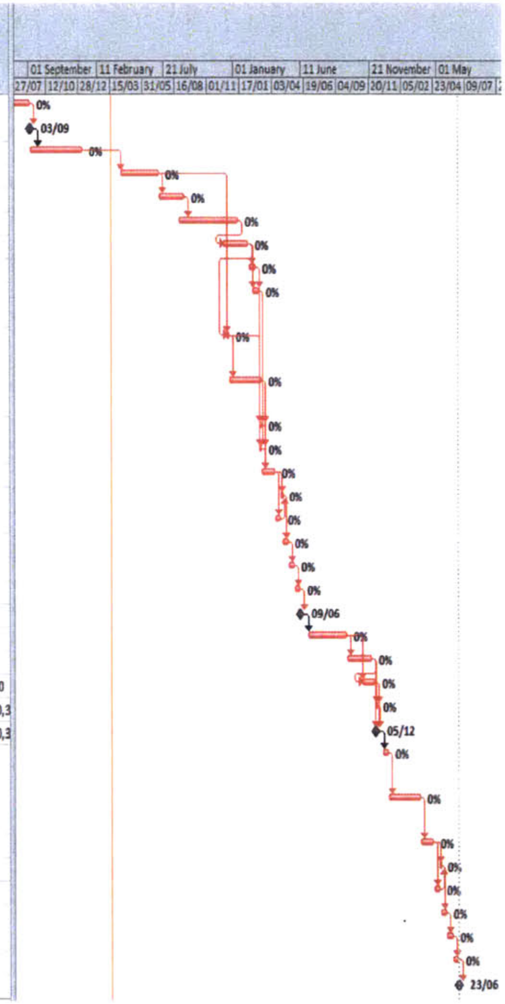

Figure 19 EDS process critical path

The groups interacting with the EDS team under the critical path are:

- Basic Design
- Systems Integration
- EDS Connectors
- Program Management
- Supplier

The critical path analysis helped to narrow the scope of the design structure matrix performed in section 4.3. From the results of the WBS and Critical Path I decided to focus efforts to reduce and avoid design iterations and reworks during the platform design phases and the first prototype build releases to provide a robust design base towards the top hat design phases and the vehicle prototype build.

4.3 EDS DSM

The DSM was used to provide graphical representation of the current EDS design and development process to identify design iterations and coupled tasks and propose a different task sequence to reduce such design iterations and rework generated by the couple tasks. As discussed in previous section based on the result of the critical path it was decided to focus the DSM analysis in the section of platform design 0, platform design 1, platform design 2 and first prototype build releases. The transition from Platform design 2 and first prototype build releases can be considered as the first bottle neck in the design phase due to the parallelism of work between platform, top hat and first prototype build release phases. High quality on the design work feeding the first prototype build releases is critical to avoid design iterations and rework in downstream tasks where the EDS team is focused on the top hat design phases and the vehicle prototype build releases. The vehicle prototype build integrates all the work done during the platform and top hat design phases.

4.3.1 Strategy followed for creation

As explained in section 2.3.1 the DSM created for this thesis follows the IR convention. Inputs to any specific task in the diagonal of the matrix are located in the same row of the task in the diagonal using a cross. Outputs of such task are located in the same column of the task in the diagonal. A cross located above the task in the diagonal is an input to an upstream task – design iteration --while a cross below the task in the diagonal is an input to a downstream task.

The DSM created for this thesis is a process DSM where activities, sequence, duration and dependencies are mapped into the matrix to identify clusters of coupled tasks and create a new sequence of activities that could reduce the number of crosses above the diagonal. The crosses above the diagonal represent iterations or inputs to upstream tasks that were thought as completed but based on downstream work have to be performed again, thereby causing delays, rework, unplanned expenses and re validations at the component, subsystem and system level. These unplanned iterations trigger managerial decisions along the project such as overtime approval and work intensity pressure which in turn could generate knock-on effects such as fatigue, generation of errors on errors, low morale and lower productivity.

Figure 20 shows the process DSM created for the EDS design process containing platform design 0, platform design 1, platform design 2 and first prototype build releases. It contains 87 tasks arranged in groups or clusters depending on the design phase where the tasks take place. Figure 21 shows the DSM tasks and the colors used to identify each tasks by the proper design phase where the task takes place. The tasks in pink and violet color are part of the platform design 0 sign off, tasks in green are part of the platform design 1 phase, tasks in blue are part of the platform design 2 phase and items in orange are tasks part of the first prototype build release phase. The matrix in Figure 20 shows 131 feedback marks above the diagonal representing potential iterations and rework to upstream tasks. The main purpose of the clustering and sequencing activities performed as the next step and showed in Figure 22 is to reduce the number of marks above the diagonal to reduce design iterations and rework.

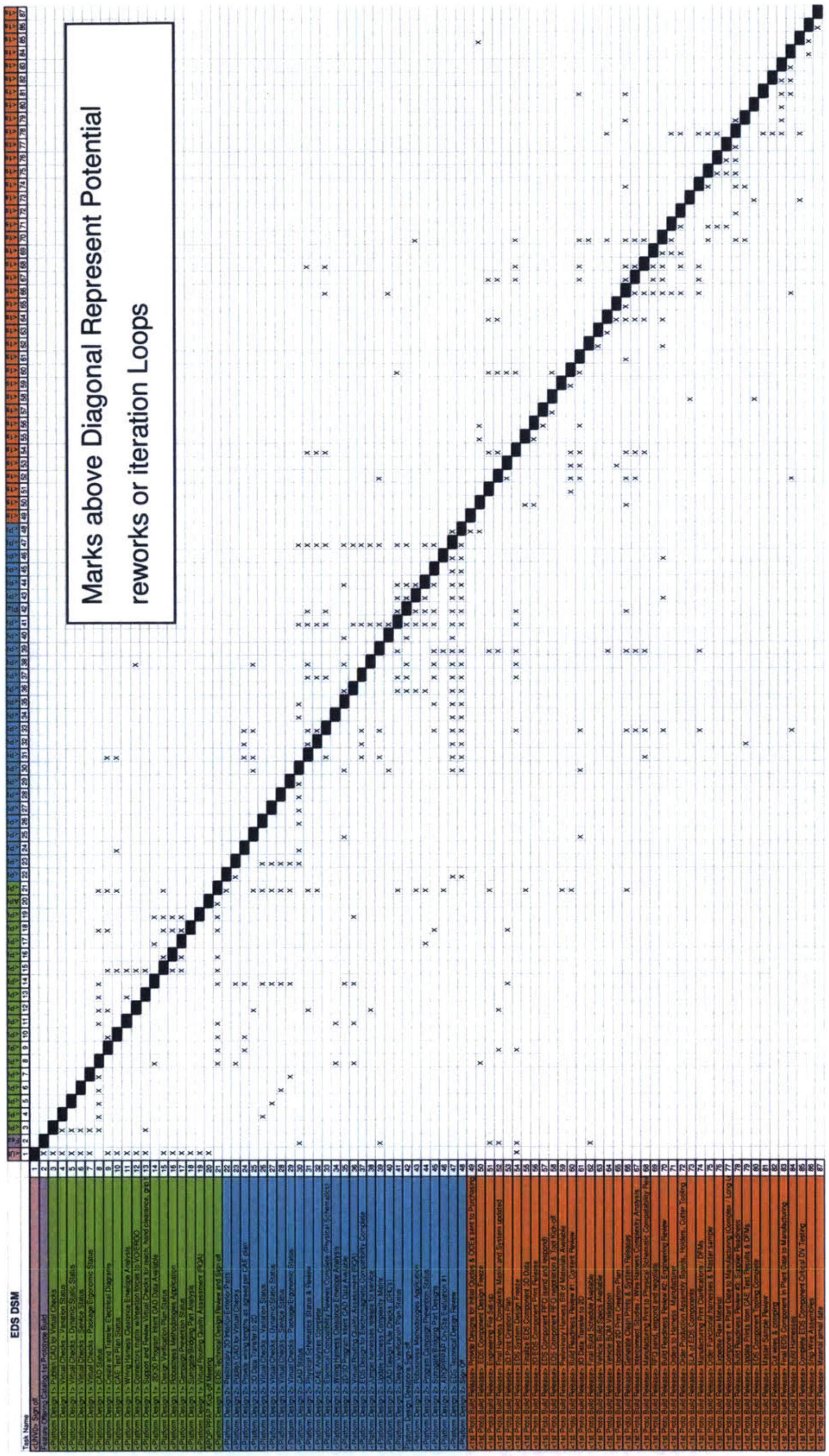

Figure 20 EDS Process DSM before clustering and sequencing

<Platform Design 0> Sign off
Feature Offering Catalog 1st Prototype Build
<Platform Design 1> Publish CAD for Virtual Checks
<Platform Design 1> Virtual Checks - Variation Status
<Platform Design 1> Virtual Checks - Dynamic/Static Status
<Platform Design 1> Virtual Checks - Service Status
<Platform Design 1> Virtual Checks - Package/Ergonomic Status
<Platform Design 1> CAD Status
<Platform Design 1> Create and Transfer Electrical Diagrams
<Platform Design 1> CAE Test Plan Status
<Platform Design 1> Wiring Harness Clearance Envelope Analysis
<Platform Design 1> Connectors matrix w/insertion forces to VO/ERGO
<Platform Design 1> Support and Review Virtual Checks for reach, hand clearance, grip t
<Platform Design 1> 2D/3D Program Intent CAD Data Available
<Platform Design 1> Design Verification Plan Status
<Platform Design 1> Robustness Methodologies Application
<Platform Design 1> Campaign Prevention Status
<Platform Design 1> Surrogate/Bridging Part Analysis
<Platform Design 1> Virtual Routing Quality Assessment (RQA)
APQP/PPAP Kick-off Meeting
<Platform Design 1> EDS Technical Design Review and Sign off
<Platform Design 2> Preliminary 3D Interior/Exterior Parts
<Platform Design 2> Publish CAD for Virtual Checks
<Platform Design 2> Provide wiring lengths as agreed per CAE plan
<Platform Design 2> 3D Data Transfer to 2D
<Platform Design 2> Virtual Checks - Variation Status
<Platform Design 2> Virtual Checks - Dynamic/Static Status
<Platform Design 2> Virtual Checks - Service Status
<Platform Design 2> Virtual Checks - Package/Ergonomic Status
<Platform Design 2> CAD Status
<Platform Design 2> Physical Schematics Status & Review
<Platform Design 2> CAE Analyses Complete
<Platform Design 2> Electrical Compatibility Reviews Complete (Physical Schematics)
<Platform Design 2> Wiring Harness Clearance Envelope Analysis
<Platform Design 2> 2D/3D Program Intent CAD Data Available
<Platform Design 2> Virtual Routing Quality Assessment (RQA)
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<Platform Design 2> Jumper harnesses release for service
<Platform Design 2> Update Harness Complexity Matrix
<Platform Design 2> CAD Design Rule Checks (DRC's)
<Platform Design 2> Design Verification Plan Status
Platform Design Deviations Sign-off
<Platform Design 2> Robustness Methodologies Application
<Platform Design 2> Program Campaign Prevention Status
<Platform Design 2> Surrogate/Bridging Part Designs
<Platform Design 2> APQP/PPAP On-Site Evaluation #1
<Platform Design 2> EDS Technical Design Review
<Platform Design 2> Sign Off
<1st Proto Build Release> Provide Designs for Initial Quotes & OCEs sent to Purchasing
<1st Proto Build Release> EDS Component Design Freeze
<1st Proto Build Release> Engineering File Set-up
<1st Proto Build Release> Final Harness Complexity Matrix and System updated
<1st Proto Build Release> 2D Print Creation Plan
<1st Proto Build Release> EDS System Design Freeze
<1st Proto Build Release> Finalize EDS Component 3D Data
<1st Proto Build Release> 2D EDS Component Print Release
<1st Proto Build Release> EDS Component RFQ (send and respond)
<1st Proto Build Release> EDS Component RFQ negotiation & Tool Kick-off
<1st Proto Build Release> Preliminary Harness Bill of Materials Available
<1st Proto Build Release> Build Readiness Review #1: Content Review
<1st Proto Build Release> 3D Data Transfer to 2D
<1st Proto Build Release> Final Build Schedule Available
<1st Proto Build Release> Vehicle Build Specs Available
<1st Proto Build Release> Vehicle BOM Validation
<1st Proto Build Release> Updated 2D Print Creation Plan
<1st Proto Build Release> Generate Clean Prints & System Releases
<1st Proto Build Release> Interconnect Studies / Wire Harness Complexity Analysis
<1st Proto Build Release> Manufacturing Print to Physical Schematic Compatability Rev
<1st Proto Build Release> RFQ send, respond and negotiate
<1st Proto Build Release> Build Readiness Review #2: Engineering Review
<1st Proto Build Release> Orders to Harness Manufacturer
<1st Proto Build Release> Order Production Assembly Boards, Holders, Cutter Tooling
<1st Proto Build Release> SLA of EDS Components
<1st Proto Build Release> Manufacturing Print Clarifications / DFMs
<1st Proto Build Release> Order Functional harnesses & Master sample
<1st Proto Build Release> Expedite Raw Material
<1st Proto Build Release> Component In Plant Date to Manufacturing (Complex / Long L
<1st Proto Build Release> Build Readiness Review #3: Supplier Readiness
<1st Proto Build Release> Update Prints from CAE Test Results & DFMs
<1st Proto Build Release> EDS Component Tooling Complete
<1st Proto Build Release> Master Sample Review
<1st Proto Build Release> Cut wires & crimping
<1st Proto Build Release> Final EDS Component In Plant Date to Manufacturing
<1st Proto Build Release> Build Harnesses
<1st Proto Build Release> Complete EDS Component Critical DV Testing
<1st Proto Build Release> Ship Wire Assemblies
<1st Proto Build Release> Material arrival date

Figure 21 List of tasks in the EDS Process DSM

4.3.2 Results & Findings

The matrix partition to re sequence tasks to reduce iterations and rework on upstream tasks and group couple tasks into clusters was performed with the Lattix software. Figure 22 shows the results of the partition. The number of marks above the diagonal was reduced by 25% from 131 marks to 99 marks. The DSM partition helped to reduce the potential iteration loops or feedbacks to upstream tasks that could generate rework in the EDS design and development process. This has been done without modifying the duration or dependency of the tasks originally established.

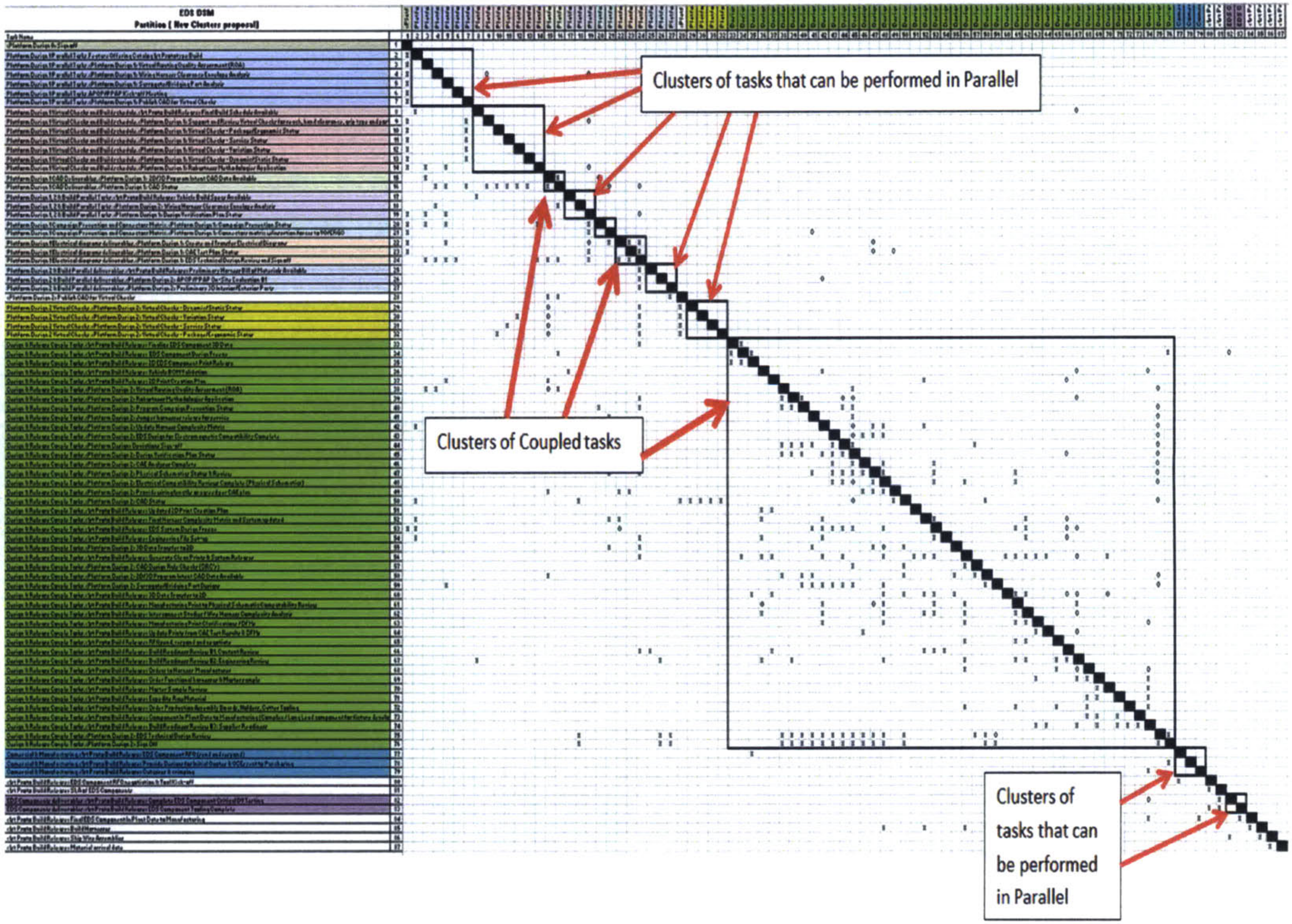

Figure 22 EDS DSM Partition

The new clusters generated by the partition are:

<Platform Design 0 Sign off>

<Platform Design 1 Parallel Tasks>

- Get Feature Offering Catalog 1^{st} Prototype Build
- <Platform Design 1> Virtual Routing Quality Assessment (RQA)
- <Platform Design 1> Wiring Harness Clearance Envelope Analysis
- <Platform Design 1> Surrogate/Bridging Part Analysis
- APQP/PPAP Kick-off Meeting
- Publish CAD for Virtual Checks

<Platform Design 1 virtual checks & first build schedule>

- <1^{st} Proto Build Release> Final Build Schedule Available
- <Platform Design 1> Support and Review Virtual Checks for reach, hand clearance, grip type and posture assessments
- <Platform Design 1> Virtual Checks – Package/Ergonomic Status
- <Platform Design 1> Virtual Checks – Service Status
- <Platform Design 1> Virtual Checks – Variation Status
- <Platform Design 1> Virtual Checks – Dynamic/Static Status
- <Platform Design 1> Robustness Methodologies Application

<Platform Design 1 CAD Delivery>

- <Platform Design 1> 2D/3D Program Intent CAD Data Available
- <Platform Design 1> CAD Status

<Platform Design 1, 2 & Build Parallel Tasks>

- <1^{st} Proto Build Release> Vehicle Build Specs Available
- <Platform Design 2> Wiring Harness Clearance Envelope Analysis
- <Platform Design 1> Design Verification Plan Status

<Platform Design 1 Campaign Prevention and Connectors Matrix>

- <Platform Design 1> Campaign Prevention Status
- <Platform Design 1> Connectors matrix w/insertion forces to VO/ERGO

<Platform Design 1 Electrical Diagrams Deliverables & Sign Off>

- <Platform Design 1> Create and Transfer Electrical Diagrams
- <Platform Design 1> CAE Test Plan Status
- <Platform Design 1> Sign off

<Platform Design 2 & Build Parallel Deliverables>

- <1^{st} Proto Build Release> Preliminary Harness Bill of Materials Available
- <Platform Design 2> APQP/PPAP On-Site Evaluation #1
- <Platform Design 2> Preliminary 3D Interior/Exterior Parts

<Platform Design 2 Publish CAD for Virtual Checks>

<Platform Design 2 Virtual Checks>

- <Platform Design 2> Virtual Checks – Dynamic/Static Status
- <Platform Design 2> Virtual Checks – Variation Status
- <Platform Design 2> Virtual Checks – Service Status
- <Platform Design 2> Virtual Checks – Package/Ergonomic Status

<Design and Release Couple tasks>

- <1^{st} Proto Build Release> Finalize EDS Component 3D Data
- <1^{st} Proto Build Release> EDS Component Design Freeze
- <1^{st} Proto Build Release> 2D EDS Component Print Release
- <1^{st} Proto Build Release> Vehicle BOM Validation
- <1^{st} Proto Build Release> 2D Print Creation Plan
- <Platform Design 2> Virtual Routing Quality Assessment (RQA)

<Platform Design 2> Robustness Methodologies Application
<Platform Design 2> Program Campaign Prevention Status
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<Platform Design 2> Design Verification Plan Status
<Platform Design 2> CAE Analyses Complete
<Platform Design 2> Physical Schematics Status & Review
<Platform Design 2> Electrical Compatibility Reviews Complete (Physical Schematics)
<Platform Design 2> Provide wiring lengths as agreed per CAE plan
<Platform Design 2> CAD Status
<1st Proto Build Release> Updated 2D Print Creation Plan
<1st Proto Build Release> Final Harness Complexity Matrix and System updated
<1st Proto Build Release> EDS System Design Freeze
<1st Proto Build Release> Engineering File Set-up
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<1st Proto Build Release> Build Readiness Review #1: Content Review
<1st Proto Build Release> Build Readiness Review #2: Engineering Review
<1st Proto Build Release> Orders to Harness Manufacturer
<1st Proto Build Release> Order Functional harnesses & Master sample
<1st Proto Build Release> Master Sample Review
<1st Proto Build Release> Expedite Raw Material
<1st Proto Build Release> Order Production Assembly Boards, Holders, Cutter Tooling
<1st Proto Build Release> Component In Plant Date to Manufacturing (Complex / Long Lead component for fixture development)
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<Platform Design 2> Sign Off

<Commercial & Manufacturing>

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<1st Proto Build Release> Provide Designs for Initial Quotes & OCEs sent to Purchasing
<1st Proto Build Release> Cut wires & crimping

<EDS Component RFQ negotiation & tooling kick off>

<SLA of EDS Components>

<EDS Components Deliverables>

<1st Proto Build Release> Complete EDS Component Critical DV Testing
<1st Proto Build Release> EDS Component Tooling Complete

<Final EDS Component In Plant Date to Manufacturing>

<Build Harnesses>

<Ship Wire assemblies>

<Material Arrival Date>

The main takeaways from the DSM partition are:

- The majority of the activities under first prototype build releases phase should be combined with the platform design 2 cluster to ensure minimum iterations once the manufacturing prints of the harnesses are created.
- 3D CAD activities such as virtual checks, routing assessments, wiring harness Clearance Envelope analysis and 3D CAD generation should be completed at the beginning of each design phase.
- Special coordination efforts should be established on the cluster of coupled tasks called <Platform Design 1 Electrical Diagrams Deliverables & Sign Off>. This cluster contains two cross functional activities critical to ensure high quality on the downstream activities of the EDS Design and development which are the creation of the electrical diagrams and the Electrical CAE Test status.

Once the clusters generated by the DSM partition were analyzed the interaction with cross functional groups was mapped on top of the partition result in order to provide a graphical representation and increase awareness of the special efforts that the EDS team has to put in place to ensure information flows on time and with the quality required to avoid design iterations and rework downstream.

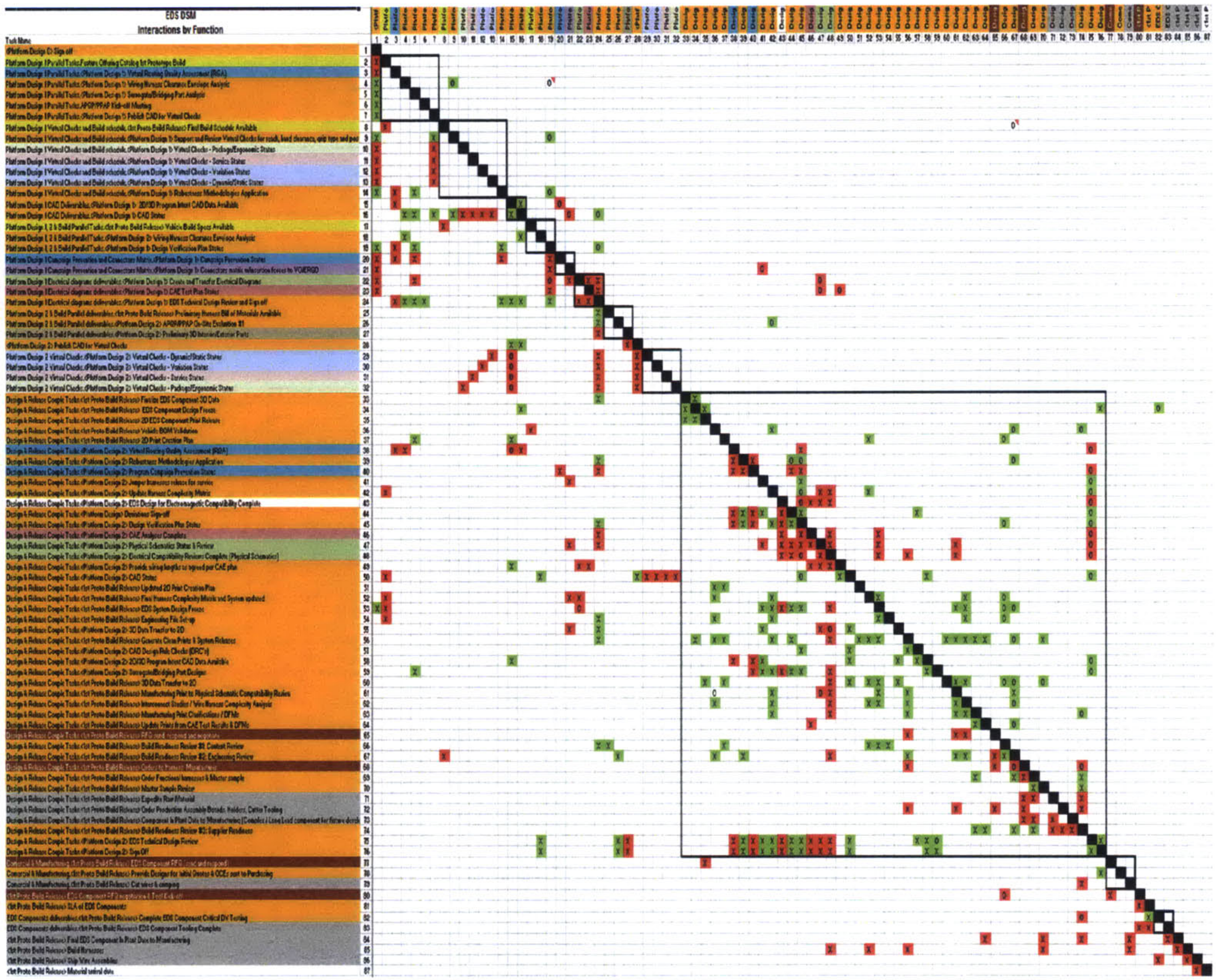


Figure 23 Cross functional groups interaction mapping

The main cross functional groups involved in the mapping presented in Figure 23 are:

○ **EDS (Orange)**	○ **EDS Supplier (Grey)**
○ **Program Management (Yellow)**	○ **Purchasing (Brown)**
○ **EDS Core & Connectors (Blue and Violet)**	○ **Electromagnetic compatibility engineering (White)**
○ **Body interior/exterior (Light brown)**	○ **Ergo/Vehicle Operations (Light green)**
○ **Systems integration (Green)**	○ **Service (Light pink)**
○ **Electrical CAE (Dark pink)**	○ **Block Leaders – 3D CAD Coordinators (Light blue)**

There are 427 interactions in the EDS DSM partition. 214 of those interactions are within the EDS team (Internal communication and information to complete the task) and 213 interactions are with cross functional groups (External communication and information to complete the task). Marks colored in green represent the interactions inside the EDS team to complete the tasks on the diagonal, while the marks in red indicate the interaction with groups outside the EDS team to complete the tasks on the diagonal. This is a powerful representation to acknowledge the need of special coordination efforts with groups outside the EDS team to ensure tasks are completed in time and with high quality.

The main takeaways from the interactions mapping are:

- Special coordination efforts between system integration group and CAE group should be planned ahead to ensure deliverables such as the creation of electrical diagrams, CAE test plan and report and compatibility reviews are finished on time to avoid late delivery of EDS tasks.
- Special coordination efforts between EDS Core and connectors groups should be planned ahead to ensure virtual routing assessments and campaign prevention reviews are completed on time to avoid late delivery of EDS tasks.
- Special coordination efforts between purchasing should be planned ahead to ensure supplier quotes are received on time and tooling orders are released with enough time for parts creation and delivery at the assembly plant.

4.4 SD Model

The system dynamics model provides a post mortem analysis of the SUV case study where we can observe how the project features emulate the work process of the project by representing tasks, sequence, managerial responses, ripple and knock-on effects already explained in section 2.3.2.2. The creation of this model provides a safe environment to test proposals to reduce design iterations or rework in the current EDS design and development process, and to observe the magnitude of improvement such proposals could have on the iron triangle parameters of the project. This model can estimate the effects managerial decisions have on achieving project goals and how such decisions generate unintended side effects –ripple and knock-on effects- that impact the performance of the team and create policy resistance.

4.4.1 Case study data

In order to create the model based on the SUV Project several interviews with engineers involved in the project were conducted along with the survey presented in section 4.1.3. Quality and management databases internal to the OEM were reviewed to understand the project design life cycle, the main issues encountered during the design phase, the time required to solve such issues, and the quantity of people involved in the project at each point of time. This information collected through the sources mentioned before was divided in three main categories: work done during platform design phases, work done during the first prototype build and work done during the top hat design phases.

Figure 24 shows the data collected for the platform design phase and first prototype build. The number of tasks is aligned with the EDS WBS and EDS DSM created in previous sections. Calculation of the effort required to complete each task was generated by multiplying the number of people required to perform each task by the duration in weeks per task, divided by the actual time allocated for each task per week. A similar exercise was performed for the top hat design phases.
The effort required by the EDS staff to complete all the first prototype build activities was calculated analyzing the number of design issues encountered during the SUV project first prototype build -35 issues- and defining the number of people, duration of each activity and time allocated per week for each activity. The 35 issues analyzed in the case study were classified in the following categories: incorrect 3D CAD assessment, electrical characteristics of a module not received on time, electrical compatibility reviews not performed correctly, functionality test not performed correctly, incorrect assessment of design rules and 2D representation of the wiring harness 3D CAD.

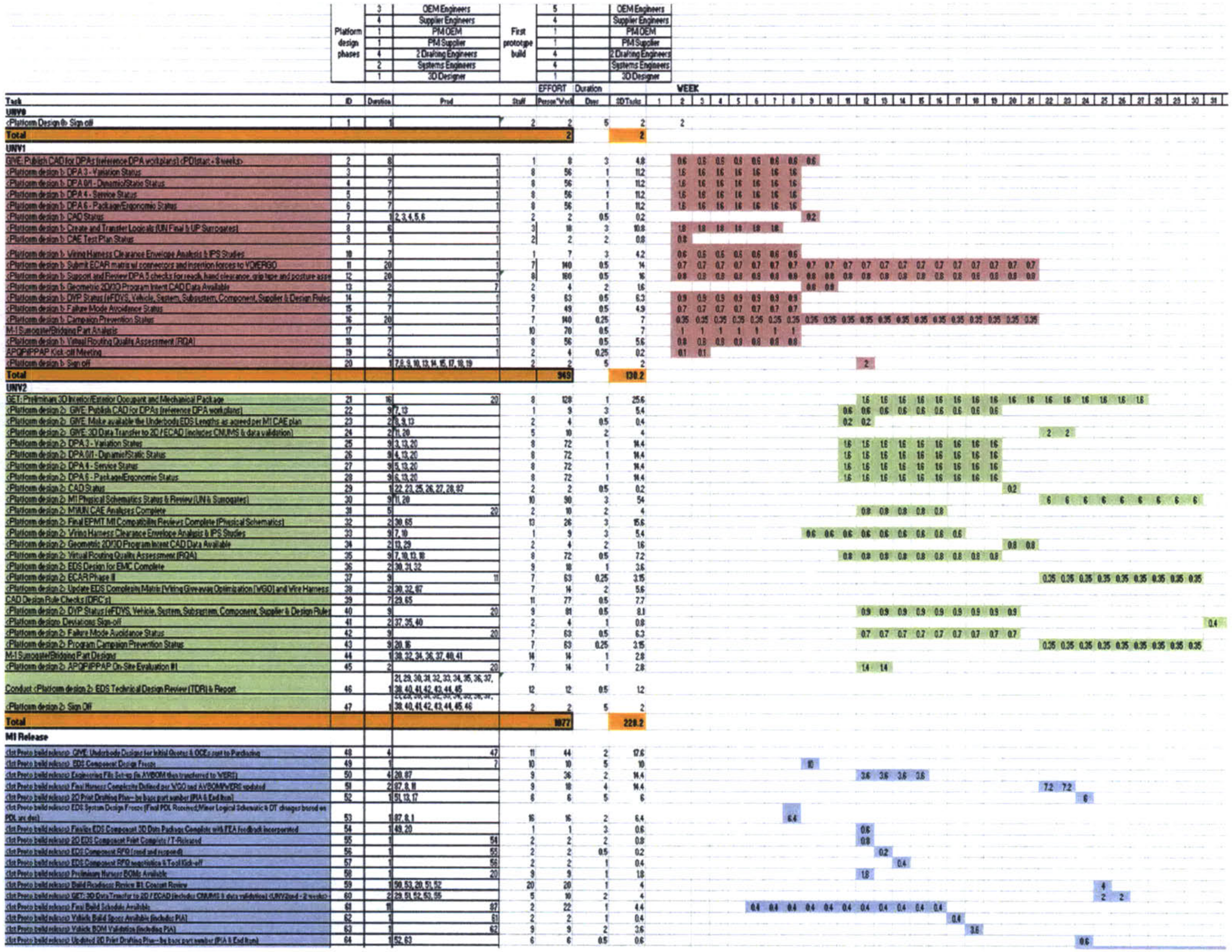


Figure 24: Data collected for SD model

4.4.2 Strategy followed for creation/usage

The system dynamics model was created using as a base a four stock-one rework cycle model created by Dr. James Lyneis similar to the one explained in section 2.3.2. The model created by Dr. Lyneis was modified adding some structures unique to the EDS case study such as overtime policies, original staff allocated to the project, duration of each phase of the project, SUV project tasks sequence, normal fraction of work correct during the SUV project, normal productivity during the SUV project, original work to do for platform design, top hat design and first prototype build. The model is presented below in five sectors: the rework cycle, tasks sequence, fraction correct and productivity, rework discovery, and prototype build. A complete listing of model equations is contained in Appendix C.

Figure 25 shows the rework cycle view of the system dynamics model created for the SUV project. The four stocks in the center represent the basic rework cycle presented in section 2.3.2. All variables in green are part of the staff allocation structure, the variables in blue are part of the structure generated to capture the EDS cost during the different phases of the design based on the amount of overtime to be paid to cover all the rework and design iterations found. The variables in orange are part of the overtime policy structure to define the amount of overtime hours the staff worked at each point of the design phase, and the variables in pink are part of the structure created to measure effort and amount of rework generated during each of the design phases and the first prototype build.

The original work to do for platform design phases was 663 tasks; this value was calculated based on the data gathered for the SUV project shown in Figure 24. The work to do during the first prototype build was 320 tasks based on the 35 issues found in the case study and the amount of the time and resources required to complete the work on time. The work to do during the top hat design phases was 529 tasks based on the case study development and result.

The total design phase from <platform design 0 sign off> to <top hat design 2 end> takes around 60 weeks to complete under the normal OEM EDS process. The staff structure in the model has a normal planned staff of 16 EDS engineers from week 0 to week 44 –when first prototype build starts- and then an additional four EDS engineers after week 44 which aligns with the case study staff allocation. The staff is allocated based on the amount of work available, the priority to work on platform design tasks to complete work for the first prototype build, the amount of engineers available to perform a task, the time remaining towards the design phase deadline, and the amount of time required to finish a task.

Overtime required is calculated based on the amount of work remaining (original work to do and rework to do), the fraction of work correct and the productivity of the staff. The maximum overtime allowed is 50% of extra work per engineer per week.

Overtime costs are calculated based on work done above 100% of each engineer's workload multiplied by the cost of overtime per week. The overtime cost varies depending of the period in the project. For overtime costs when the first prototype build did not start –before week 44 in the model- the cost is set up to $600 USD per week considering the engineer works in his/her office without the need to pay additional expenses such as fly tickets, hotel or rental car. For overtime costs when the first prototype build started the cost is set up to $1,625 USD per week considering the engineer has to provide on- site support at the assembly plant and the expenses listed above have to be covered. The normal workload per week by engineer is 40 hours which accounts for the 100% workload. Overtime costs are paid double after the workload of an engineer exceeds 25% of the maximum workload, this means that the first 10 hours of overtime are paid according with the quantities described above, but starting the 11^{th} hour of overtime the hours are paid double.

The effort during platform design, top hat design and first prototype build is calculated by monitoring the original work done correctly, the rework being generated on original work, the rework generated on rework and the rework done correctly. The measurement of total rework generated during the program is critical to validate the effectiveness of any proposal to change the design process.

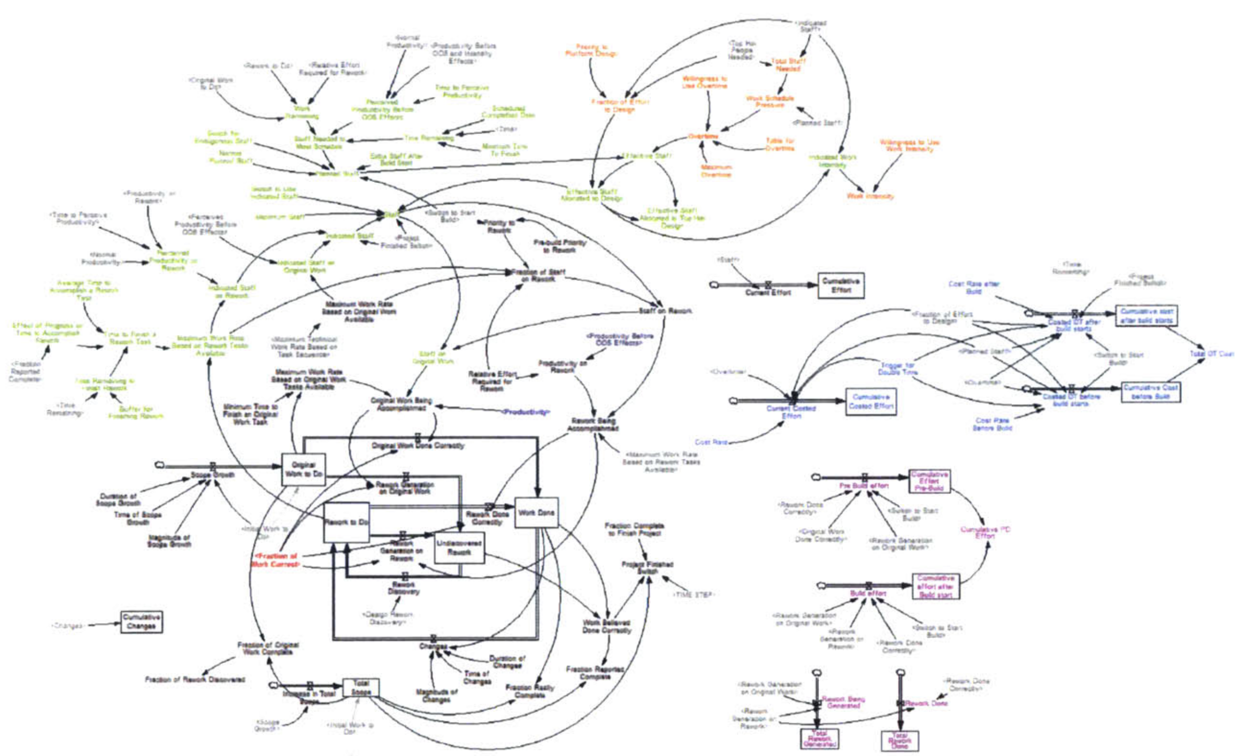


Figure 25: Rework cycle view

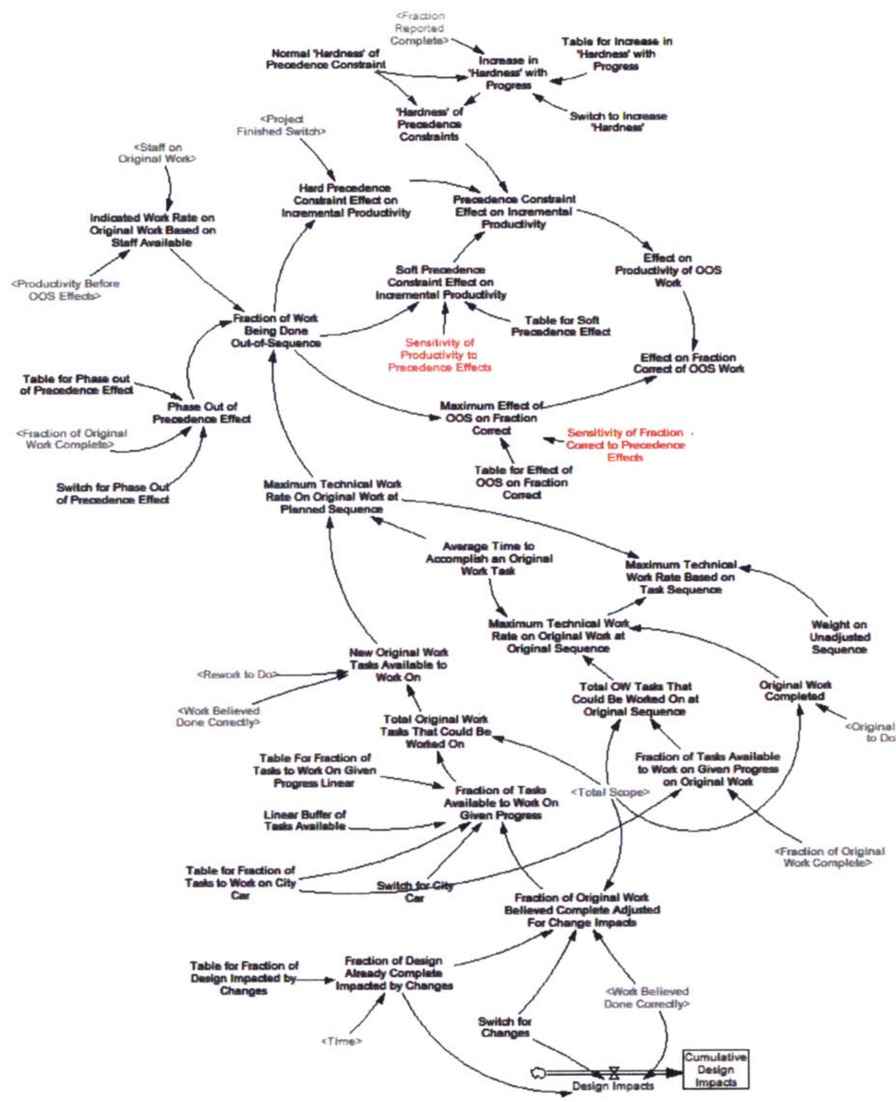


Figure 26: Task precedence view

Figure 26 shows the model structure for task precedence and out of sequence work. This structure was generated to constrain the amount of work that is available at each point of time in the project. As showed in the WBS presented in previous sections, the EDS design and development process has a defined task sequence with fixed task duration and fixed successors and predecessors for each task. The structure presented in figure 26 determines the optimal sequence and staff assuming work on downstream tasks occurs only when upstream tasks have been completed. Out of sequence work is the term used to describe doing tasks in the less-than optimal sequence. There are three main causes of working out of sequence: applying staff in excess for tasks available, rework on upstream tasks and late design changes that could impact upstream work. Out-of-sequence work affects fraction correct and productivity. The sensitivities of fraction correct and productivity to precedence effects were calibrated to obtain model results similar to the case study. The values used for each sensitivity are showed below:

- Sensitivity of fraction correct to precedence effects (Out of sequence rework) = 0.25
- Sensitivity of productivity to precedence effects (Out of sequence rework) = 0.5

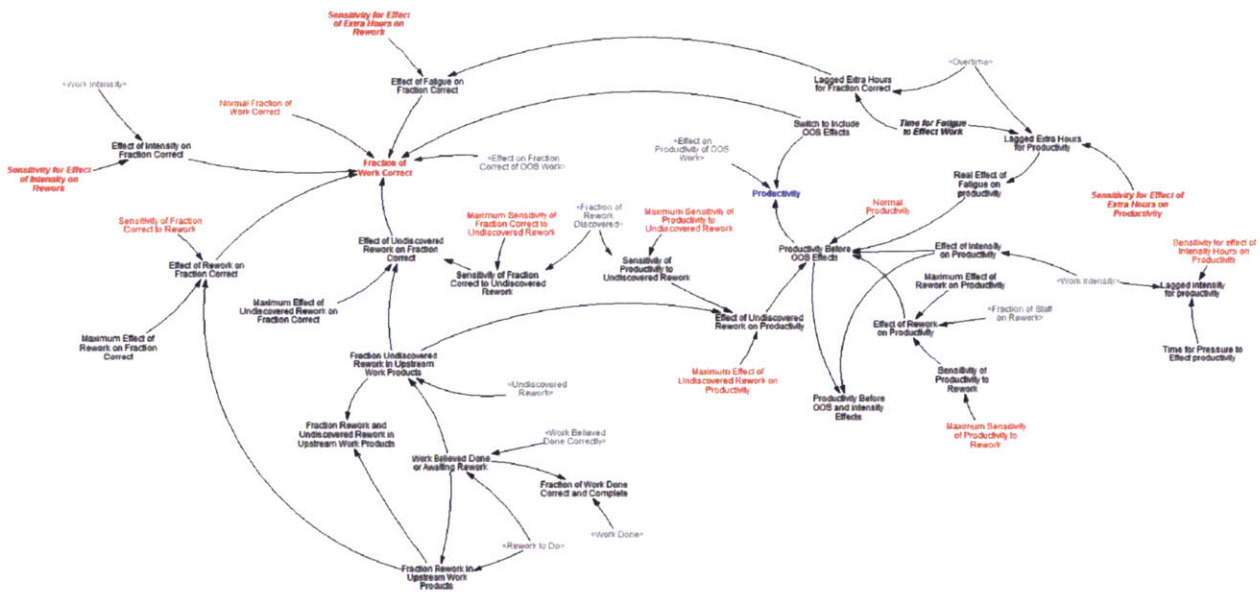


Figure 27: Fraction of work correct and productivity

Figure 27 shows the model structure for fraction of work correct and productivity. The fraction of work correct and productivity can be impacted over the course of the project by several factors that could be technical or human factors. The technical factors introduced in the model are: rework, undiscovered rework and out of sequence work. Undiscovered rework represents the situation of building errors into downstream work affecting both fraction of work correct and productivity. Rework generates out of sequence work and consumes time in the project that was not originally planned. The human factors introduced in the model are: fatigue and work intensity. Fatigue is a consequence of the usage of overtime to keep delivering tasks according to plan. Fatigue can reduce the fraction of work correct and the productivity of the staff when overtime is used in excess. Work intensity provides a boost in productivity by delivering tasks quickly but it could also produce more errors affecting eventually the fraction of work correct and reducing productivity by allocating time to fix errors on upstream tasks. It is important to mention that the sensitivities of the effect of each human and technical factor on Fraction correct and productivity showed in figure 27 were calibrated in order to simulate the results from the case study. The values for each sensitivity were fixed for all the scenarios presented in section 4.4.4 to keep a base line and avoid manipulation of the sensitivities to obtain results that would show an improvement in the model but that would not represent a real improvement in the case study.

The default values used for each sensitivity are:

- Sensitivity for effect of intensity on rework = 0.4
- Sensitivity for effect of extra hours (overtime) on rework = 0.4
- Sensitivity for effect of intensity on productivity = 0.5
- Sensitivity for effect of extra hours (overtime) on productivity = 0.3
- Maximum sensitivity of fraction correct to undiscovered rework = 0.95
- Maximum sensitivity of productivity to undiscovered rework = 0.4
- Sensitivity of fraction correct to rework = 0.5
- Maximum sensitivity of productivity to rework = 0.25
- Maximum effect of undiscovered rework on productivity = Graph based on the EDS task sequence
- Normal fraction correct = 0.95
- Normal productivity = 1

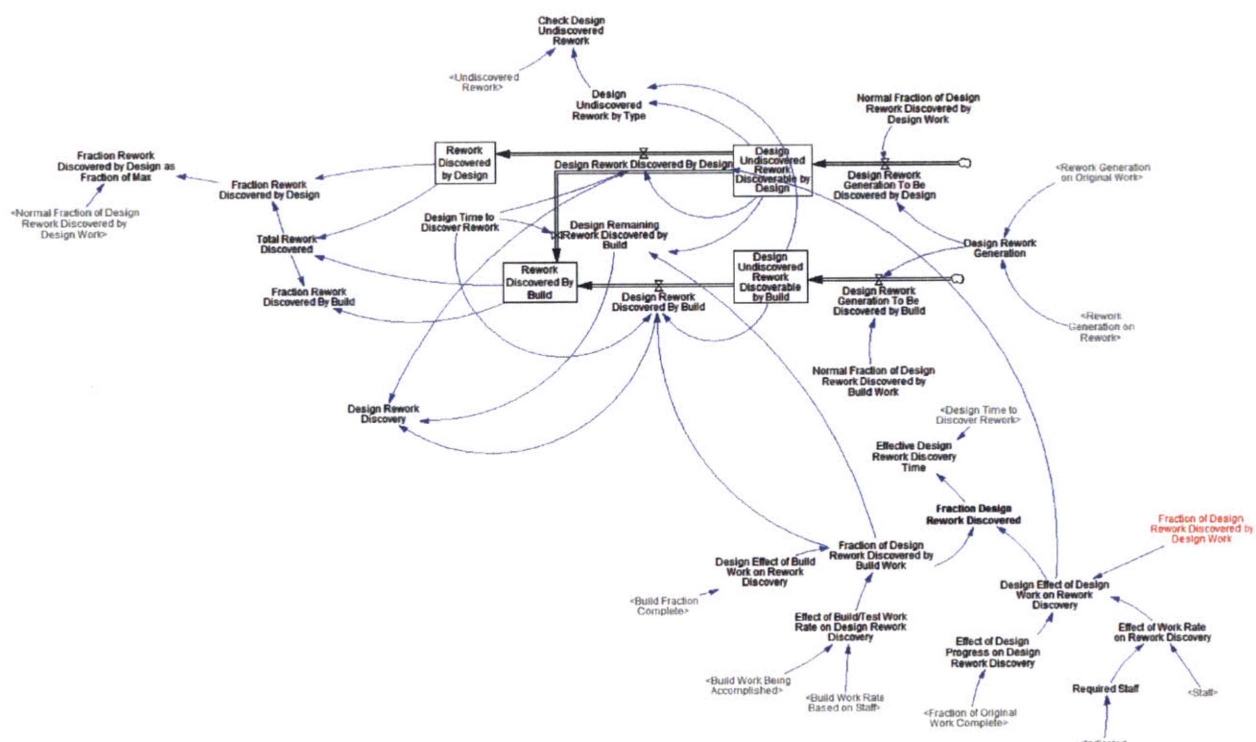


Figure 28: Rework discovery view

Figure 28 shows the structure created to monitor how much of the rework was discovered during the design phase and how much of the rework was discovered during the first prototype build. The monitoring of this data is important to analyze how effective is the design process to fix all issues prior to building physical products. The discovery of rework during physical builds such as the first prototype build is more expensive and time consuming than discovering and fixing errors during the design phases. The value of the variable called Fraction of Design rework discovered by design work was set to 0.2 in the model in order to align with the case study data. In the case study the majority of the rework was discovered during the prototype build. This shows that the work done during the design phase contained multiple errors that were not discovered until the validation in the prototypes.

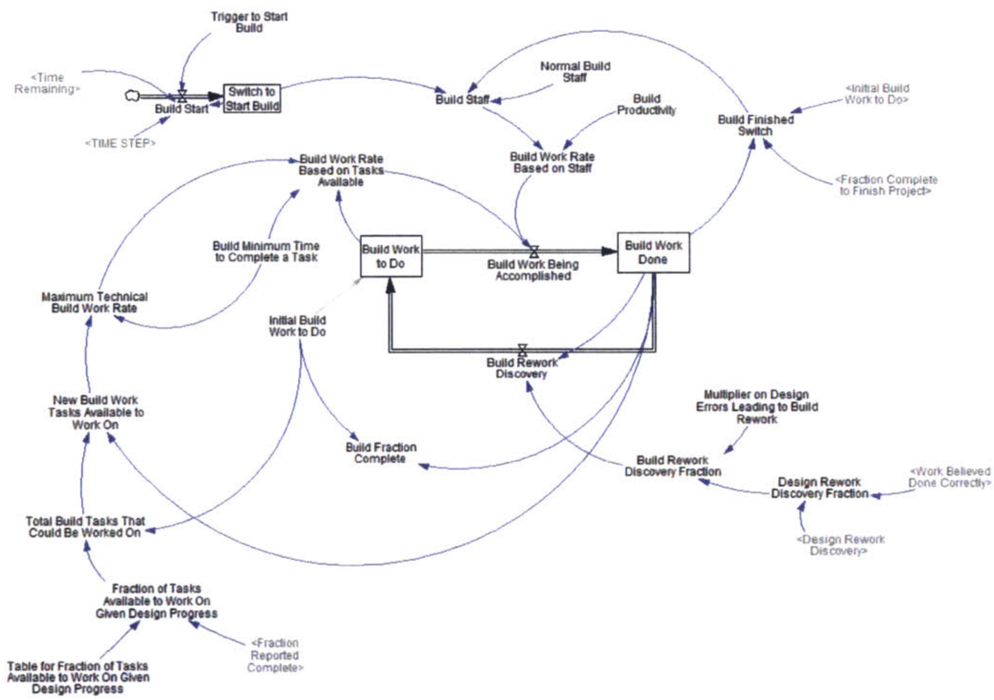


Figure 29: First prototype build view

Figure 29 shows the structure created to represent the start of the first prototype build. The original work to do during the build is set to 320 tasks to align with the case study as explained before. The amount of rework discovered during the build depends on the quality of work done during the design phase.

4.4.3 Results & Findings

After creating all the structures described above the initial parameters of the case study were entered into the model to confirm the alignment between the model output and the SUV project results.

Case study parameters

The model represents the following sections of the EDS D&D Process

- ✓ **Platform Design (End of PD0, PD1 & PD2)**

  Duration: 60 Weeks

  Initial work to do: 663 tasks

  Design Staff: 16 engineers and 4 additional engineers after build starts

- ✓ **Top Hat Design (THD0, THD1 & THD2)**

  Duration: 60 Weeks (simultaneous with platform design)

  Initial work to do: 529 tasks

  Staff: Shared with platform design

- ✓ **1st Prototype build**

  Duration: 16 weeks (the last 16 weeks of the 60 weeks allocated for the design phases)

  Initial work to do: 320 tasks

  Rework discoverable by design discovered by build: 80%

  Rework discoverable by build discovered by build: 20%

  Staff: 20

Design engineers overtime payment

The first 10 hours of overtime each week are paid within the normal rate of $600 USD/week before the first prototype build starts and $1650 USD/week after build starts. Starting the 11th hour of overtime the payment is double.

Rework discovery and overtime payment after build starts

After the first prototype build started any work performed by the design team is more expensive since work has to be done onsite and expenses such as airplane tickets, hotel, per diem and rental car have to be covered by the company.

In order to confirm the alignment between the system dynamics model and the SUV project outcome the graphs below were generated.

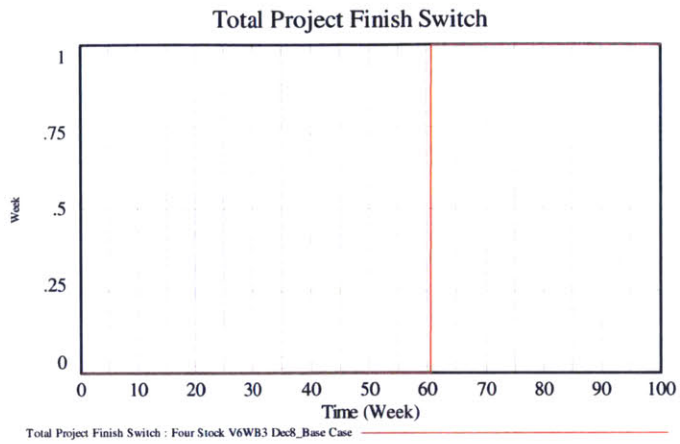


Figure 30: Project Finish graph

Figure 30 shows the project completion at week 60 which is aligned with the results from the case study.

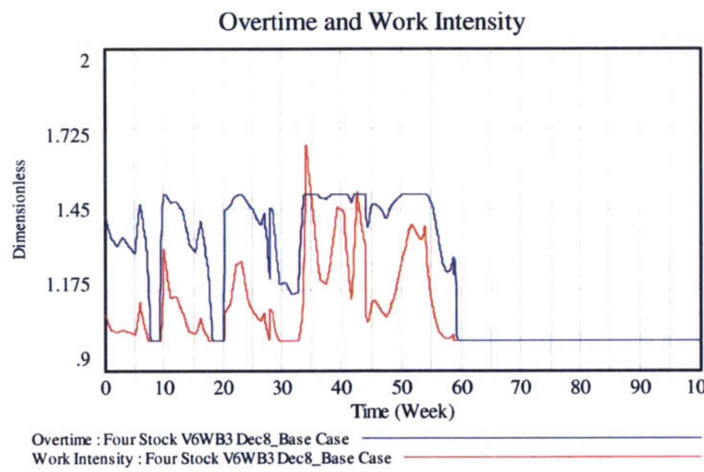


Figure 31: Overtime and work intensity graph

Figure 31 shows the overtime and intensity rates over the project life cycle. Normal workload represents the value of 1 in the y axis. While we do not have time series data on overtime, the case study was known by the high rates of overtime and work intensity to deliver results on time and avoid project delays.

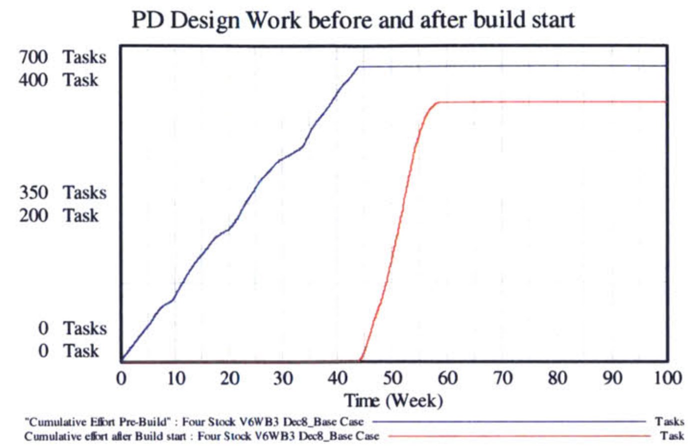


Figure 32: Work done during platform design and first prototype build

Figure 32 shows the results from the model for the work done during the platform design phases and the first prototype build. The results match with the SUV project results of 663 tasks done for platform design and 320 tasks for the prototype build.

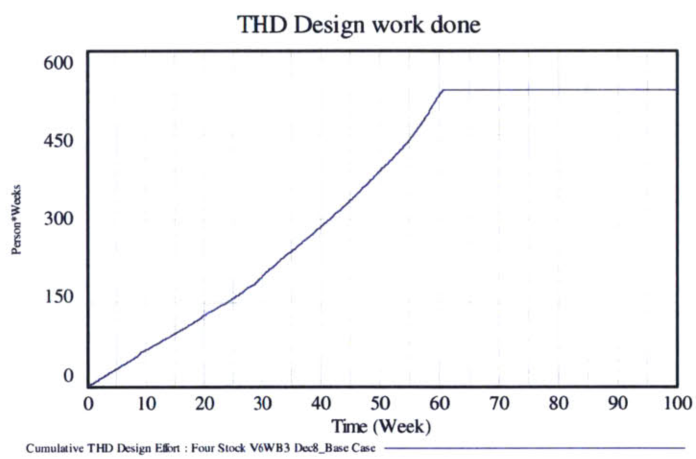


Figure 33: Work done during top hat design

Figure 33 shows the results from the model for the work done during the top hat design phases. The result matches with the SUV project result of 529 tasks done during the top hat design phases.

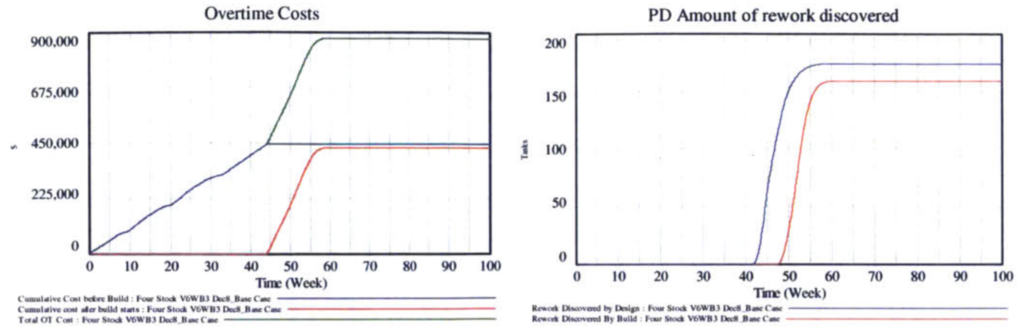


Figure 34: Overtime costs and rework discovery

Figure 34 shows the results from the model for the overtime costs and rework discovery. The case study quantities are aligned with the numbers shown in the graph and with the distribution of overtime costs between build and design phases. As we can observe in Figure 34, overtime costs during the build –red curve- were very similar to the overtime costs during the design phases –blue curve- due to the amount of rework discovered during the prototype build as a result of the low fraction of work done correctly during the platform design phases.

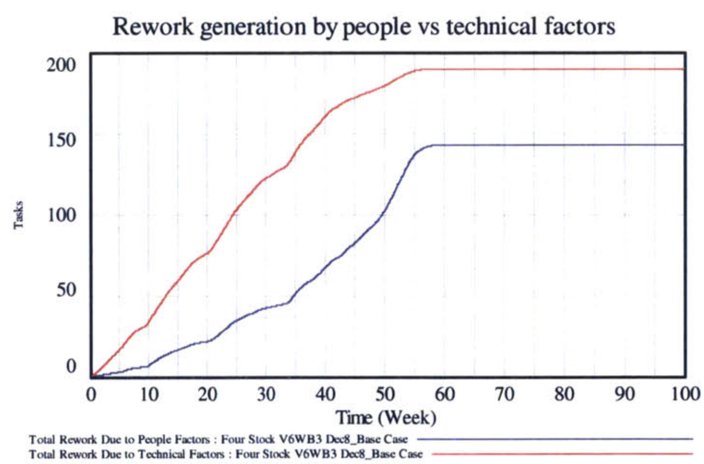


Figure 35: Source of Rework (human vs technical factors)

Figure 35 shows the results from the model for the rework generation. The source of rework can be from human factors such as fatigue and work intensity, or from technical factors such as undiscovered rework and out of sequence work. In the case study the majority of rework was generated by technical factors as the amount of errors built into design tasks was high, thereby producing a lot of design iterations and rework further down in the process. Fatigue was the factor impacting the most from the human side, where the high overtime rates produced fatigue and therefore the fraction of work done correct decreased as fatigue increased.

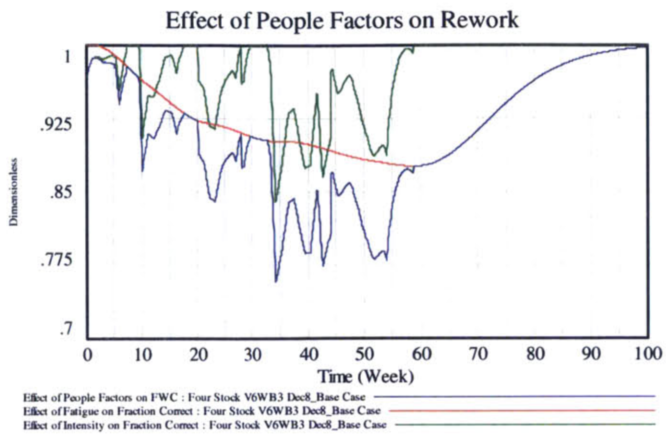


Figure 36: Effect of Human factors on rework

Figure 36 shows the impact of fatigue and intensity –human factors- on the fraction of work correct. The closer the curve is to zero, the greater the impact on fraction of work correct. The effect of intensity has some variability along the project life cycle as a result of variations in the planned task sequence. The effect of fatigue increases more slowly as the project advances because this effect is related to smoothed overtime worked during the project.

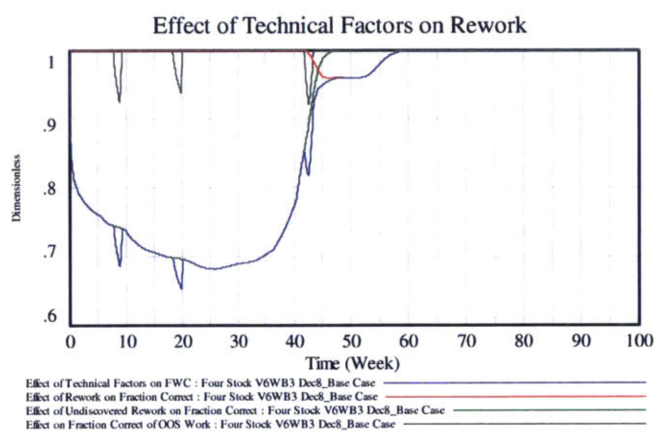


Figure 37: Effect of technical factors on rework

Figure 37 shows the impact of rework, undiscovered rework and out of sequence work on fraction correct. The closer the curve is to zero, the greater the impact on fraction of work correct. The effect of undiscovered rework has the largest impact on fraction of work correct. This, as explained above, is the effect of building errors into downstream tasks from undiscovered errors in upstream tasks (that will be discovered further down in the design or build phase).

The results from the model are aligned with the case study dynamics and results which give confidence to use this model as a base to test the magnitude of improvement in rework done, project completion date and overtime cost of the proposals to modify the EDS design process.

4.4.4 Test of Policies based on WBS, CPM & DSM

Once the case study result was simulated by the system dynamics model four scenarios were tested in order to probe their effectiveness in reducing rework and overtime costs. These scenarios were chosen from the main takeaways of the EDS survey, WBS, CPM, DSM and product development literature.

Scenario 1: ***Separate group working on (work from week 18 to 36) EDS Part Release***

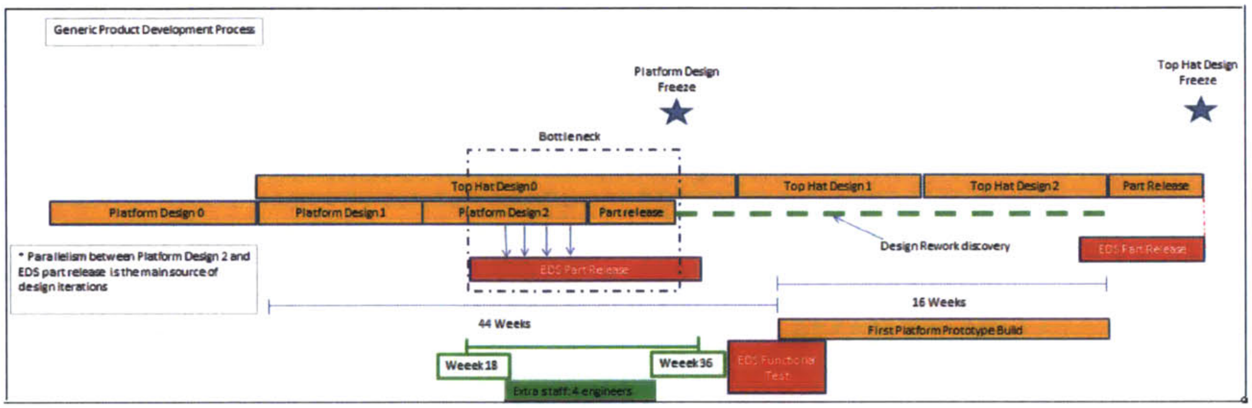


Figure 38: Scenario 1 overview

Requirements: 4 extra engineers working from week 18 to week 36

Model Parameters being modified:

- ✓ Planned staff increased by 4 engineers from week 18 to week 36

Expected impact:

- ✓ Increase on fraction of work correct
- ✓ More rework discovered during platform design (before week 44)
- ✓ Earlier PD finish
- ✓ Less rework discovered during build (After week 44)
- ✓ Reduce overtime after week 36

Model results

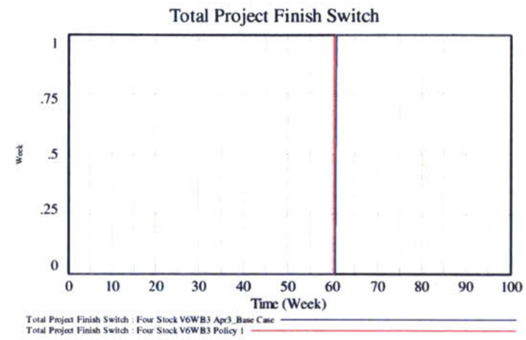


Figure 39: Scenario 1 project finish date

Figure 39 shows the project completion in 59 weeks for scenario 1 against the 60 weeks project completion in the base case (which was the plan, so we would not expect a significantly earlier finish).

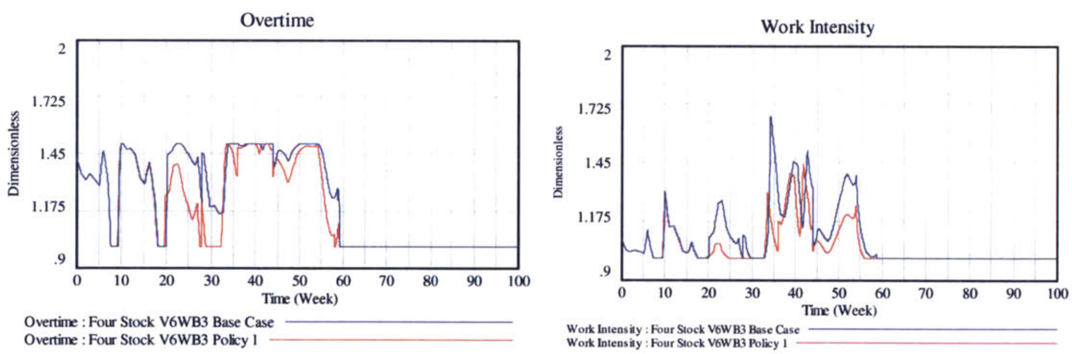


Figure 40: Scenario 1 overtime and work intensity

Figure 40 shows a decrease in overtime and work intensity by adding the separate group of engineers working on the EDS part release activities. Most of the reduction is in Work Intensity as engineers are assumed to work overtime first, before working more intensely.

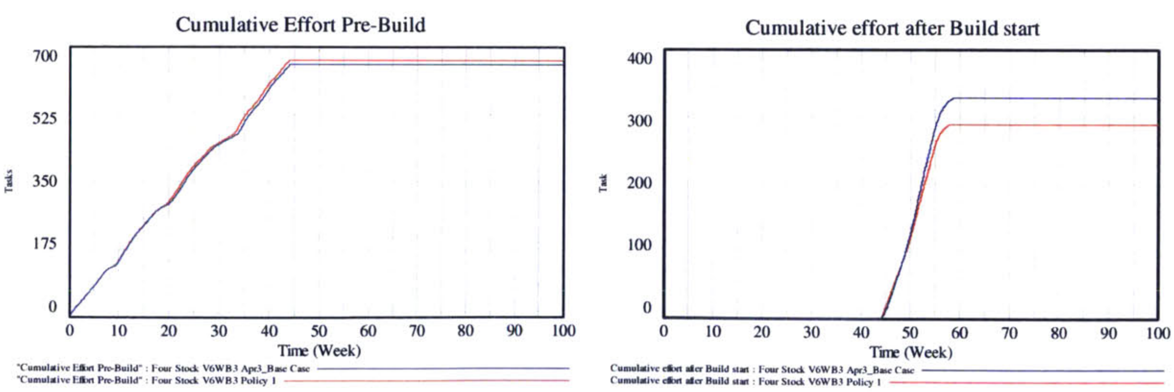


Figure 41: Scenario 1 cumulative effort during platform design and first prototype build

Figure 41 shows a 2% increase in effort during platform design phase and then a 12% decrease of effort once the first prototype build started. As discussed below, this results from an increase in the quality of the design work done during platform design accompanying the reduction of work intensity and overtime fatigue, in turn resulting in the reduction of errors and rework discovered during the prototype build.

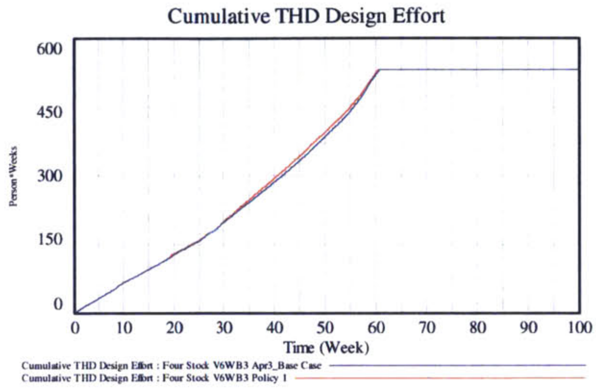
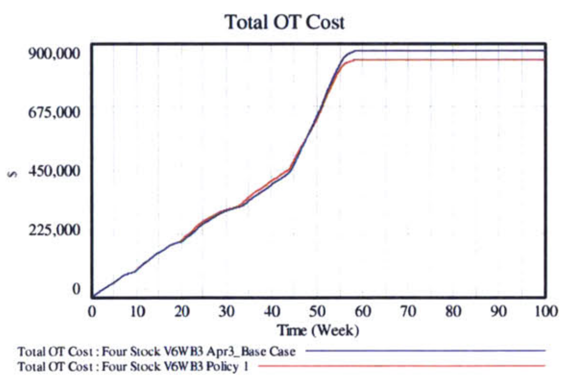


Figure 42: Scenario 1 work done during top hat design

Figure 42 shows no difference in the work done through the top hat design phases. This is a good result since there is no impact on the efforts to complete top hat design within the 60 weeks timeframe presented in the base case.



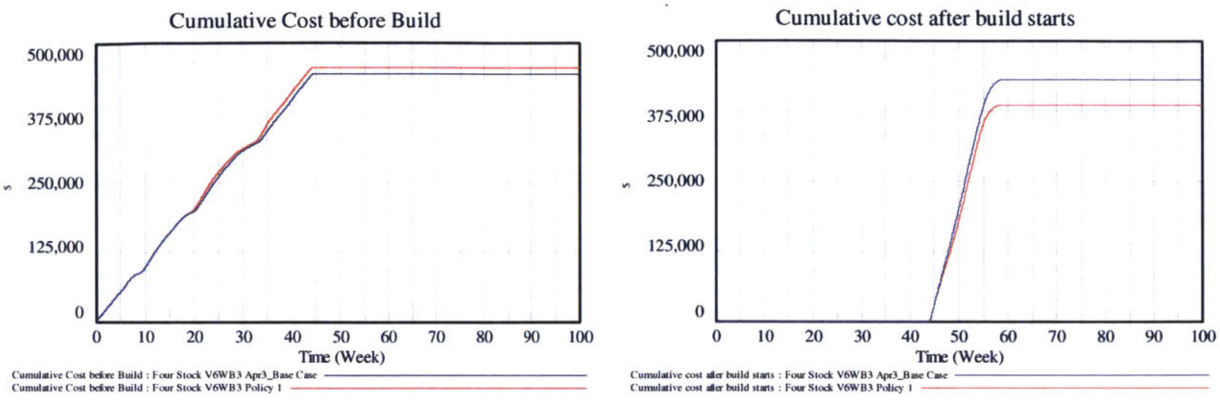


Figure 43: Scenario 1 overtime costs

Figure 43 shows an overall overtime cost reduction of 4%. The overtime cost during the platform design phases increased slightly by 1% but it had a decrease of 11% once the prototype build started. This is another indication of the increase in quality during the platform design phases resulting in less rework or design iterations during the prototype build.

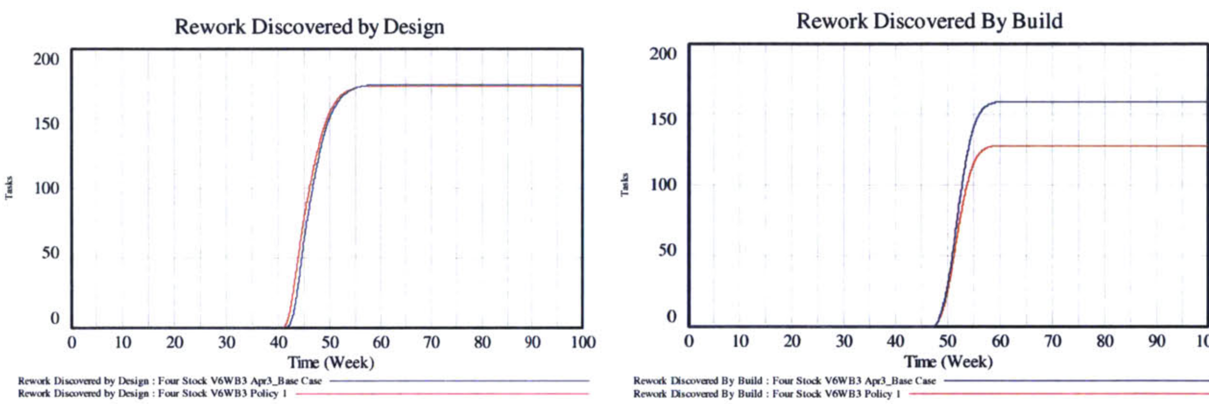


Figure 44: Scenario 1 rework discovery

Figure 44 shows how the rework discovered during the platform design phase is similar between the case study and the scenario 1 but it shows a reduction of 20% of rework discovery during the first prototype build. This reduction of rework discovery during build is a consequence of the higher quality of the work done during the platform design phases.

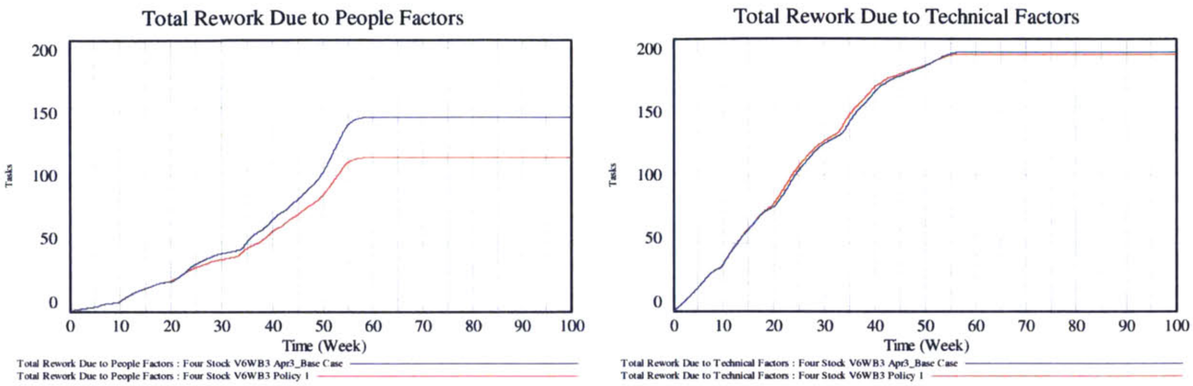


Figure 45: Scenario 1 source of rework (human vs technical factors)

Figure 45 shows how the amount of rework caused by human factors –fatigue and work intensity- decreased by 22% while the amount of rework caused by technical factors – undiscovered rework and out of sequence work- is very similar. The improvement on the amount of rework caused by human factors comes from the fact that the additional group working on the releases reduced the amount of workload of the EDS team and reduced the fatigue and work intensity caused by the use of excessive overtime.

Overall project outcome improves by introducing a separate group working on the EDS part release activities. The extra dedicated staff helps to reduce the workload from the EDS team, the fraction of work correct increases causing less rework during the first prototype build and reducing overtime costs. Figure 46 shows the scenario 1 fraction of work correct value which is the main driver of improvement in project completion date, rework done and overtime costs.

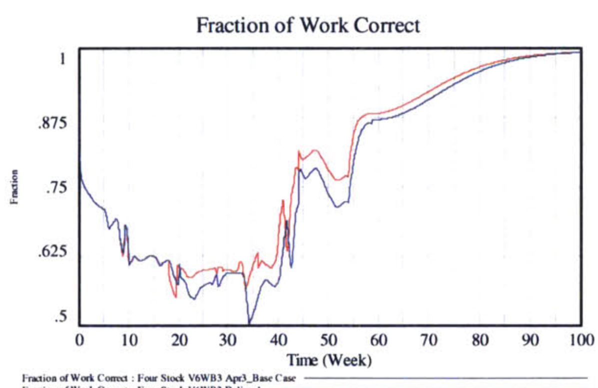


Figure 46: Scenario 1 Fraction of work correct

Scenario 2: ***EDS Team focused in accomplishing working-level tasks and coupled clusters from EDS DSM (week 0 to week 28)***

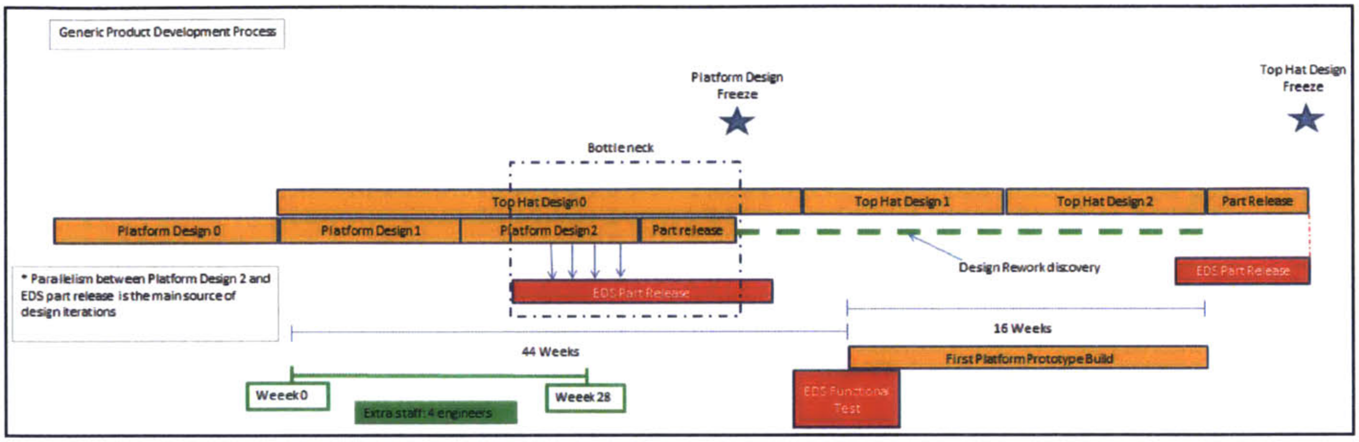


Figure 47: Scenario 2 overview

Requirements: 4 extra engineers working from week 0 to week 28

Model parameters modified:

- ✓ Planned staff increased by 4 engineers from week 0 to week 28
- ✓ Policy 2 Normal productivity = (Extra staff*NewPDY+Planned staff*Normal PDY) / (Extra staff+planned staff) = [(4*2)+(16+1)]/20 = 1.2
- ✓ Policy 2 Normal Fraction Correct= (Extra staff*NewFC+Planned staff*Normal FC) / (Extra staff+planned staff) = [(4*.98)+(16*.95)]/20 = .956

Expected Impact:

- ✓ Increase on fraction of work correct
- ✓ Increase in productivity
- ✓ Reduction of rework
- ✓ The amount of rework discovered after week 44 is small relative to the rework discovered- before week 44
- ✓ Earlier PD finish
- ✓ THD finish earlier
- ✓ Reduce overtime after week 28

Model results

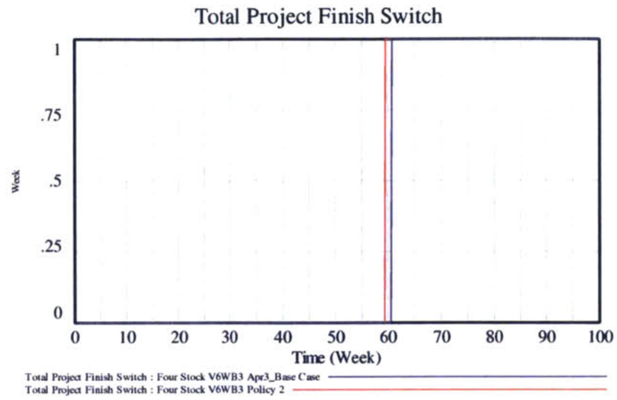


Figure 48: Scenario 2 project finish date

Figure 48 shows the project completion in 59 weeks for scenario 2 against the 60 weeks project completion in the base case

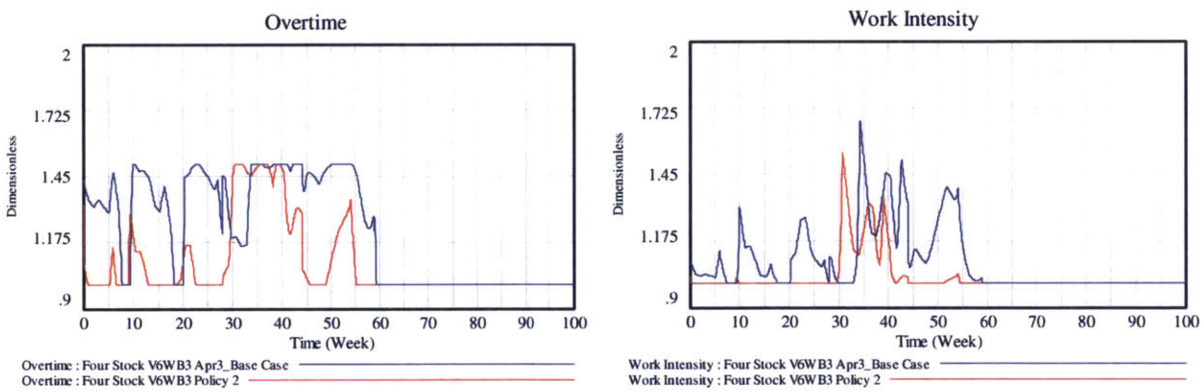


Figure 49: Scenario 2 overtime and work intensity

Figure 49 shows a decrease in overtime and work intensity by adding the extra staff to work on the working-level tasks and coupled clusters of the EDS design and development process during the platform design phases.

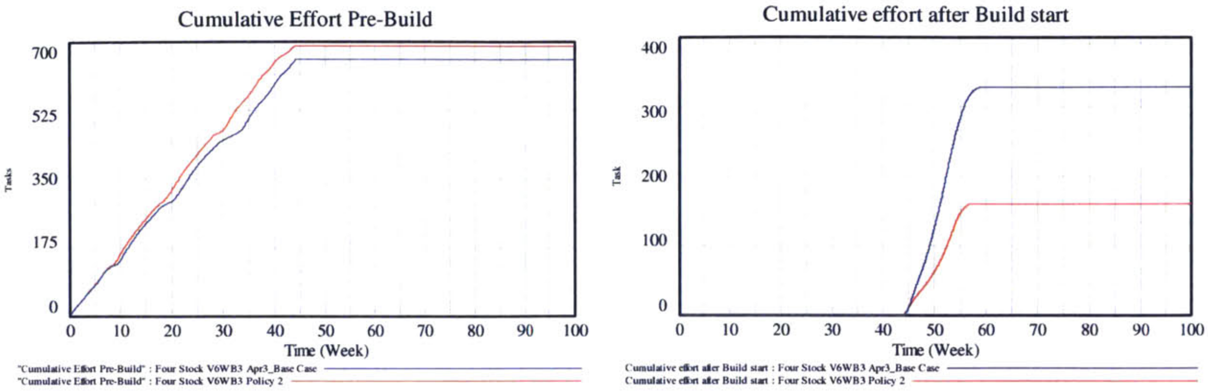


Figure 50: Scenario 2 cumulative effort during platform design and first prototype build

Figure 50 shows 5% increase of effort during platform design and then a 52% decrease of effort once the first prototype build started. This represents an increase of quality in the design work done during platform design resulting in the reduction of errors and rework discovered during the prototype build. The increase in effort during platform design phase represents the extra activities --such as design reviews and double check of work-- the EDS team can perform due to the extra staff supporting the working-level activities.

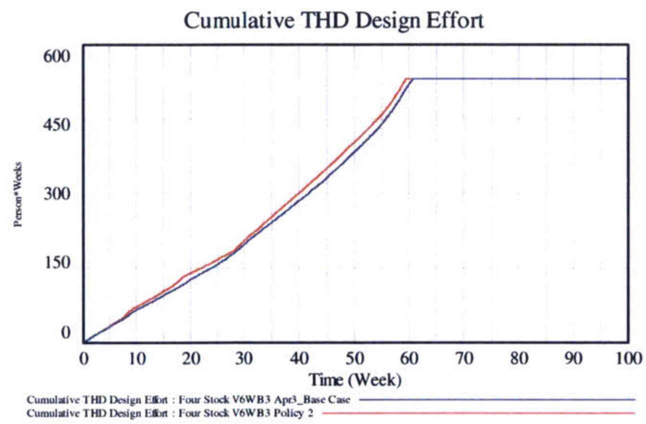


Figure 51: Scenario 2 work done during top hat design

Figure 51 shows slight difference in the work done through the top hat design phases. This is a good result since there is no impact on the efforts to complete top hat design within the 60 weeks timeframe presented in the base case.

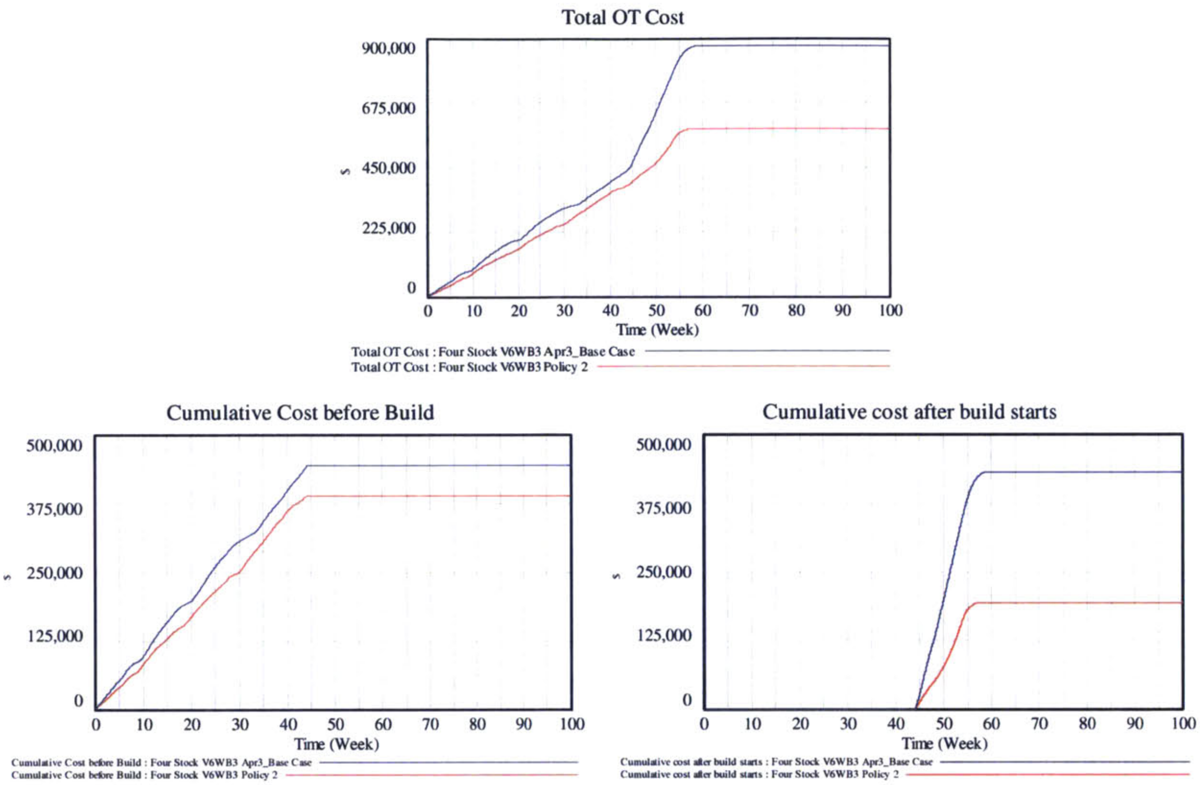


Figure 52: Scenario 2 overtime costs

Figure 52 shows an overall overtime cost reduction of 34%. The overtime cost during the platform design phases decreased 13%, while the overtime cost once the prototype build started decreased 55%. This is another indication of the increase in quality during the platform design phases resulting in less rework or design iterations during the prototype build.

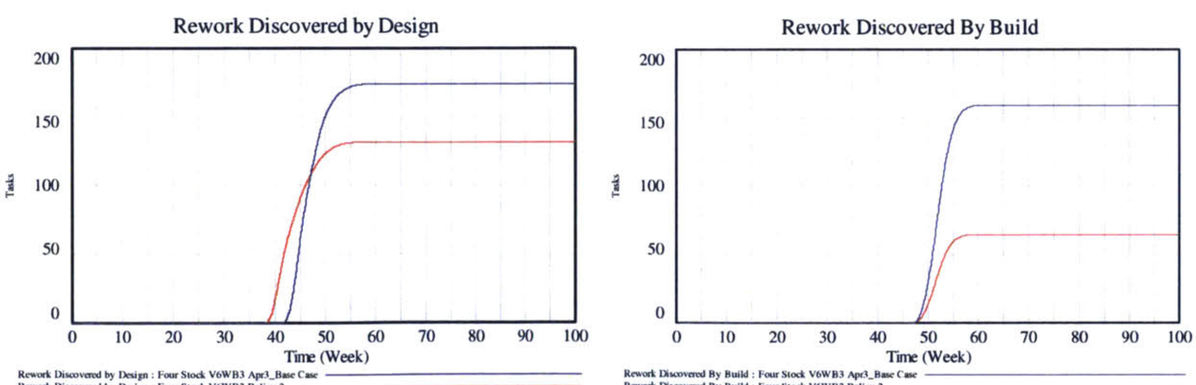


Figure 53: Scenario 2 rework discovery

Figure 53 shows a decrease in the rework discovered across the project. For the platform design phases the rework discovered decreased by 25%, while the rework discovered during the first prototype build decreased 60%. This decrease in rework is caused by the increase of fraction of work correct in the early stages of the design building less errors into downstream tasks.

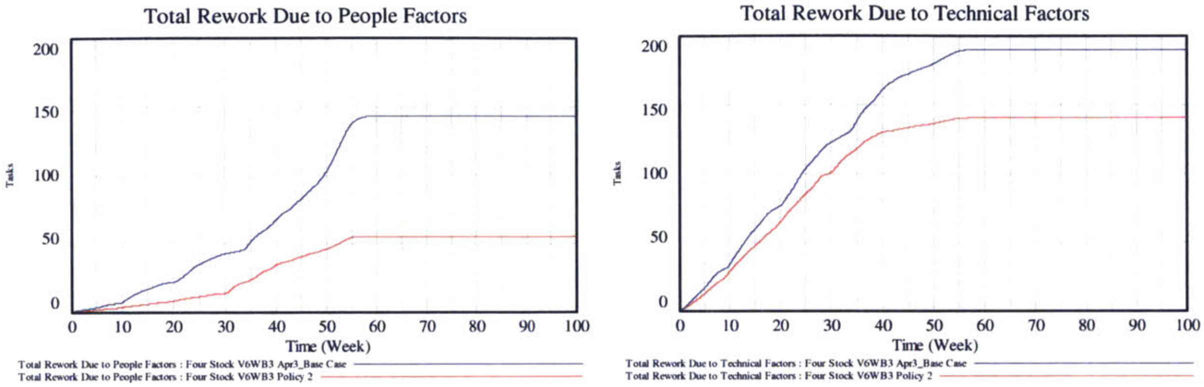


Figure 54: Scenario 2 source of rework (human vs technical factors)

Figure 54 shows how the amount of rework caused by human factors –fatigue and work intensity- decreased by 62% while the amount of rework caused by technical factors – undiscovered rework and out of sequence work- decreased by 27%. The improvement on the amount of rework caused by human factors comes from the fact that the additional group working on the releases reduced the amount of workload of the EDS team and reduced the fatigue and work intensity caused by the use of excessive overtime. The improvement on the amount of rework caused by technical factors comes from the fact that the fraction of work correct increased when the extra staff was introduced to help in the working-level activities. This situation built fewer errors in downstream tasks reducing the amount of rework to be discovered and the out of sequence tasks.

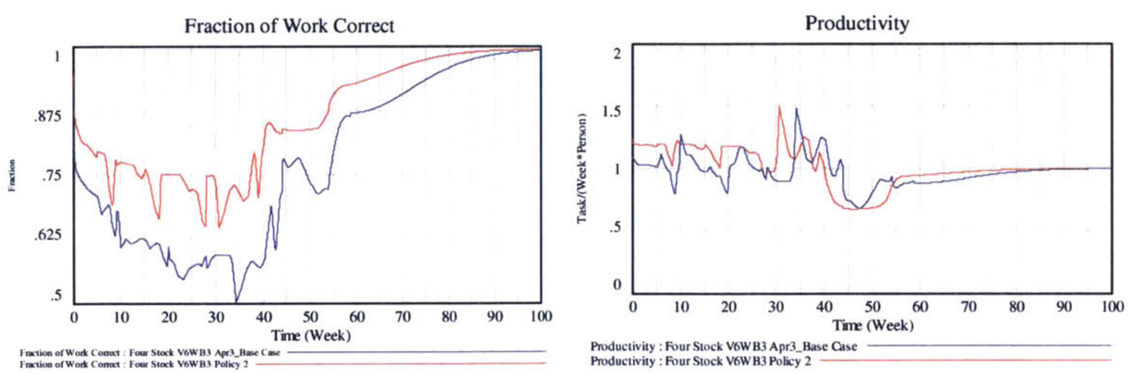


Figure 55: Scenario 2 fraction of work correct and productivity

Figure 55 shows the boost in fraction of work correct and productivity along the project generated by the "extra hands" introduced to work on the platform design phases. The decrease of workload for the EDS team generated time to double-check work and perform design reviews to ensure fewer errors are built into downstream tasks producing an overall reduction of the rework discovery and overtime costs. The overall overtime reduction decreased the effects of the human factors in rework generation. This decrease in rework generation reduced the effects of technical factors such as undiscovered rework and out of sequence tasks.

Scenario 3: Extra functional test to start during platform design 2 (week 18)

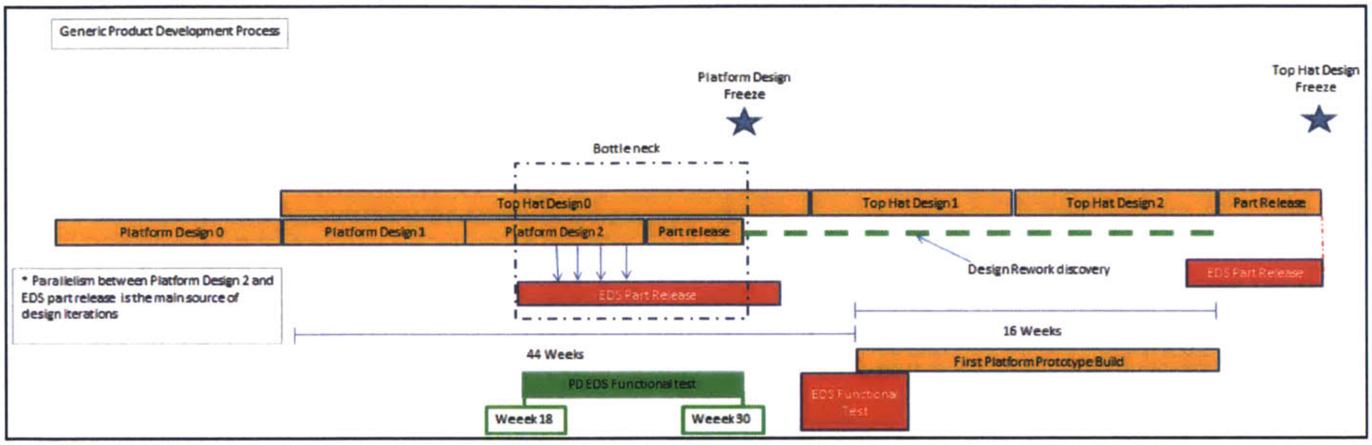


Figure 56: Scenario 3 overview

Requirements: Increase the amount of out of sequence work due to the new functional test to be performed starting platform design 2.
Approve more overtime during period when the functional test will be performed (Maximum overtime from 50% to 75%)

Model parameters modified:

- ✓ Modify graph of effect of design progress on rework discovery to start fixing 30% of errors around week 18
- ✓ Increase Maximum OT to 1.75 from week 18 to week 30
- ✓ Fraction of design rework discovered by design work= 0.85

Expected Impact:

- ✓ Increase the amount of rework discovered by design
- ✓ Decrease rework discovery during first prototype build
- ✓ Reduction of rework
- ✓ Reduction of fraction correct and productivity during functional test
- ✓ Earlier PD finish
- ✓ Reduce overtime after week 30

Model results

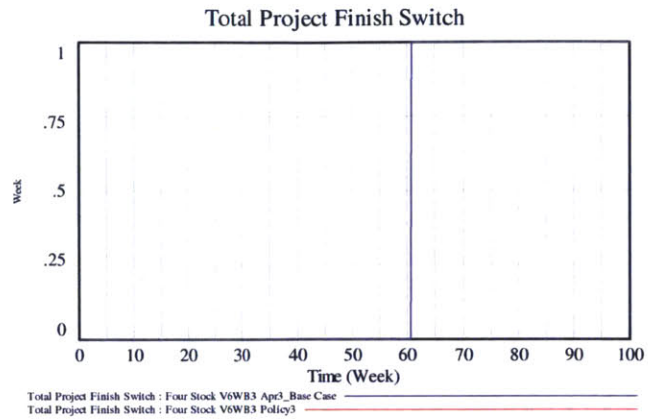


Figure 57: Scenario 3 project finish date

Figure 57 shows that the project completion date remains in 60 weeks. No improvement achieved on project timing with scenario 3 but no delays occur based on the introduction of this new functional test.

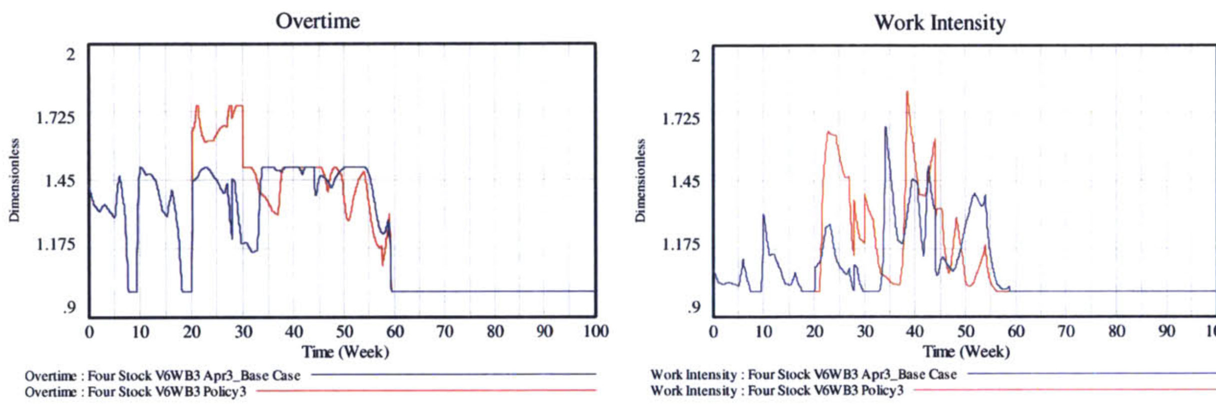


Figure 58: Scenario 3 overtime and work intensity

Figure 58 shows an increase in overtime during the period of time when the new functional test is introduced. Work intensity is higher with this scenario once the functional test is started and remains high along the platform design phases and then decreases once the prototype build starts in week 44.

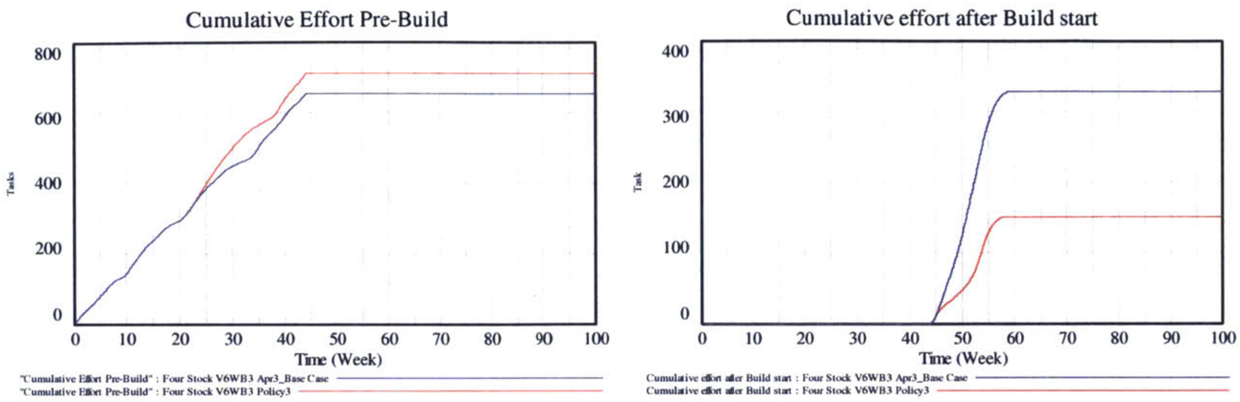


Figure 59: Scenario 3 cumulative effort during platform design and first prototype build

Figure 59 shows 8% increase of effort during platform design phase and then a 55% decrease of effort once the first prototype build started. This represents the discovery of more errors during the design phase and the fix of such errors prior to the build start.

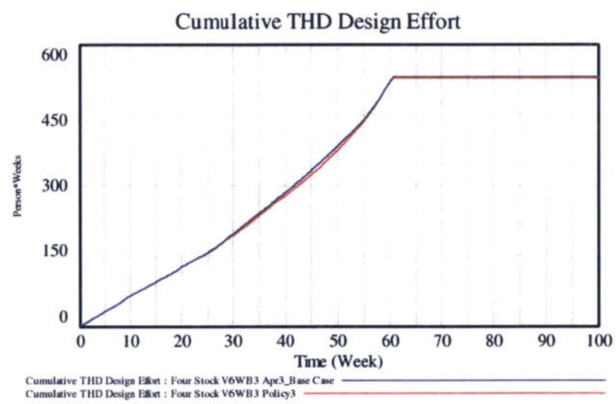


Figure 60: Scenario 3 work done during top hat design

Figure 60 shows no difference in the work done through the top hat design phases. This is a good result since there is no impact on the efforts to complete top hat design within the 60 weeks timeframe presented in the base case.

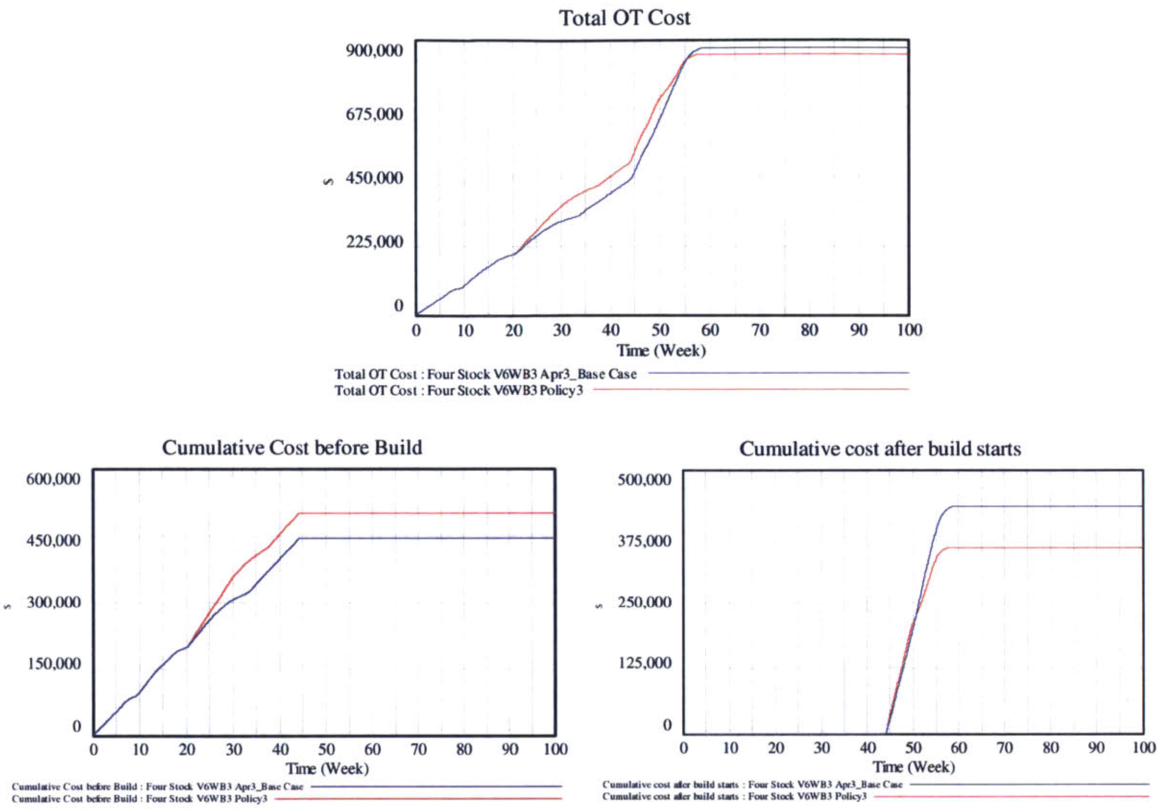


Figure 61: Scenario 3 overtime costs

Figure 61shows an overall overtime cost reduction of 3%. The overtime cost during the platform design phases increases by 12%, but it had a decrease of 19% once the prototype build started. This is not related directly to an increase in quality of the design tasks performed but it is related to a "Build little, test little" effect due to the introduction of the functional test in earlier stages of the design process which generates fewer errors during the prototype build by discovering and fixing problems during the platform design phases.

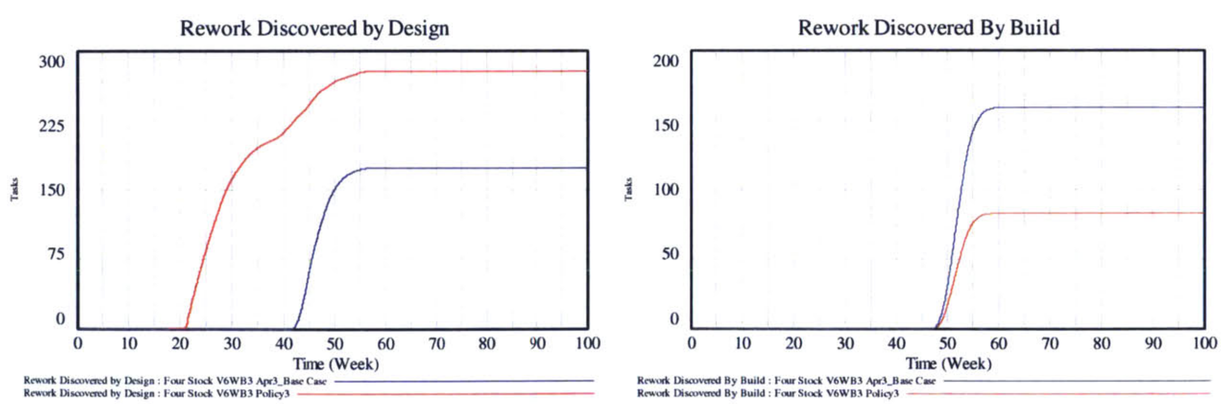


Figure 62: Scenario 3 rework discovery

Figure 44 shows how the rework discovered during platform design increased by 60% due to the introduction of the functional test in week 18 and a decrease of 49% of rework discovered during the first prototype build. This reduction of rework discovery during build is a consequence of the increased amount of errors discovered and fixed during the platform design phases.

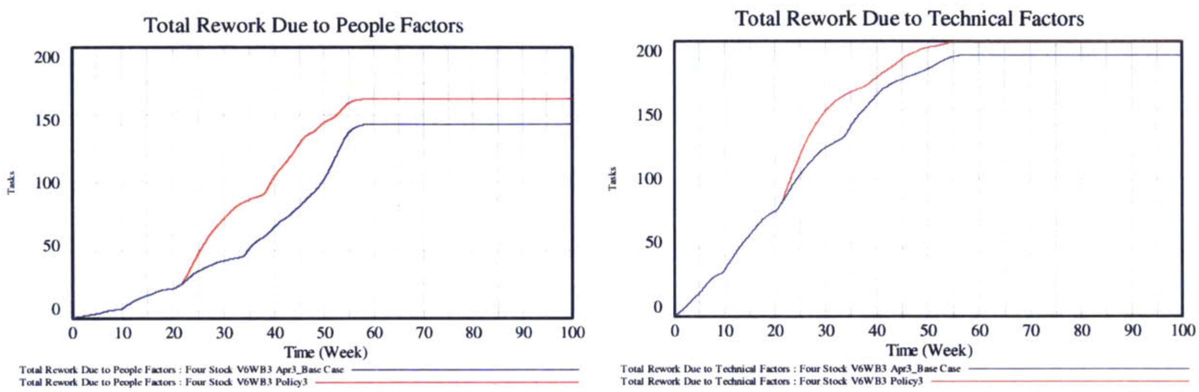


Figure 63: Scenario 3 source of rework (human vs technical factors)

Figure 63 shows the amount of rework caused by human factors – fatigue and work intensity – increased by 13% while the amount of rework caused by technical factors – undiscovered rework and out of sequence work – increased by 4%. The results are aligned with the decisions took in scenario 3 of increasing the overtime available for the engineers and the introduction of the new functional test so early in the design phase. The increase in overtime produced more fatigue for the EDS team and increased the intensity of work to complete the functional test introduced. The out of sequence work was a big impact from the technical factors due to testing designs not mature enough.

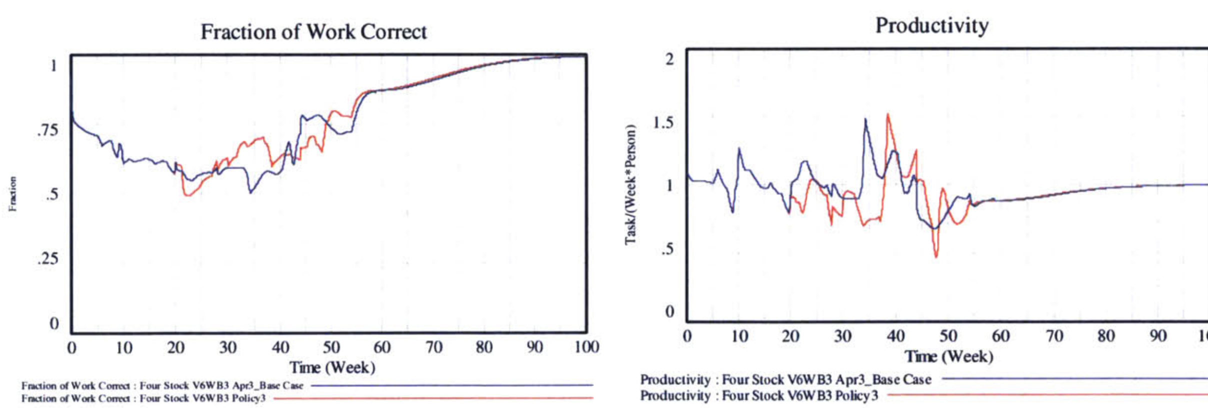


Figure 64: Scenario 3 fraction of work correct and productivity

Figure 64 shows that fraction of work correct decreased right after the functional test started due to the work being done out of sequence, but then there was an improvement once issues were fixed during and after the functional test. Productivity decreased across the project mainly due to high levels of fatigue, intensity and out of sequence work generated by the high levels of overtime and the introduction of the new functional test. This scenario shows slight improvements on overall cost and time but the improvements on the amount of rework generated and the cost of rework once the first prototype build started are satisfactory. It is important to mention that in this scenario no extra staff was added to perform the new functional test. The high levels of fatigue and work intensity could be reduced if the EDS organization decides to add extra staff to support this functional test. However, the effects of out of sequence work would remain high but this is a trade off the organization could decide to do in order to reduce the amount of rework to be discovered once the prototype build started.

Scenario 4: Work cell organizational change

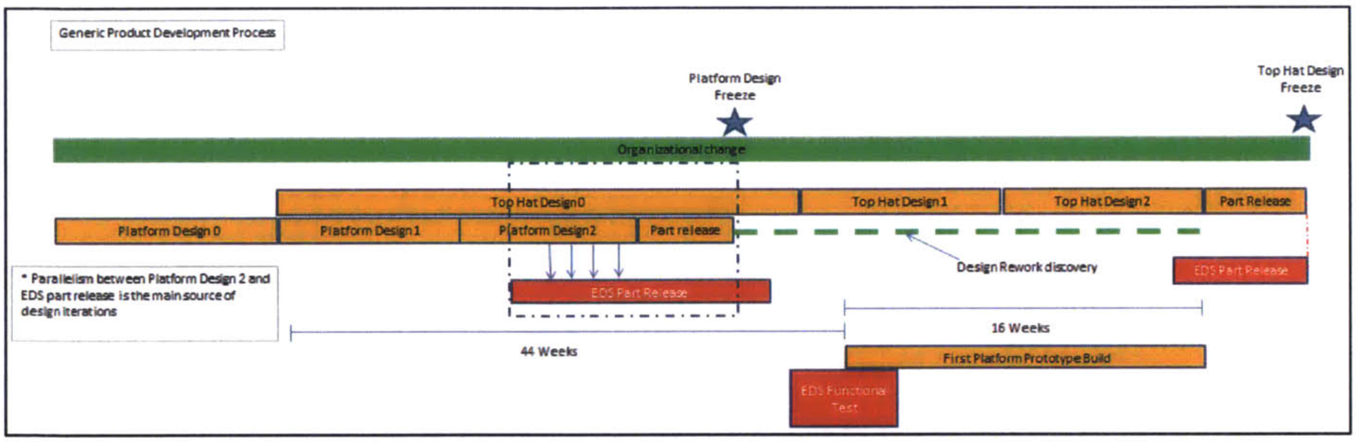


Figure 65: Scenario 4 overview

Requirements: Organizational change. This refers to the designation of roles and responsibilities to each engineer by type of work to perform (packaging, quality, systems, change control, etc.) rather than the distribution of work by harness piece. Currently, the EDS organization assigns each engineer a particular wiring piece in the vehicle, each engineer has to perform all the packaging, quality, systems and change control activities for their respective harness part. The organizational change consists in assigning engineers to larger sections of the vehicle that contain multiple harnesses, but with fewer responsibilities. For example an engineer can be assigned to the wiring packaging activities for the entire engine compartment. The engineer will be responsible for multiple wiring parts in the vehicle but only for the packaging activities. Other engineers will be assigned to perform quality, systems and change control activities to the same section of the vehicle, working on the same multiple harnesses but in very specific activities. This organizational change would be aligned with the EDS deliverables for each design phase and progress can be achieved quickly without distributing harness parts among engineers.

Model parameters modified:

- ✓ Policy 4 normal Productivity = 1.25
- ✓ Policy 4 normal Fraction correct = .96
- ✓ Max Overtime = 1.3

Expected Impact:

- ✓ Increase in productivity
- ✓ Increase in fraction of work correct
- ✓ Reduction of rework
- ✓ Earlier PD finish
- ✓ Reduce overtime

Model results

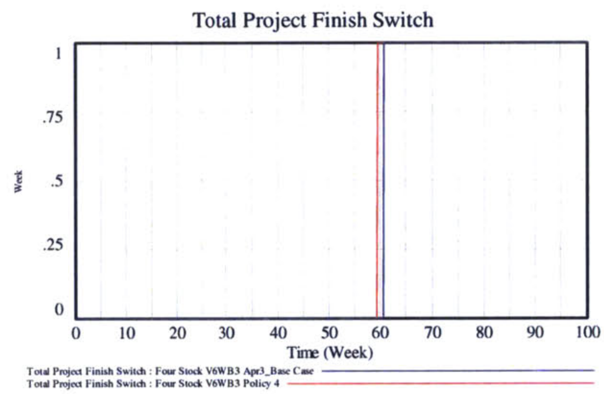


Figure 66: Scenario 4 project finish date

Figure 66 shows the project completion in 59 weeks for scenario 4 against the 60 weeks project completion in the base case.

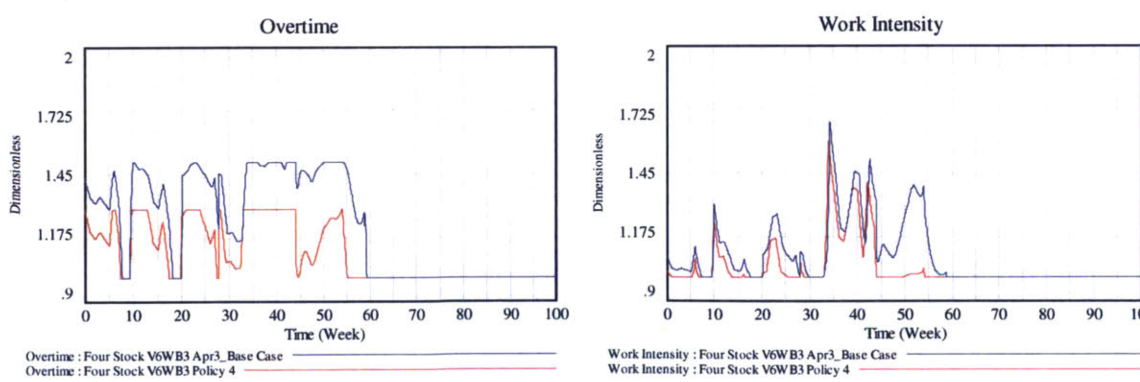


Figure 67: Scenario 4 overtime and work intensity

Figure 67 shows a decrease in overtime and work intensity by changing the way work is distributed among the EDS engineers to better align to the EDS and OEM generic product development system deliverables.

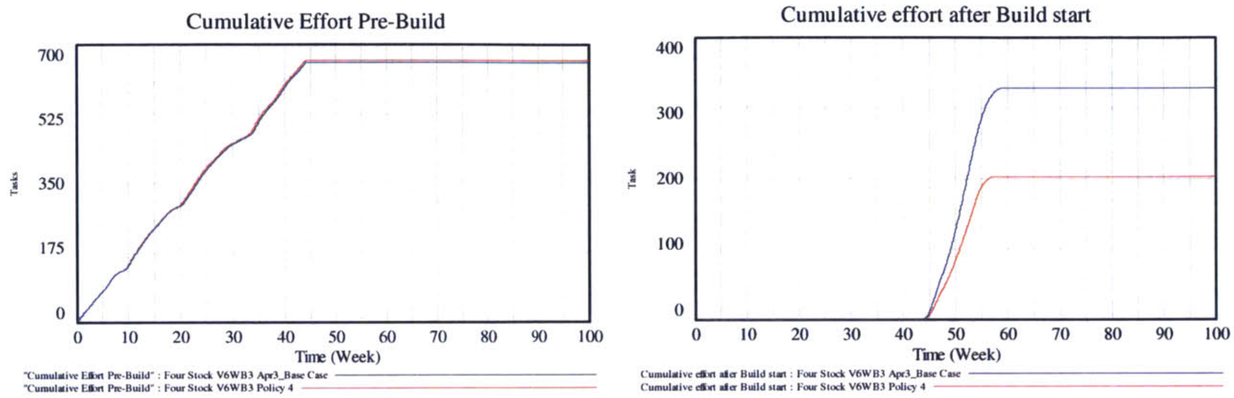


Figure 68: Scenario 4 cumulative effort during platform and first prototype build

Figure 68 shows no change in effort during platform design phases. The effort during the first prototype build decreased by 38%. This represents the increase in fraction of work correct by changing the way work is distributed among engineers. The increase in fraction of work correct reduces the errors built in downstream tasks generating less rework during the prototype build. The new distribution of work permits engineers to dedicate more time to perform specific tasks, perform design reviews and double-check the work done.

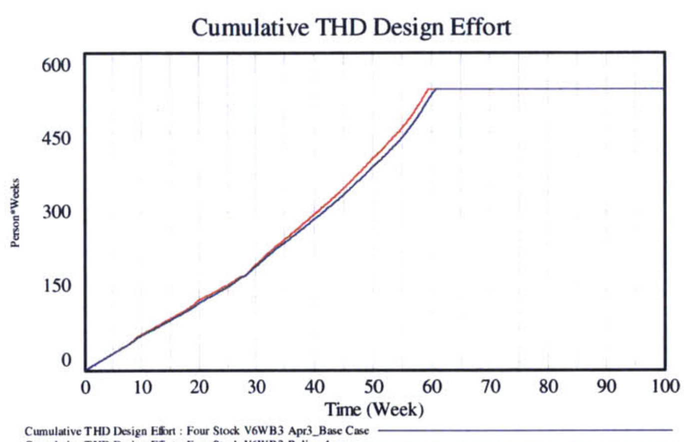


Figure 69: Scenario 4 work done during top hat design

Figure 69 shows slight difference in the work done through the top hat design phases. This is a good result since there is no impact on the efforts to complete top hat design within the 60 weeks timeframe presented in the base case.

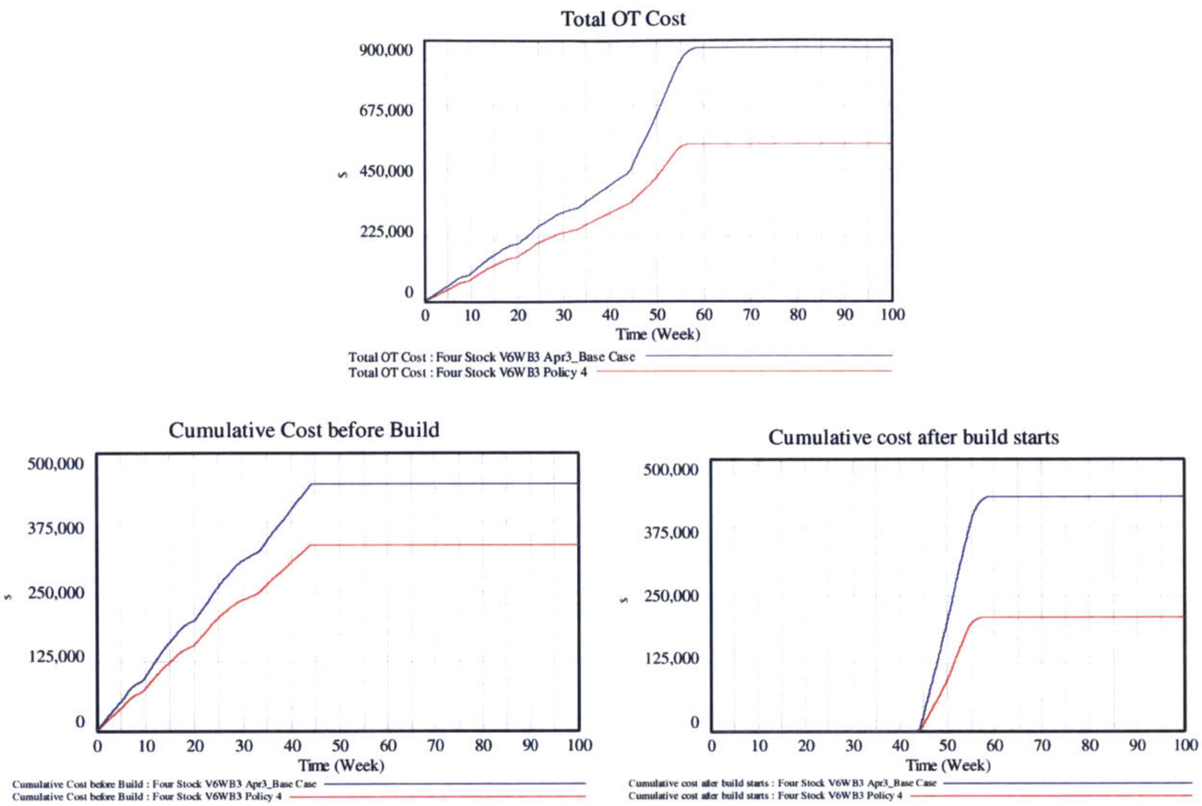


Figure 70: Scenario 4 overtime costs

Figure 70 shows an overall overtime cost reduction of 38%. The overtime cost during the platform design phases decreased 25%, while the overtime cost once the prototype build started decreased 52%. These overtime cost reductions are consequence of the increase of fraction of work correct and productivity generated by the change of work distribution inside the EDS organization.

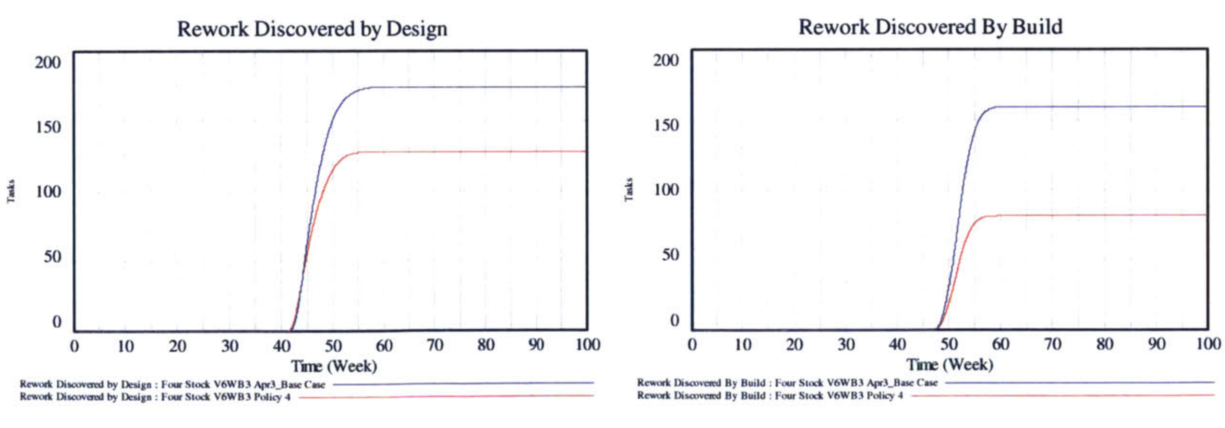


Figure 71: Scenario 4 rework discovery

Figure 71 shows a decrease in the rework discovered across the project. For the platform design phases the rework discovered decreased by 27%, while the rework discovered during the first prototype build decreased 49%. This decrease in rework is caused by the increase of fraction of work correct in the early stages of the design building less errors into downstream tasks.

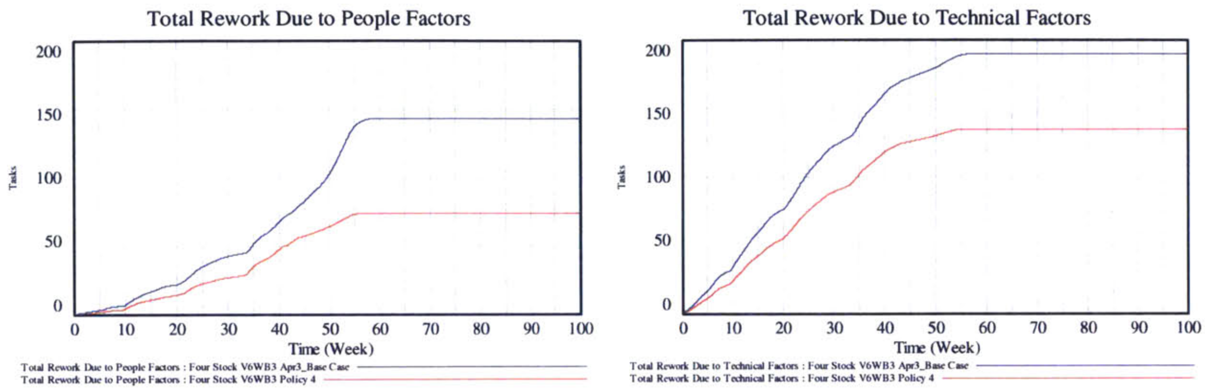


Figure 72: Scenario 4 source of rework (human vs technical factors)

Figure 72 shows how the amount of rework caused by human factors –fatigue and work intensity- decreased by 48% while the amount of rework caused by technical factors – undiscovered rework and out of sequence work- decreased by 30%. The improvement in the amount of rework caused by human factors comes from the fact that the change in work distribution reduced the amount of workload for the EDS team and reduced the fatigue and work intensity caused by the use of excessive overtime. The improvement on the amount of rework caused by technical factors comes from the fact that the fraction of work correct increased when the staff focused on fewer tasks to perform across multiple wiring harnesses. This situation built fewer errors in downstream tasks reducing the amount of rework to be discovered and the out of sequence tasks.

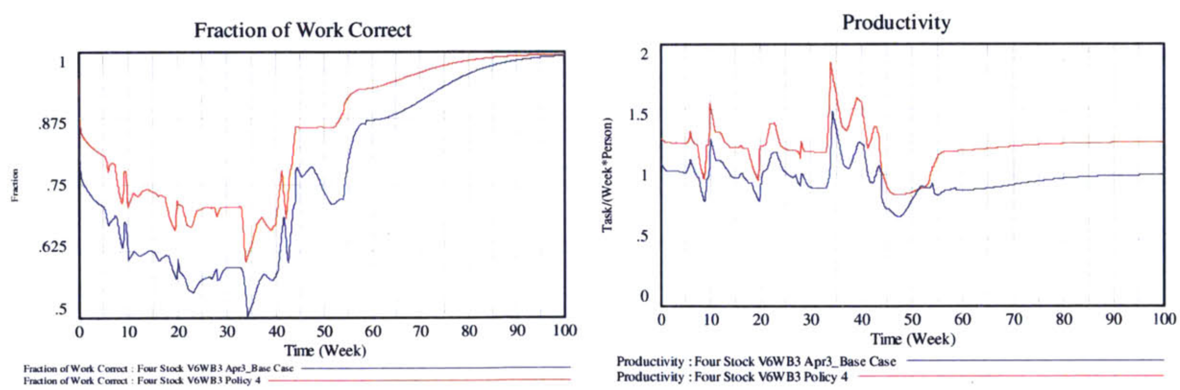


Figure 73: Scenario 4 fraction of work correct and productivity

Figure 73 shows the boost in fraction of work correct and productivity along the project generated by the change in work distribution adopted in the EDS team. The new distribution of activities decreased workload for the EDS team generating time to double-check work and perform design reviews to ensure fewer errors are built into downstream tasks producing an overall reduction of the rework discovery and overtime costs. The overall overtime reduction decreased the effects of the human factors in rework generation. The new distribution of work reduced the effects of technical factors such as undiscovered rework and out of sequence tasks.

Scenario	Cumulative PD effort	Cumulative Rework	Completion date	Amount of Rework discovered in Design	Amount of rework discovered in Build	Amount of rework caused by technical/process factors	Amount of rework caused by people factors	Staff	Fraction of work correct	Productivity	Overtime	Work intensity	OT Cost before Build	OT Cost after Buiild	Total OT Cost
Base Case	653	328	60	52%	48%	58%	42%	16	-	-	-	-	443,200	431,000	874,200
Policy 1	664	289	59	59%	41%	65%	35%	20	↑	↑	↓	↓	455,200	385,100	840,300
Policy 2	659	195	59	67%	33%	71%	29%	20	↑	↑	↓	↓	389,00	194,300	583,300
Policy 3	711	360	60	77%	23%	55%	45%	16	↑	↓	↑	↑	500,400	352,800	853,200
Policy 4	658	202	59	63%	37%	67%	33%	16	↑	↑	↓	↓	334,700	208,500	543,200

Figure 74: Summary table of key results

Figure 74 shows the compilation of results described above for each scenario.

Chapter 5: Conclusions and Recommendations

The design and development of electrical distribution systems is very complex due to the nonlinear nature of the task flow, dependency between tasks, interaction between cross-functional groups, global distribution of the product development team, culture differences, limited time to launch products into the market and integration of work through the systems engineering V-model. The usage of traditional project management tools does not help to deal with this complexity, and the resultant risk, uncertainty, unplanned design iterations and rework. The use of such project management tools is often the reason iron triangle targets cannot be efficiently achieve along the project life cycle. The usage of modern project management tools such as Design Structure Matrix and System Dynamics helps to deal with these challenges by uncovering coupled tasks and, unplanned iterations. These tools also provide a forecast of the project outcome based on initial project parameters -- resources, time, sequence of work and newness of the project -- and the impact of technical, managerial and human factors in the development of the project.

The following sections provide a summary of the key findings resulting from the work done during this thesis and a set of recommendations to deal with design iterations and rework to achieve iron triangle targets in the EDS product development. While the summary and recommendations are specific to EDS product development, it is hoped that the use of both traditional and modern project management tools described in this thesis can serve as a model for those in other industries.

5.1 Conclusions

1) The average experience of an EDS engineer inside the OEM is around ten to twenty years. The majority of them already completed two to four vehicle programs from concept to launch. However, engineers still struggle to accomplish deliverables within the time provided in the generic product development system due to the late design changes in the program, lack of information from cross-functional groups, poor communication between stakeholders and lack of robust tools to perform their work more efficiently and in less time.

2) In order to perform a robust EDS design and development the EDS engineers consider that systems integration and program management teams are the key stakeholders that have to work closely with EDS to ensure design information is communicated in time and implications due to changes to original design assumptions are communicated back to the chief engineer to increase awareness of the challenges the EDS community phases.

3) The EDS community considers that in order to avoid design iterations and rework along the current EDS design and development process electrical compatibility reviews have to be completed on time and by each milestone. However, the activity consumes a lot of time and there is not an automated tool that could help the engineers to do this activity efficiently.

4) The EDS community considers that in order to avoid design iterations and rework a separate team of engineers should be devoted to work on working-level tasks and part releases in order to reduce EDS team workload and invest more time in completing design reviews and check work done twice.

5) The Generic Product Development System shows a linear task flow while the specific EDS design and development process is nonlinear. The creation of the EDS work break down structure show additional tasks not considered in the generic system which consume time, resources and create a potential redesign of upstream tasks. The time to complete tasks under the EDS process is not always aligned with the time under the generic system due to the interaction with Tier 1 and 2 suppliers and the dependency in cross-functional tasks completion that share the same design freeze time.

6) The generic product development system gives 3 months from the Platform design 2 phase completion to the first prototype build functional test parts arrival to the plant, while some EDS Platform design 2 deliverables such as the design freeze and tooling kick off of harness components (i.e. plastic shields and grommets) have to be completed 7 months prior to the actual functional test during the first prototype build. This situation generates a lot of rework and design iterations since the design freeze for shields and grommets happen 4 months in advance to the actual platform design 2 phase finish date. During these 4 months there are a lot of design changes in the vehicle components interacting with the harness components and tooling modifications and last minute design changes have to be performed to align harness design with the latest vehicle components design completed at the end of Platform design 2 phase.

7) Critical EDS tasks in Platform design 2 phase are not feeding 100% the release of harness manufacturing prints for the first prototype build. Tasks such as 3D CAD, Virtual layout assessments, Electrical schematics, electrical compatibility reviews, Harness complexity and design requirements deviations are not fully completed when the harness 2D prints have to be prepared for the first prototype build. This situation introduces a lot of rework during the functional test performed at the beginning of the first prototype build. Design iterations increase due to the lack of maturity in the data used for the physical creation of the prototype harnesses.

8) First prototype release overlaps with Platform and top hat activities. This creates a peak in the workload of the EDS team since now the engineering time has to be allocated between three different clusters. This split of time could cause the team to start cutting corners and stop double checking work in order to meet deadlines. This situation can generate design iterations and rework on downstream tasks and the quality of the overall design work could be affected.

9) EDS design and development process DSM shows 131 feedback marks to upstream tasks that could generate design iterations and rework. These feedback marks are not considered in the perfect drawing plan that the EDS community uses to plan the activities to perform for a new product.

10) Partition of the process DSM shows that by changing the sequence of tasks, 25% of the unplanned iteration can be eliminated. This will improve the EDS design and development process and will provide a better chance to meet project deliverables

11) The interaction mapping DSM shows that 51% of the interactions the EDS team has to complete the platform and first prototype build releases are with cross-functional groups, while the other 49% of the interactions are with engineers inside the organization. This is a good indicator of the communication efforts the team has to consider in order to ensure timely flow of information.

12) The excessive usage of overtime to meet project deadlines has strong effects on the fraction of work correct and productivity due to the side effects such as fatigue, out of sequence work, errors build errors and haste makes waste. These negative effects delay project completion even more.

13) The addition of extra engineers to work on sections of the design can help to boost fraction of work correct and productivity by reducing the workload of the team and providing time to double check work done and perform design reviews.

14) The introduction of functional test earlier in the design process can help to discover more errors and fix them prior to the assembly of physical prototypes, but the out of sequence work will increase and the fraction of work correct and the productivity will decrease for some period of the design phases.

5.2 Recommendations

The recommendations below are generated based on the results observed using traditional and modern project management tools, comments from the surveys performed and the review of product development literature.

Use of traditional project management tools

a) EDS Engineers working on the harnesses part of a subassembly should not work on harnesses that are final assembly for the manufacturing plant as well.

The Engineers responsible for EDS parts shipped to Tier 1 suppliers should not be responsible for the design of EDS parts shipped to the assembly plant as well. The design of parts that have to be shipped to a Tier 1 supplier needs to be completed one month prior to the design of parts going straight to the assembly plant. Having engineers working on both designs increases workload and the need to do tradeoffs between time and quality. The electrical systems impacting harnesses shipped to Tier 1 suppliers should be identified and shared with the systems integration team in order to assign priorities for the completion of the design of such systems. The generic product development system does not account for a separate design time for tier 1 parts in order to support the delivery of information one month prior to the actual design freeze of parts going to the final assembly plant, so it is responsibility of the EDS organization to distribute work in the best way possible to avoid high peaks of workload and coordinate efforts to obtain electrical systems design earlier in the process to support the tier 1 harness design and development.

b) EDS engineers working in platform harnesses should not handle top hat harnesses as well

There should be separate EDS engineering teams working on Platform (Underbody) and Top Hat (Upper Body) activities. In order to avoid tradeoffs between time and quality -or time and process- boundaries should be established between these two teams. Special coordination through an EDS project manager should be introduced to ensure information flows from one group to the other. This split of work would help to alleviate the bottle neck presented in the current EDS design and development where around week eighteen the EDS engineers have to work simultaneously in platform, top hat and build release activities. This simultaneous work, forces the team to work overtime and more intense in order to meet deadlines but as we saw in the system dynamics scenarios this decision generative negative effects that produce even more errors downstream.

c) The Generic product development process should be modified to consider the need to finish functional test & tier 1 harnesses design one month in advance of the actual design freeze of parts that are final assembly in the manufacturing plant.

The generic product development process should be modified to enforce the completion of the design of parts interacting with tier 1 EDS parts one month prior to the normal design freeze of parts that are installed directly in the assembly plant. This modification will ensure the EDS team receives the necessary information from cross-functional groups on time for a robust EDS design.

Use of modern project management tools

a) The EDS organization needs to assign a separate group of engineers to handle all the first prototype build releases based on the work the EDS team is doing for platform design phases.

The addition of a separate team working on prototype build releases, as illustrated by scenario 1 of the system dynamics model, can help to increase the fraction of work correct by reducing the workload of the EDS team. This reduction of workload will allow the team to perform design reviews and check the work done again in order to discover errors and fix them prior to the start of the prototype build. The investment of time doing design reviews and checking work done will ensure the completion of the design phase in time, the rework during the build will be reduced and the overall overtime will be reduced as well.

b) The EDS organization needs to assign a separate group of engineers focused on accomplishing critical working level tasks such as electrical compatibility reviews, complexity updates, system sign off and release, PDL changes review, device transmittal – module electrical characteristics -- tracking and electrical diagrams tracking,

There should be a group inside EESE, integrated by EDS and systems integration team, to lead the working level activities critical for a robust product design. This group won't have specific design responsibilities but heavy management and coordination duties to ensure data from outside EESE is being received on time. This group will be responsible to ensure the critical working level activities are performed across programs. The benefits of this strategy are illustrated by scenario 2 of the system dynamics model, where the fraction of work done correct and productivity increased. The overall rework and overtime decreased and the project completion time improved.

c) A unique team working on a functional test early during platform design phases should be created in order to increase the amount of design work that can be validated prior to the first prototype build releases.

The EDS team should introduce flexibility into their process by building and testing earlier. Functionality checks should be introduced during platform design phases, with high level wiring lengths and assumptions to start receiving physical feedback from the design intent. This functional test should be performed at the product development center where the EDS team is located, and supplier on-site support should be required to start assembling "primitive" harnesses to test functionality at subsystem and system level rather to wait until the vehicle level test or the official functional test few days prior to the first prototype build. The benefits of this strategy are illustrated by scenario 3 of the system dynamics model, where the amount of errors discovered and fixed during platform design phases increased, rework and design iterations during the prototype build decreased, overtime decreased as well as fatigue and work intensity and project completion time improved.

d) Change the way Roles and Responsibilities are assigned to each EDS Engineer

In the current EDS D&D each harness family is assigned to a specific engineer. This engineer is responsible for performing all the activities related to this harness such as 3D CAD review and updates, virtual checks, quality assessments, complexity creation, electrical compatibility reviews, design change requests and the release of the EDS parts in the system. The engineer has to work in parallel on all these tasks making the design and release process slow and time consuming. If the EDS organization changes to a "work cell" strategy where three or four engineers are assigned to a specific vehicle zone (engine compartment, cabin, rear closures, etc.) and the split of responsibilities are aligned in better way to the generic product development system deliverables (packaging engineer, systems analyst, design quality, design change control, and part release analyst), the engineers will be able to focus on less variety of tasks but covering several harnesses according to the vehicle zone they are assigned. The benefits of this strategy are illustrated by scenario 4 of the system dynamics model, where productivity and fraction of work correct increase producing less errors and less rework downstream. The generation of fewer errors and rework produce a reduction on overtime and project completion time.

e) Introduce System Dynamics modeling as part of the project along the define, design, validate and launch phases

The usage of system dynamics models with proper project parameters, rework cycles, project controls and ripple and knock-on effect loops can help the EDS organization to simulate multiple project outcomes and observe how different decisions taken along the project affect iron triangle parameters. Every time the project is deviated from the plan and the management team wants to take actions to get the project back on track the system dynamics models can provide a good reference in how the project will advance depending on the changes to the original plan.

f) Introduce DSM as part of the current perfect drawing plan the EDS team uses for project management

Perfect drawing plan is a derivative of the work break down structure. As we reviewed during this thesis, the work break down structure enforces linearity and loses track of iteration loops and feedback to upstream tasks. The introduction of DSM -- as illustrated in Chapter 4 -- in the initial project plan can help to uncover unplanned iterations and potential sources of rework and the EDS organization can work in changing the sequence of tasks –DSM partition – in order to reduce the risk of unplanned feedback to upstream tasks in late stages of the design. The EDS organization will be able to focus on particular clusters of couple tasks to improve communication and coordination with cross-functional groups to ensure design information is communicated in time to complete EDS design.

g) Majority of the activities under first prototype build releases phase should be combined with the platform design 2 cluster to ensure minimum iterations once the manufacturing prints of the harnesses are created.

The EDS partition shows that in order to reduce design iterations and sources of rework majority of the build release activities should be included as part of the platform design 2 phase. This strategy will allow immediate feed of design information into the manufacturing prints and will allow the team to check in advance if there are any manufacturing concerns while still working on the final parts of the design. The creation of manufacturing prints in advance will allow the team to fix problems in the design before sending the final print to the supplier. This strategy will reduce design iterations and rework by working simultaneously in design and manufacturing.

h) 3D CAD activities such as virtual checks, routing assessments, wiring harness Clearance Envelope analysis and 3D CAD generation should be completed at the beginning of each design phase.

The EDS partition shows that majority of 3D CAD activities can be moved to the beginning of each design phase since these activities do not depend on many of the other design activities to perform. These activities depend more on the maturity of the 3D data from previous phases. This strategy will allow the team design and validate 3D designs earlier in the design process and fix any errors encountered right there reducing the length of the design iterations. The 3D CAD activities will be completed at once and the team can focus efforts towards completion of other tasks that cannot be moved to the beginning of each design phase based on the dependency on other design tasks that are performed in parallel.

i) Special coordination efforts should be established on the cluster of coupled tasks called <Platform Design 1 Electrical Diagrams Deliverables & Sign Off>. This cluster contains two cross functional activities critical to ensure high quality on the downstream activities of the EDS Design and development which are the creation of the electrical diagrams and the Electrical CAE Test status.

The partition of the EDS DSM shows a cluster of coupled tasks called <Platform Design 1 Electrical Diagrams Deliverables & Sign Off>. The activities inside this cluster are also part of the EDS critical path. The completion of these activities is led by the system integration team and their completion is fundamental to provide a robust EDS design. Therefore, the EDS organization should introduce special coordination efforts through an EDS project manager to keep track of the status of these tasks and help to remove obstacles that could cause a late delivery of these tasks.

Review of product development literature

a) Introduce set based concurrent engineering methodology during the platform and top hat design phases.

Training should be provided for the EDS community to exercise concurrent engineering in problem solving during the design phases in order to develop multiple alternatives to fix a particular problem. The generation of multiple alternatives will reduce the length of design iterations when validation through the systems engineering V-model is not satisfactory for a particular concept. Concurrent set based engineering as reviewed in the Manhattan project introduces flexibility in the design and avoid the risk of long design iterations and rework by having always an option B ready to be introduced if the original concept or solution is not satisfactory.

b) Introduce modular teams in the EDS organization for future design and development projects

Based on the interviews and surveys performed inside the EDS organization, a big piece of the rework generated during the prototype builds is a consequence of a late engagement of the manufacturing team into the design process. The introduction of modular teams inside the EDS organization will provide instantaneous feedback from manufacturing to the designs being developed during the early stages of the program, and will reduce the amount of rework and design iterations generated by designs not covering the needs from the manufacturing plant.

Recommendations generated based on surveys

a) Develop standard wiring harness routings by vehicle segment in order to reduce the amount of design to be done for new vehicles

The design and development of layout and routing paths along the vehicle for the EDS is one of the key tasks the EDS team performs across the design phases and one of the main sources of rework during the prototype builds. Even though the portfolio of vehicles inside the OEM varies in size and shape and EDS layout and package differ from car to car, there is still opportunity to generate common wiring layouts across vehicles from the same platform where the chassis and engine compartment are very similar. If package standardization is achieved then the design and development of layout and package can have a mature start point that would help the team to do minor modifications according to specific vehicle requirements and avoid the complete re design of package every time a new vehicle is developed. By using common routings and layouts the team ensures that the design proposed has been validated in other vehicles before and the design iterations and rework to validate such layouts again will be reduced.

b) Invest in the generation of automated tools for time consuming tasks currently performed manually in the EDS design and development process.

The majority of the EDS engineers consider electrical compatibility reviews as one of the fundamental tasks to perform to ensure a robust EDS design. This comment is supported by the EDS critical path developed in Chapter 4 where electrical compatibility reviews feed a lot of downstream tasks and the quality of such reviews will impact the amount of design iterations and rework in later stages of the program. However, currently the OEM does not have tools supporting the completion of this activity. The reviews are done manually and consume a lot of time to complete. The EDS organization should invest in the creation of tools that allow the completion of this fundamental task in less time and with less human resources.

It is important to mention that some of the recommendations illustrated in this thesis are being implemented in the EDS organization after the review with the EDS management team of the work done here. The magnitude of improvement for these recommendations beyond the results obtained in the system dynamics and the DSM models will be outside of the scope of this thesis.

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

- Create a robust model to assign EDS staff according with the electrical newness and complexity of each vehicle program.

- Develop common standards for wiring design tools and process. Areas of significant interest include the issue of electrical compatibility reviews.

- Extend the CAD tool applications in the aerospace wiring to automotive wiring, especially the usage of tools upstream.

- Perform a detailed analysis of all the clusters generated by the DSM partition and request the support from the EDS management team to test the new sequence of tasks in a pilot vehicle program to further understand the advantages and disadvantages of the new tasks sequence.

- Measure the success of the recommendations provided.

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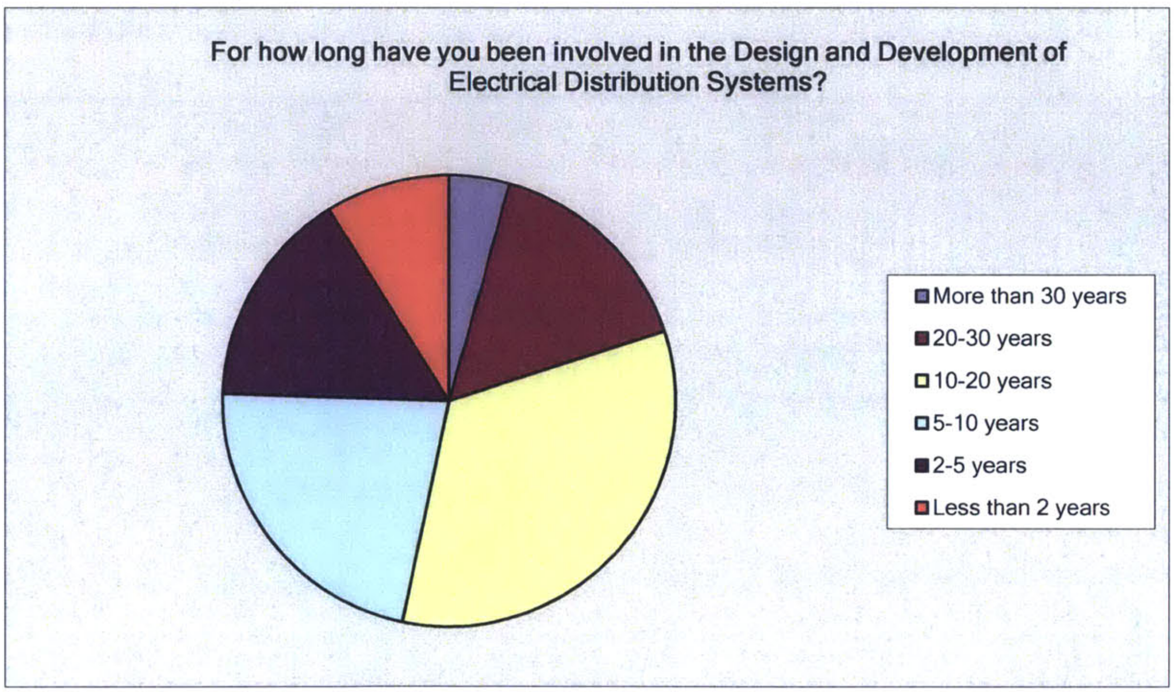
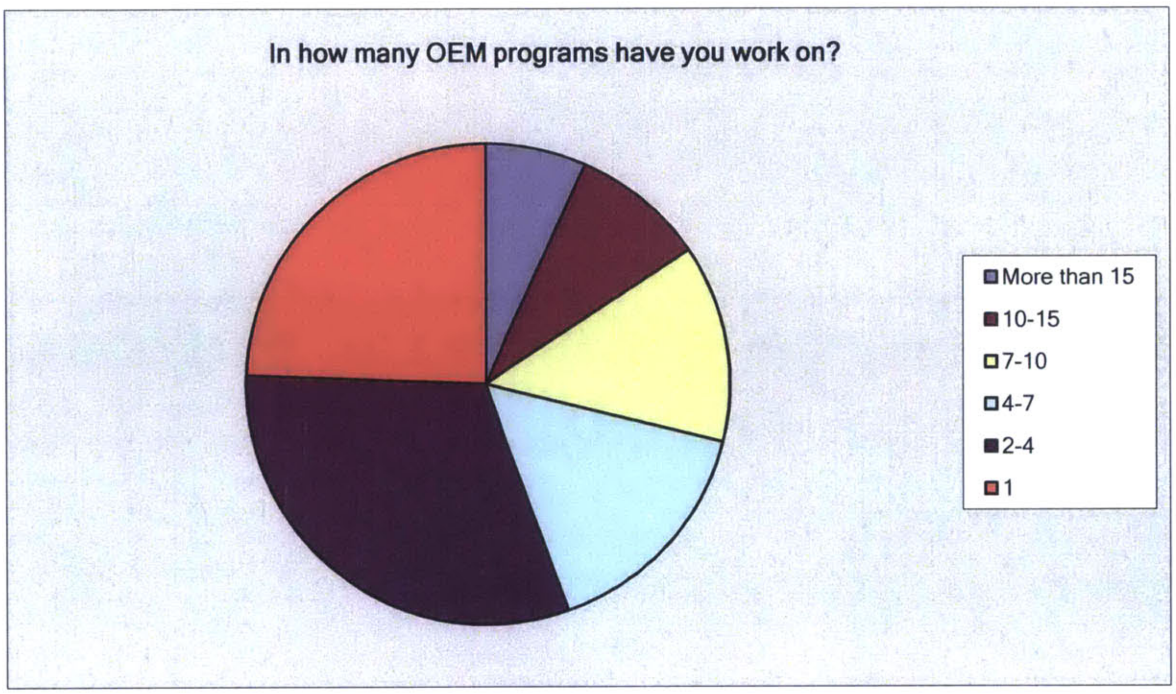
Appendix A – EDS design in-house survey

For how long have you been involved in the Design and Development of Electrical Distribution Systems?		
Answer Options	**Response Percent**	**Response Count**
More than 30 years	4.4%	2
20-30 years	15.6%	7
10-20 years	33.3%	15
5-10 years	22.2%	10
2-5 years	15.6%	7
Less than 2 years	8.9%	4
	answered question	45
	skipped question	0



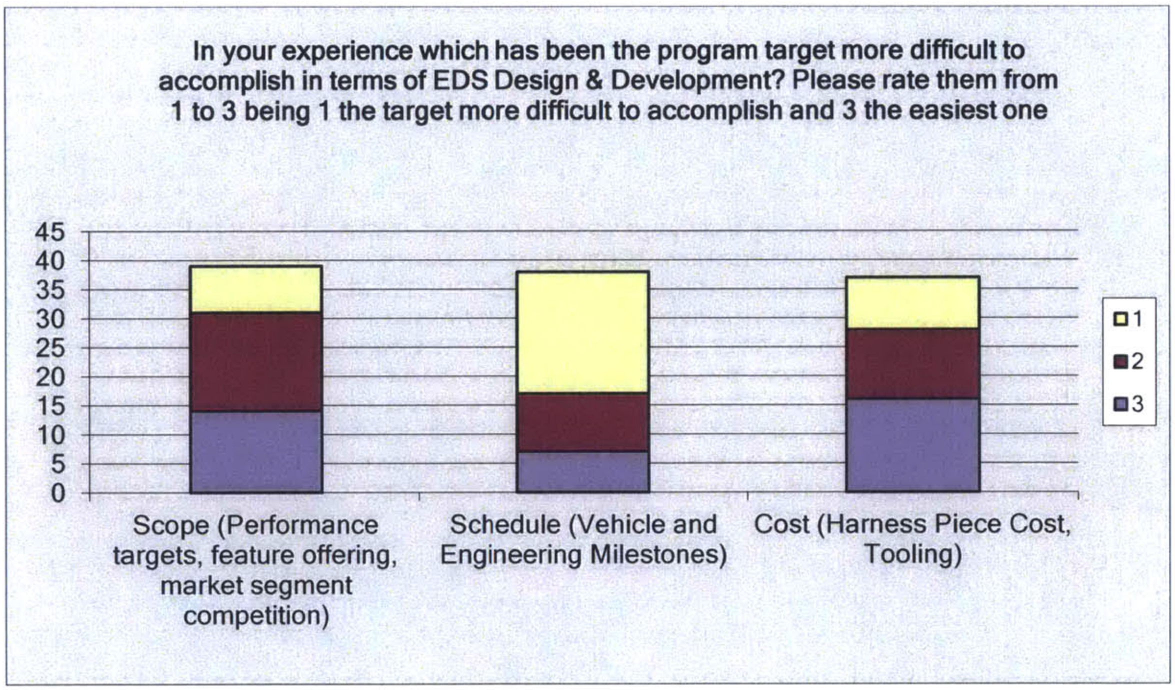
In how many OEM programs have you work on?		
Answer Options	**Response Percent**	**Response Count**
More than 15	6.7%	3
10-15	8.9%	4
7-10	13.3%	6
4-7	15.6%	7
2-4	31.1%	14
1	24.4%	11
	answered question	45
	skipped question	0



What was the last OEM program where you had the chance to go through more than 80% of the Generic Product Development cycle?	
Answer Options	**Response Count**
	42
answered question	42
skipped question	3

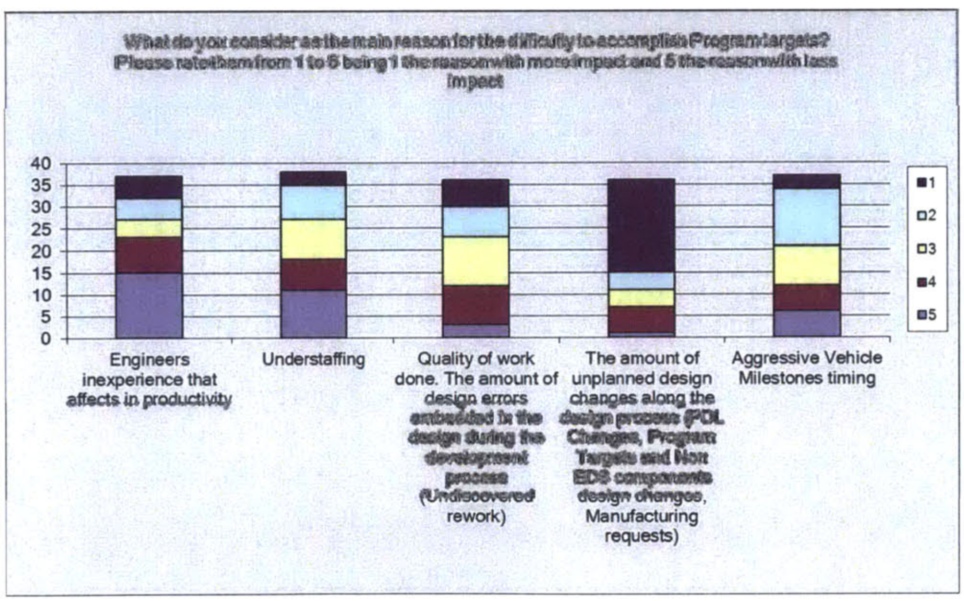
Number	Response Date	Response Text
1	jul 29, 2014 2:45 p.m.	CD391N
2	jul 25, 2014 7:53 a.m.	D568C
3	jul 22, 2014 6:49 p.m.	I've just worked for OPD programs (CD4.1)
4	jul 16, 2014 5:14 p.m.	N/A
5	jul 16, 2014 7:23 a.m.	D568C
6	jul 15, 2014 3:09 p.m.	CD4.1
7	jul 15, 2014 4:46 a.m.	C520
8	jul 14, 2014 4:57 p.m.	None, at this moment.
9	jul 14, 2014 3:22 p.m.	C520
10	jul 14, 2014 12:37 p.m.	CD4.1
11	jul 14, 2014 12:08 p.m.	2003 U22X
12	jul 13, 2014 12:57 a.m.	CD4.1
13	jul 11, 2014 7:57 p.m.	2014 U38X - EDGE/MKX
14	jul 11, 2014 4:12 p.m.	CD4.1
15	jul 11, 2014 2:30 p.m.	U22X
16	jul 11, 2014 2:21 p.m.	NONE
17	jul 11, 2014 2:11 p.m.	U22X
18	jul 11, 2014 2:04 p.m.	P552
19	jul 11, 2014 1:53 p.m.	U22X
20	jul 11, 2014 1:34 p.m.	CD4.2
21	jul 11, 2014 12:02 p.m.	CD4.2
22	jul 11, 2014 11:24 a.m.	U22X
23	jul 11, 2014 8:09 a.m.	P552
24	jul 10, 2014 10:35 p.m.	none
25	jul 10, 2014 7:43 p.m.	P356
26	jul 10, 2014 7:42 p.m.	None
27	jul 10, 2014 7:27 p.m.	vn127
28	jul 10, 2014 7:20 p.m.	P552
29	jul 10, 2014 7:18 p.m.	D258/D385
30	jul 10, 2014 7:15 p.m.	2000 U22X
31	jul 10, 2014 7:11 p.m.	Not yet.
32	jul 10, 2014 6:48 p.m.	2011 U38X
33	jul 10, 2014 6:24 p.m.	2011 P473
34	jul 10, 2014 6:22 p.m.	NONE
35	jul 10, 2014 6:17 p.m.	P356
36	jul 10, 2014 6:15 p.m.	2000 U22X
37	jul 10, 2014 6:06 p.m.	P552
38	jul 10, 2014 5:54 p.m.	none, I'm in the CD4.1 MCA, but is less than 80%
39	jul 10, 2014 5:51 p.m.	N/A
40	jul 10, 2014 5:50 p.m.	CD4.1 E
41	jul 10, 2014 5:49 p.m.	CD4.1
42	jul 10, 2014 5:49 p.m.	N/A

In your experience which has been the program target more difficult to accomplish in terms of EDS Design & Development? Please rate them from 1 to 3 being 1 the target more difficult to accomplish and 3 the easiest one				
Answer Options	**1**	**2**	**3**	**Response Count**
Scope (Performance targets, feature offering, market segment competition)	8	17	14	39
Schedule (Vehicle and Engineering Milestones)	21	10	7	38
Cost (Harness Piece Cost, Tooling)	9	12	16	37
			answered question	39
			skipped question	6

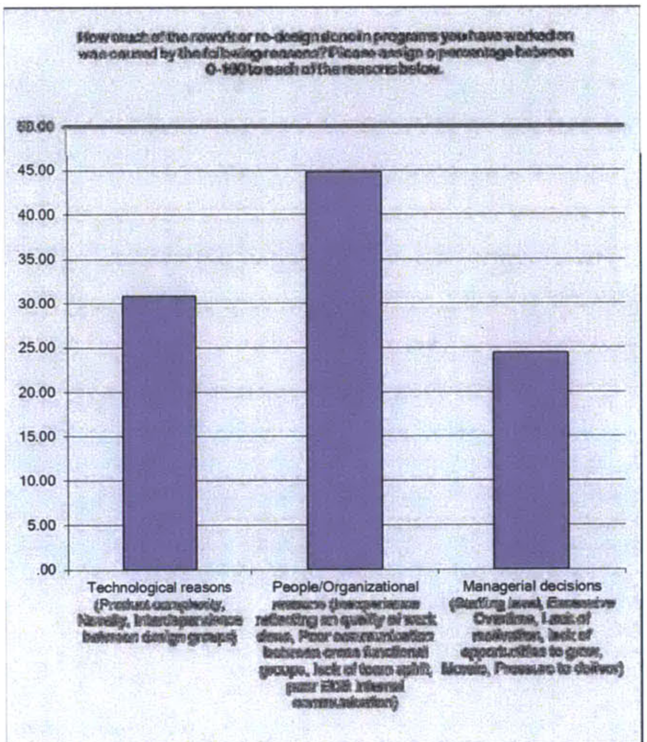


What do you consider as the main reason for the difficulty to accomplish Program targets? Please rate them from 1 to 5 being 1 the reason with more impact and 5 the reason with less impact						
Answer Options	**1**	**2**	**3**	**4**	**5**	**Response Count**
Engineers inexperience that affects in productivity	5	5	4	8	15	37
Understaffing	3	8	9	7	11	38
Quality of work done. The amount of design errors	6	7	11	9	3	36
The amount of unplanned design changes along the	21	4	4	6	1	36
Aggressive Vehicle Milestones timing	3	13	9	6	6	37
Other (please specify)						9
					answered question	38
					skipped question	7

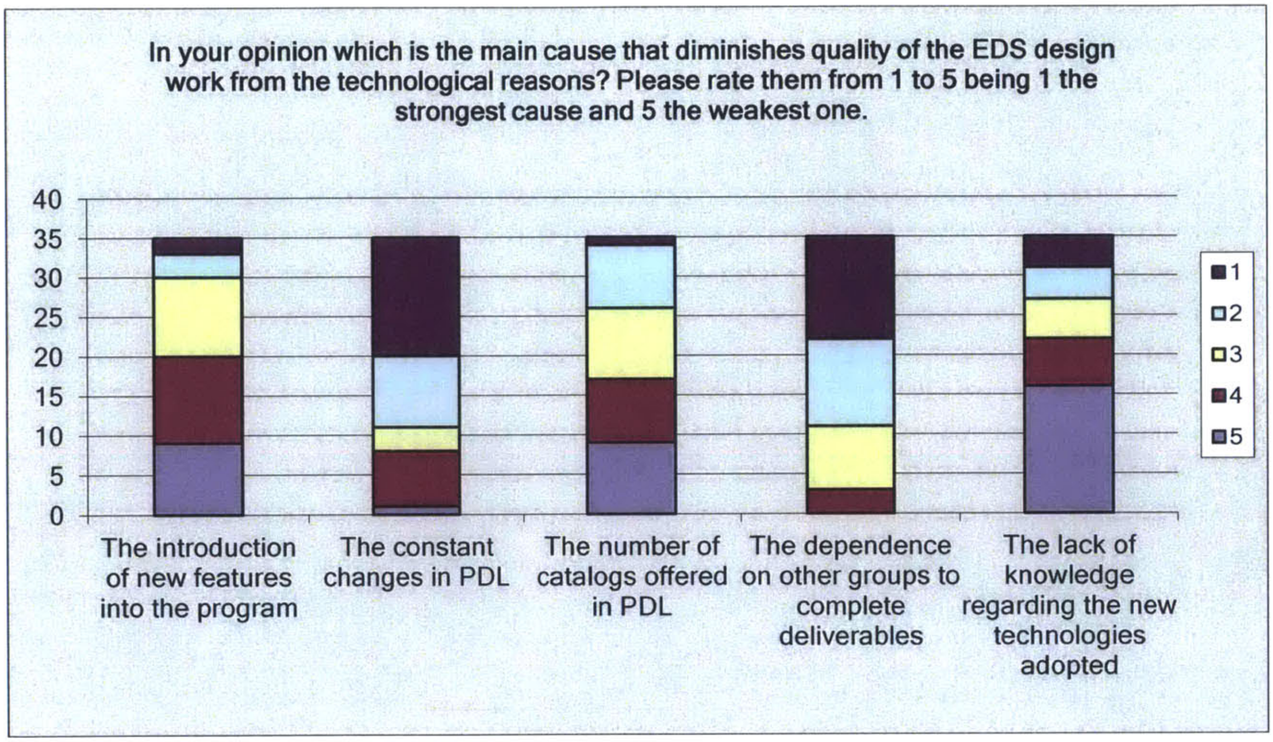
Number	Response Date	Other (please specify)
1	jul 15, 2014 4:49 a.m.	PDL never stabil and always changing. Marketing never/rarely accomodating EDS in complexity management forcing designs high in complexity and prone for errors down stream. Export Marketing not consulting with EDS.
2	jul 13, 2014 1:03 a.m.	The inability of any program to freeze a design for a build milestone...number "0"
3	jul 11, 2014 8:03 p.m.	We find several errors in the CODE vs. PDL, there is often a disconnect between the two. TIB's are released too often. Sometimes the programs direct us to Design to one, but Order to another.
4	jul 11, 2014 4:17 p.m.	Global design which overlap delivery dates and mailstones.
5	jul 11, 2014 2:04 p.m.	Your question assumes the issues are internal. But, the real problem starts outside of the department - EDS receives the necessary information for design too late and with too many errors. Logical schematics and DTs are lacking - we receive nothing at the proper time and it is impossible to complete our work to the best of our ability under these conditions. I have answered your question as if we have received all the data in a timely manner.
6	jul 11, 2014 8:18 a.m.	Starting a program (your flagship program, I might add) with system/2D design software (Zuken) that has never been used and refined beforehand on a lesser program.
7	jul 10, 2014 7:25 p.m.	Actually, the worst is that target setting and change control happening thru pre-PA processes work for parts like a headlamp, but do not work for vehicle EDS.
8	jul 10, 2014 7:15 p.m.	Late design direction. Late DT's, designs, late supplier selections, etc....
9	jul 10, 2014 6:20 p.m.	Lack of process and guidance from management is also a significant contributor to accomplishing our goals in the EDS group. Our Change management system (DCR process) is significantly lacking here as well compared to what was present when working for a Tier 1 supplier.



How much of the rework or re-design done in programs you have worked on was caused by the following reasons? Please assign a percentage between 0-100 to each of the reasons below.			
Answer Options	**Response Average**	**Response Total**	**Response Count**
Technological reasons (Product complexity, Novelty, Interdependence between design groups)	30.84	1,141	37
People/Organizational reasons (Inexperience reflecting on quality of work done, Poor communication between cross functional groups, lack of team spirit, poor EDS Internal communication)	44.81	1,658	37
Managerial decisions (Staffing level, Excessive Overtime, Lack of motivation, lack of opportunities to grow, Morale, Pressure to deliver)	24.35	901	37
		answered question	37
		skipped question	8

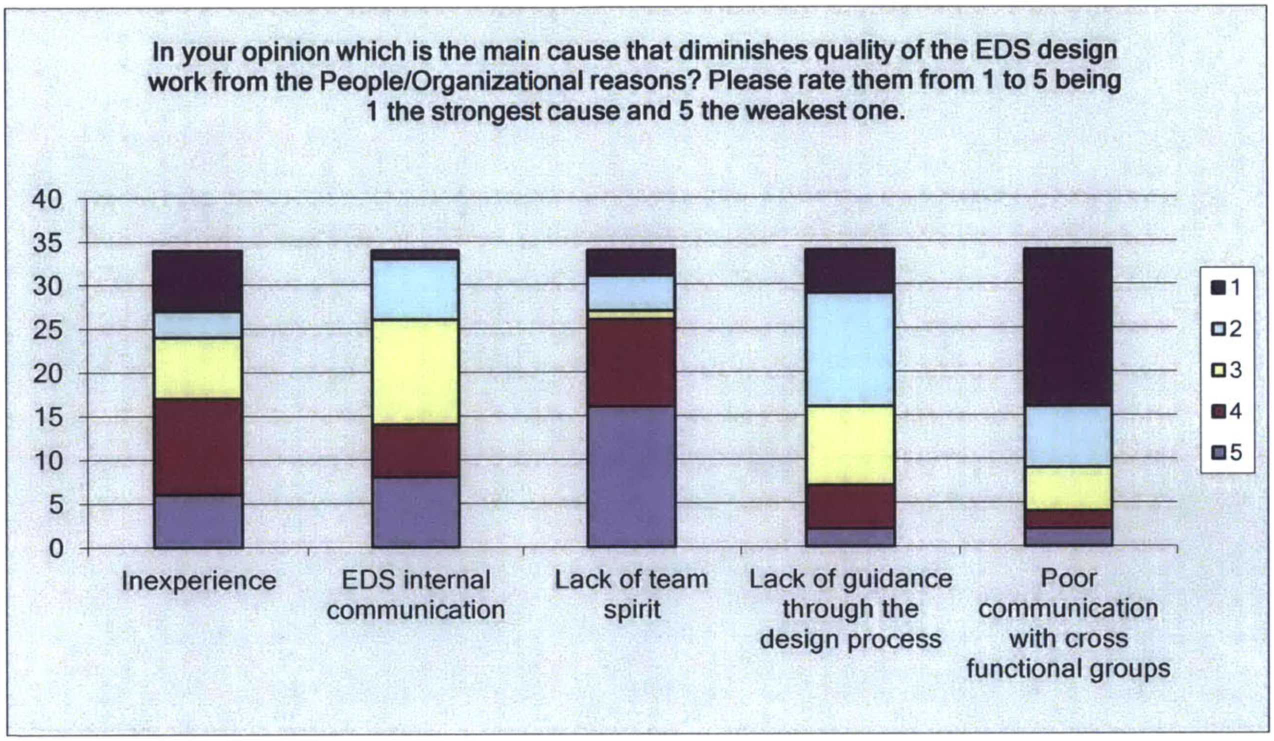


In your opinion which is the main cause that diminishes quality of the EDS design work from the technological reasons? Please rate them from 1 to 5 being 1 the strongest cause and 5 the weakest one.						
Answer Options	**1**	**2**	**3**	**4**	**5**	**Response Count**
The introduction of new features into the program	2	3	10	11	9	35
The constant changes in PDL	15	9	3	7	1	35
The number of catalogs offered in PDL	1	8	9	8	9	35
The dependence on other groups to complete	13	11	8	3	0	35
The lack of knowledge regarding the new	4	4	5	6	16	35
Other (please specify)						3
					answered question	35
					skipped question	10



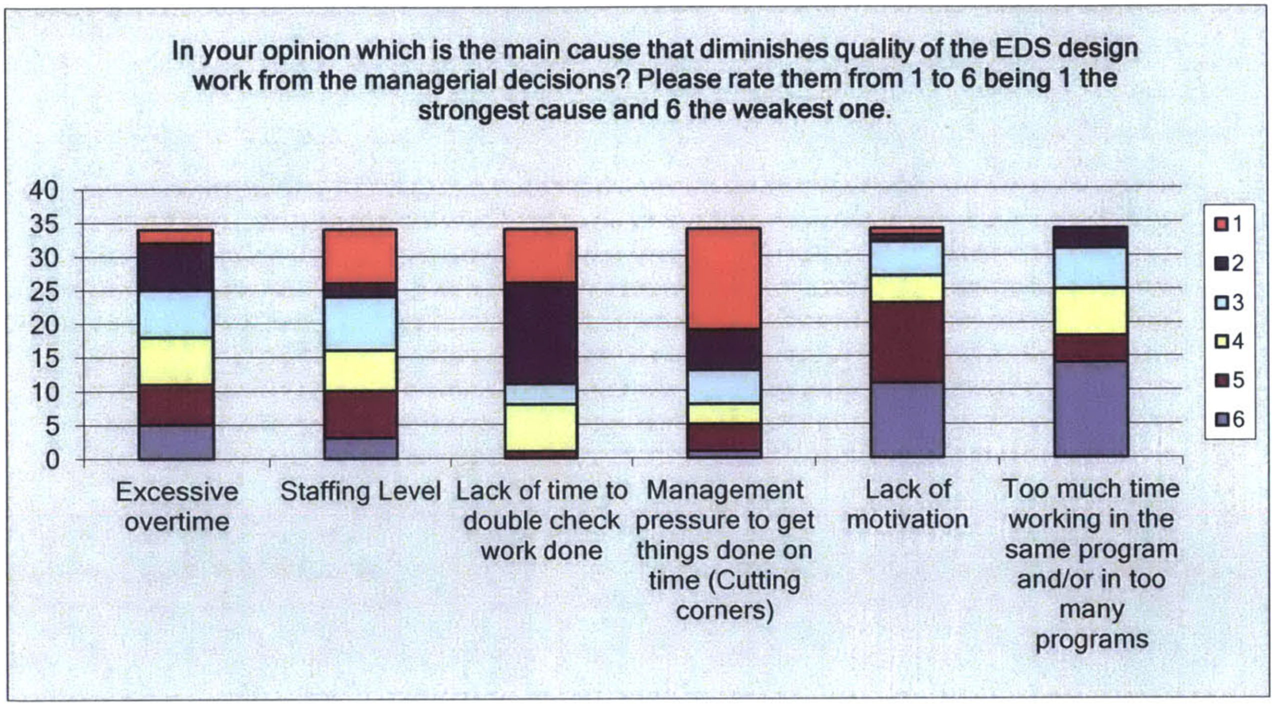
In your opinion which is the main cause that diminishes quality of the EDS design work from the People/Organizational reasons? Please rate them from 1 to 5 being 1 the strongest cause and 5 the weakest one.

Answer Options	1	2	3	4	5	Response Count
Inexperience	7	3	7	11	6	34
EDS internal communication	1	7	12	6	8	34
Lack of team spirit	3	4	1	10	16	34
Lack of guidance through the design process	5	13	9	5	2	34
Poor communication with cross functional groups	18	7	5	2	2	34
Other (please specify)						3
					answered question	34
					skipped question	11

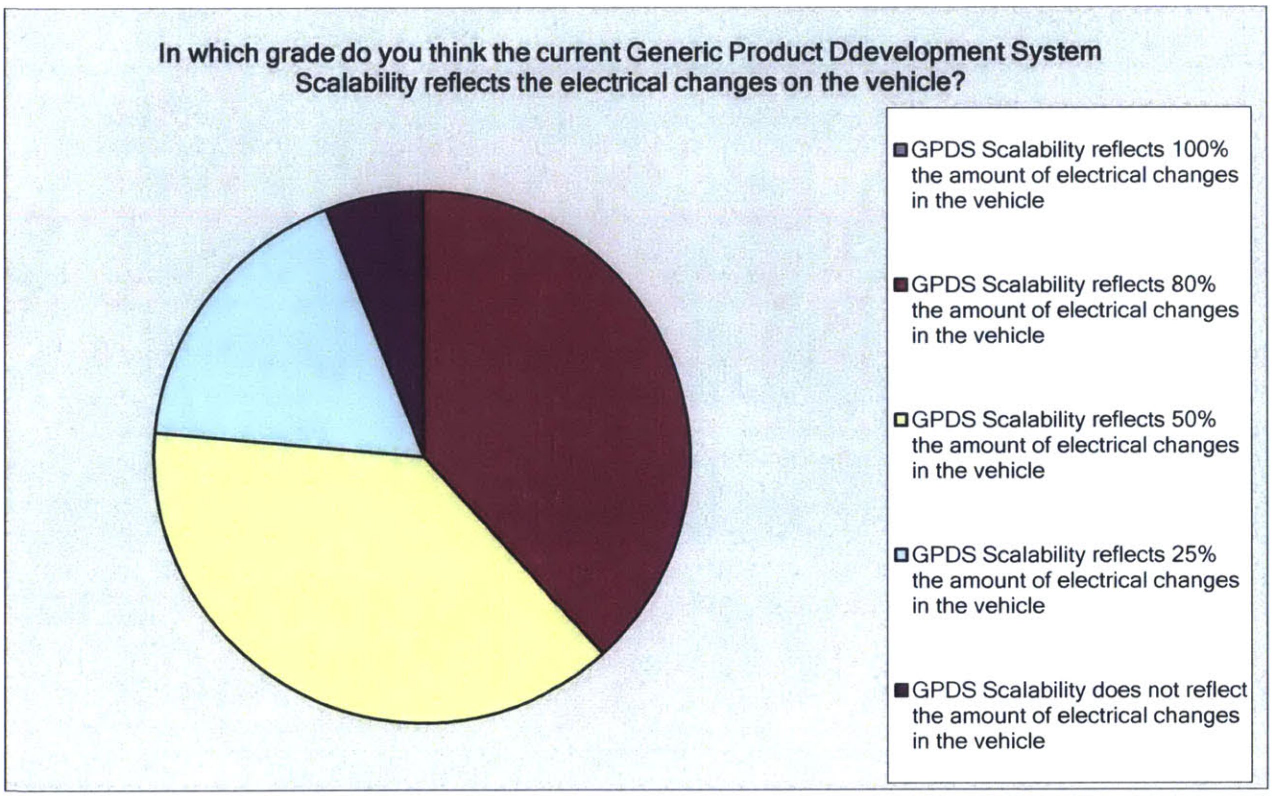


In your opinion which is the main cause that diminishes quality of the EDS design work from the managerial decisions? Please rate them from 1 to 6 being 1 the strongest cause and 6 the weakest one.

Answer Options	1	2	3	4	5	6	Response Count
Excessive overtime	2	7	7	7	6	5	34
Staffing Level	8	2	8	6	7	3	34
Lack of time to double check work done	8	15	3	7	1	0	34
Management pressure to get things done on time	15	6	5	3	4	1	34
Lack of motivation	1	1	5	4	12	11	34
Too much time working in the same program and/or in	0	3	6	7	4	14	34
Other (please specify)							2
						answered question	34
						skipped question	11

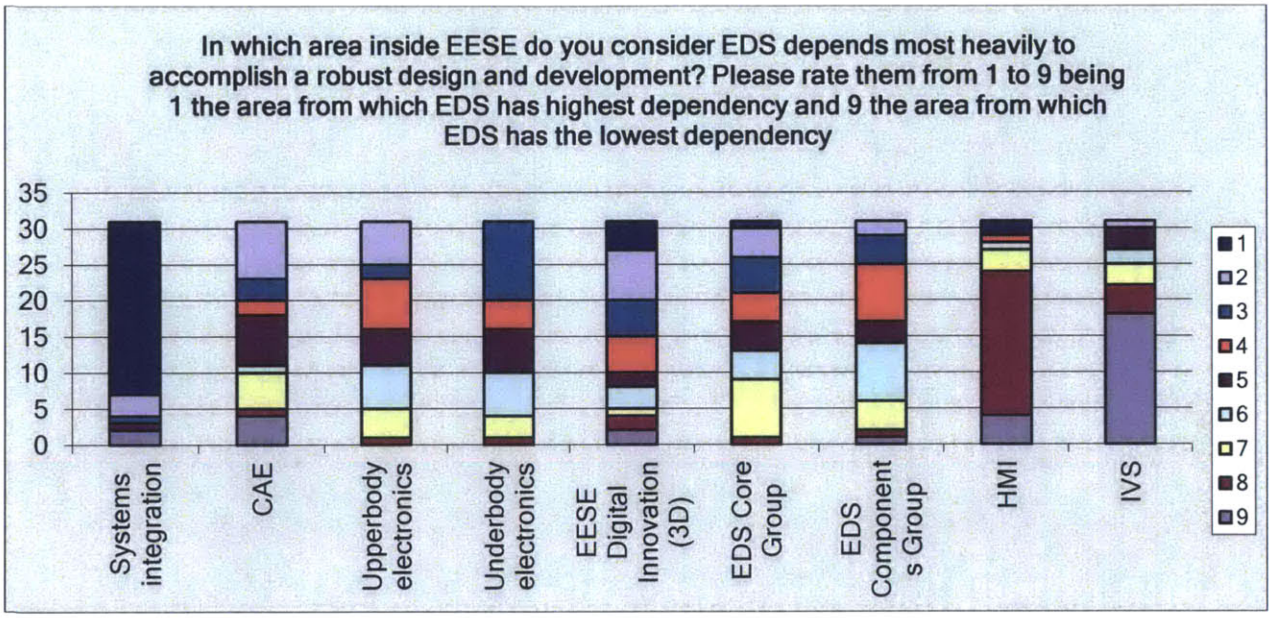


In which grade do you think the current Generic Product Ddevelopment System Scalability reflects the electrical changes on the vehicle?		
Answer Options	**Response Percent**	**Response Count**
GPDS Scalability reflects 100% the amount of electrical changes in the vehicle	0.0%	0
GPDS Scalability reflects 80% the amount of electrical changes in the vehicle	38.2%	13
GPDS Scalability reflects 50% the amount of electrical changes in the vehicle	38.2%	13
GPDS Scalability reflects 25% the amount of electrical changes in the vehicle	17.6%	6
GPDS Scalability does not reflect the amount of electrical changes in the vehicle	5.9%	2
Other (please specify)		4
	answered question	34
	skipped question	11



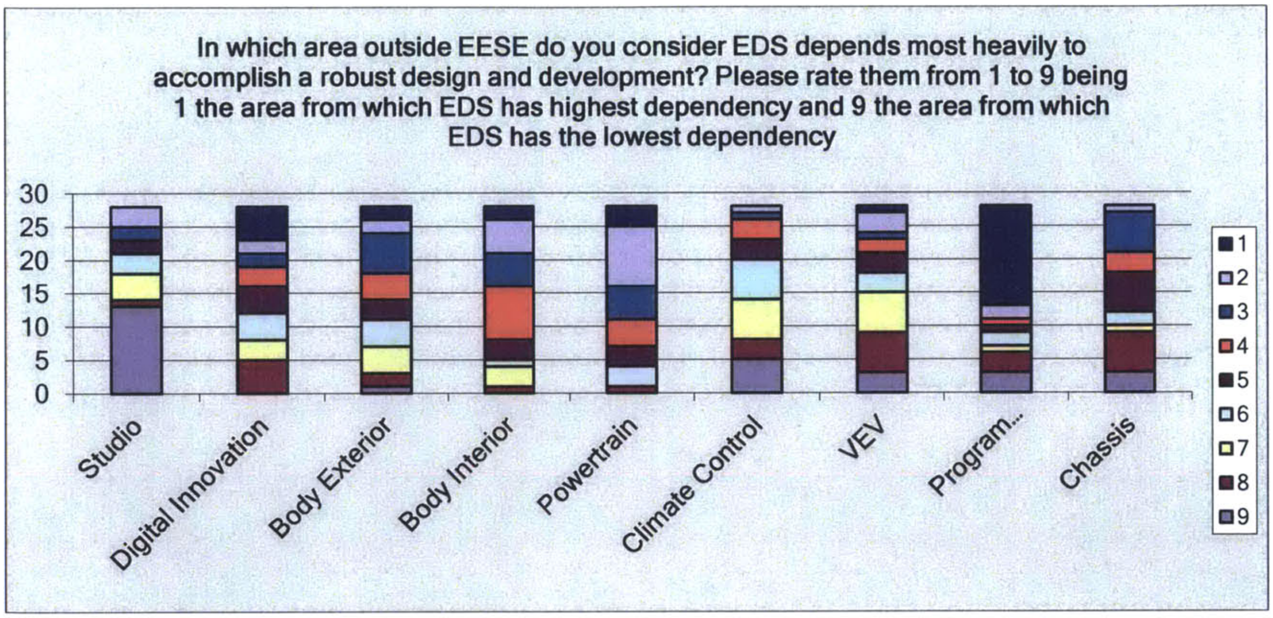
In which area inside EESE do you consider EDS depends most heavily to accomplish a robust design and development? Please rate them from 1 to 9 being 1 the area from which EDS has highest dependency and 9 the area from which EDS has the lowest dependency

Answer Options	1	2	3	4	5	6	7	8	9	Response Count
Systems integration	24	3	1	0	1	0	0	0	2	31
CAE	0	8	3	2	7	1	5	1	4	31
Upperbody electronics	0	6	2	7	5	6	4	1	0	31
Underbody electronics	0	0	11	4	6	6	3	1	0	31
EESE Digital Innovation (3D)	4	7	5	5	2	3	1	2	2	31
EDS Core Group	1	4	5	4	4	4	8	1	0	31
EDS Components Group	0	2	4	8	3	8	4	1	1	31
HMI	2	0	0	1	0	1	3	20	4	31
IVS	0	1	0	0	3	2	3	4	18	31
Other (please specify)										6
									answered question	31
									skipped question	14

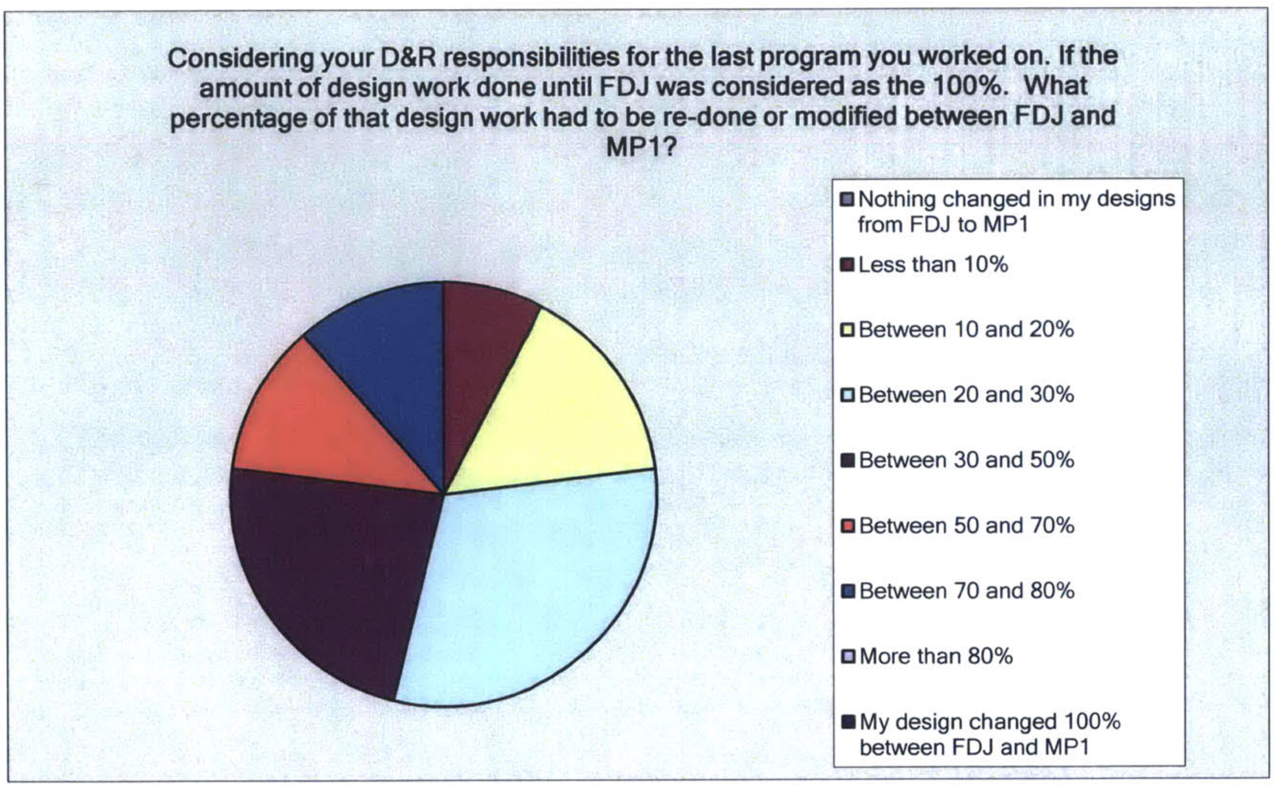


In which area outside EESE do you consider EDS depends most heavily to accomplish a robust design and development? Please rate them from 1 to 9 being 1 the area from which EDS has highest dependency and 9 the area from which EDS has the lowest dependency

Answer Options	1	2	3	4	5	6	7	8	9	Response Count
Studio	0	3	2	0	2	3	4	1	13	28
Digital Innovation	5	2	2	3	4	4	3	5	0	28
Body Exterior	2	2	6	4	3	4	4	2	1	28
Body Interior	2	5	5	8	3	1	3	1	0	28
Powertrain	3	9	5	4	3	3	0	1	0	28
Climate Control	0	1	1	3	3	6	6	3	5	28
VEV	1	3	1	2	3	3	6	6	3	28
Program Management	15	2	0	1	1	2	1	3	3	28
Chassis	0	1	6	3	6	2	1	6	3	28
Other (please specify)										2
									answered question	28
									skipped question	17



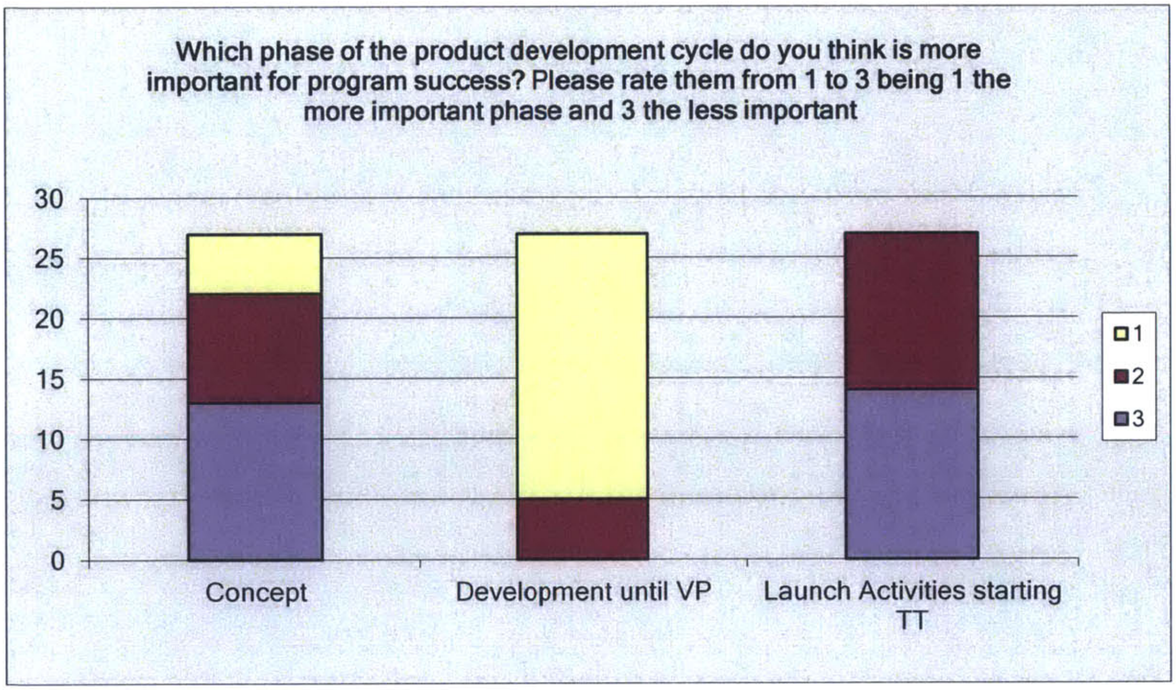
Considering your D&R responsibilities for the last program you worked on. If the amount of design work done until FDJ was considered as the 100%. What percentage of that design work had to be re-done or modified between FDJ and MP1?		
Answer Options	**Response Percent**	**Response Count**
Nothing changed in my designs from FDJ to MP1	0.0%	0
Less than 10%	7.7%	2
Between 10 and 20%	15.4%	4
Between 20 and 30%	30.8%	8
Between 30 and 50%	23.1%	6
Between 50 and 70%	11.5%	3
Between 70 and 80%	11.5%	3
More than 80%	0.0%	0
My design changed 100% between FDJ and MP1	0.0%	0
	answered question	26
	skipped question	19



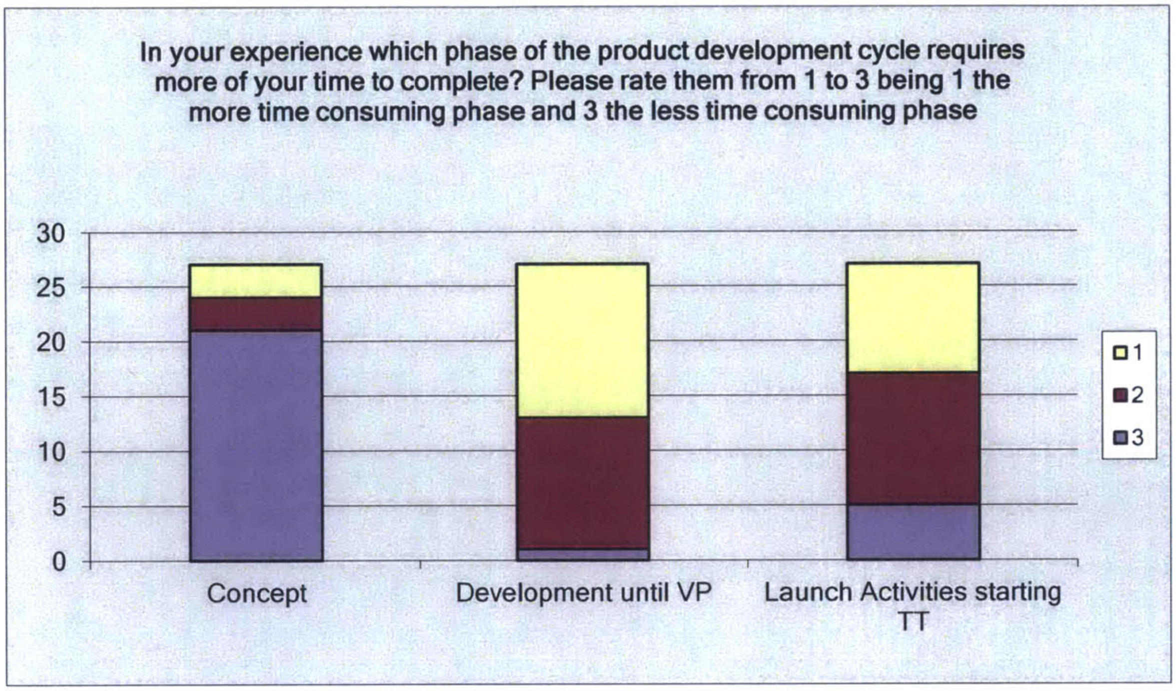
What actions do you think we could implement in the EDS Design and Development process to reduce iteration loops and reduce the need for reworks during later phases of the design process?	
Answer Options	**Response Count**
	25
answered question	25
skipped question	20

Number	Response Date	Response Text
1	jul 25, 2014 8:17 a.m.	Add the match check (2D and 3D, schemtics and 2D) in to the delivery element since lots of the unecessary design issues are due to this kind check missing
2	jul 22, 2014 8:57 p.m.	PROPER COMMUNICATION BETWEEN CROSS-FUNCTIONAL GROUPS. A REAL LEAD FOR COORDINATED CHANGES. FIRM DECISION FROM MANAGEMENT ON WHAT THE CHANGES WOULD BE, BECAUSE MISINFORMATION, OR MISINTERPRETATION ALWAYS LEADS TO REWORKS AND LOOPS IN THE PROCESS.
3	jul 16, 2014 5:23 p.m.	Assign Higher workload before FDJ to get the highest feedback possible using digital tools.
4	jul 15, 2014 3:22 p.m.	It has been the goal of EDS to reduce the amount of release for as long as I have been working in EDS. The 3D CAD tools are good but you can never predict how a wire harness will bend in reality.
5	jul 15, 2014 5:01 a.m.	Stabile PDL, more time from VP to TT to complete testing and react to re-DV items, more time to review process with VO and assembly plants in perhaps a pre-TT pilot allowing time to make changes prior to TT.
6	jul 14, 2014 5:41 p.m.	PRIORITIZE URGENCE MATTERS AND INVEST THE ENOUGH TIME FOR APPLYING ROBUST ASSESSMENTS AND SOLUTIONS. INCORRECT URGENT SENSE COULD PUSH A TEAM TO CHOOSE A LONG TERM EXPENSIVE ALTERNATIVE.
7	jul 14, 2014 3:39 p.m.	More time before DFJ in order to debug the design
8	jul 14, 2014 12:57 p.m.	- Double check of the 2D harness vs 3D data. - Complexity review between EDS systems and EDS D&Rs - Circuitry check (bingo) between EDS systems and D&R engineers
9	jul 13, 2014 1:14 a.m.	Actually have a design when you start
10	jul 11, 2014 8:14 p.m.	Follow GPDS Process in terms of freeze dates. Wiring is often getting changes as little as 10 weeks before MRD. We are requested to release to one PDL, but plants are ordering to another. There is no control with the frequent TIB's that are being released on CD4.2.
11	jul 11, 2014 6:16 p.m.	Marketing and the Program Team need to adhere to the EDS lead times required for the processing designs. EDS design/process doesn't work well with GPDS timing. To ensure robust designs the long lead durability cycle, overlapping build phases, manufacturing DFM and launch readiness doesn't allow for a clean systems and packaging validations. When going into the first pre-production build, it is very difficult to process and release prints for the following build....when your only one week into the original build. This is a huge contributor for quality issues and re-works because the supplier isn't able to react quick enough to incorporating the latest build issues (under an Alert).
12	jul 11, 2014 4:39 p.m.	More time to implement changes after Build validations, It means avoid overlap delivery dates for different regions on global design.
13	jul 11, 2014 2:15 p.m.	JC Response
14	jul 11, 2014 2:11 p.m.	Demand good DTs, keep component D&Rs responsible to design their parts, get logical schematics - ALL BY DUE DATES. These HAVE to be Quality Events! Every time we get junk our mgmt should be pouncing on it.
15	jul 11, 2014 1:55 p.m.	TDR should be a go no go Document Staffing should be completed by UNV0 Wiring should have 1 week more after the rest of the teams freeze their design
16	jul 11, 2014 12:12 p.m.	Hold to FDJ and allow late changes. Staff properly, hold the groups that owe EDS data accountable.
17	jul 11, 2014 8:35 a.m.	Allow more time between builds.
18	jul 10, 2014 8:20 p.m.	Design freeze, design buyoff from affected stakeholders
19	jul 10, 2014 7:37 p.m.	receive logicals on time and 100% correct
20	jul 10, 2014 7:37 p.m.	Management needs to stop rolling over and resist some of the changes due to other part failures.
21	jul 10, 2014 7:35 p.m.	A separate all-in-one change control system for EDS.
22	jul 10, 2014 7:01 p.m.	One thing I have noticed so far is our Systems team is always way behind and circuit/functional issues were the primary cause of reworks during the VP Build phase. Going into TT Build, we still do not have physical schematics which I feel is a huge problem for EDS as we should be conducting compatibility reviews between harness prints and schematics.
23	jul 10, 2014 7:00 p.m.	COMPATIBILITIES REVIEWS BEFORE HARNESS CONSTRUCTION, 3D VS 2D, PRINT VS SCHEMATICS, SCHEMATICS VS DT
24	jul 10, 2014 6:39 p.m.	Start tasks earlier Work in parallel - do not wait for previous task to complete before starting Make decisions more quickly Finish preliminary designs earlier and check-check-check
25	jul 10, 2014 6:28 p.m.	Thoroughly mandatory DFMEA creation and update at each design release. Create process improvements for compatibility reviews.

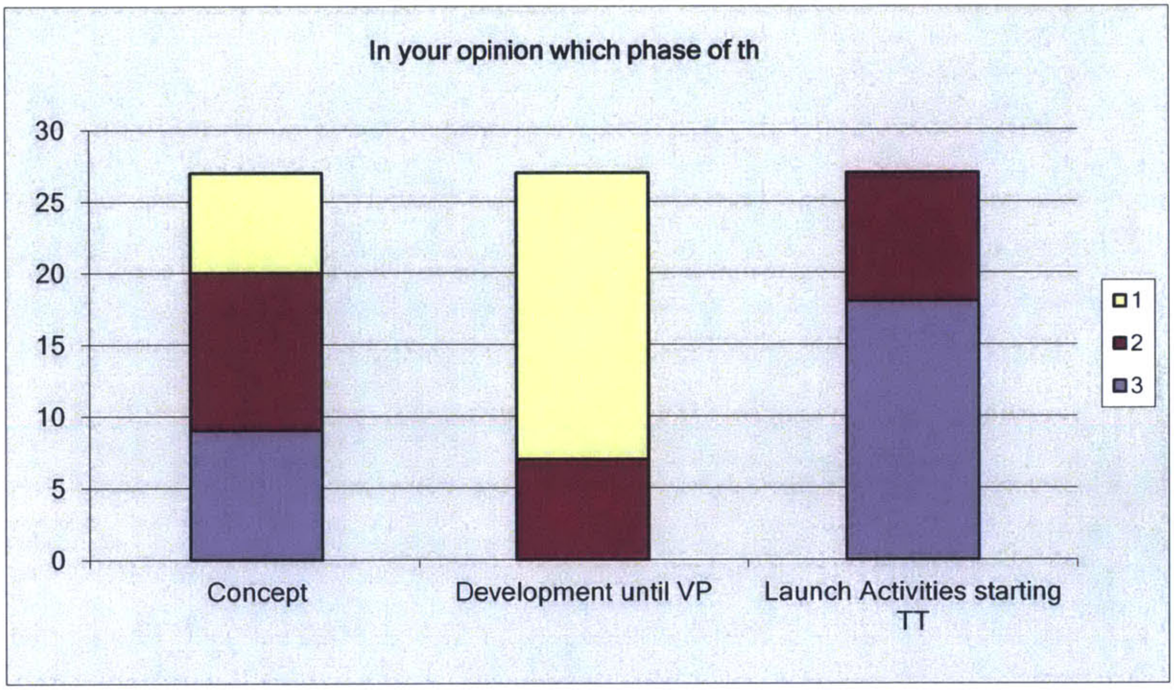
Which phase of the product development cycle do you think is more important for program success? Please rate them from 1 to 3 being 1 the more important phase and 3 the less important				
Answer Options	**1**	**2**	**3**	**Response Count**
Concept	5	9	13	27
Development until VP	22	5	0	27
Launch Activities starting TT	0	13	14	27
			answered question	27
			skipped question	18



In your experience which phase of the product development cycle requires more of your time to complete? Please rate them from 1 to 3 being 1 the more time consuming phase and 3 the less time consuming phase				
Answer Options	**1**	**2**	**3**	**Response Count**
Concept	3	3	21	27
Development until VP	14	12	1	27
Launch Activities starting TT	10	12	5	27
			answered question	27
			skipped question	18



In your opinion which phase of the product development cycle depends more on information from cross functional areas in order for you to complete? Please rate them from 1 to 3 being 1 the phase with more cross functional dependencies and 3 the phase with less cross functional dependencies				
Answer Options	**1**	**2**	**3**	**Response Count**
Concept	7	11	9	27
Development until VP	20	7	0	27
Launch Activities starting TT	0	9	18	27
			answered question	27
			skipped question	18

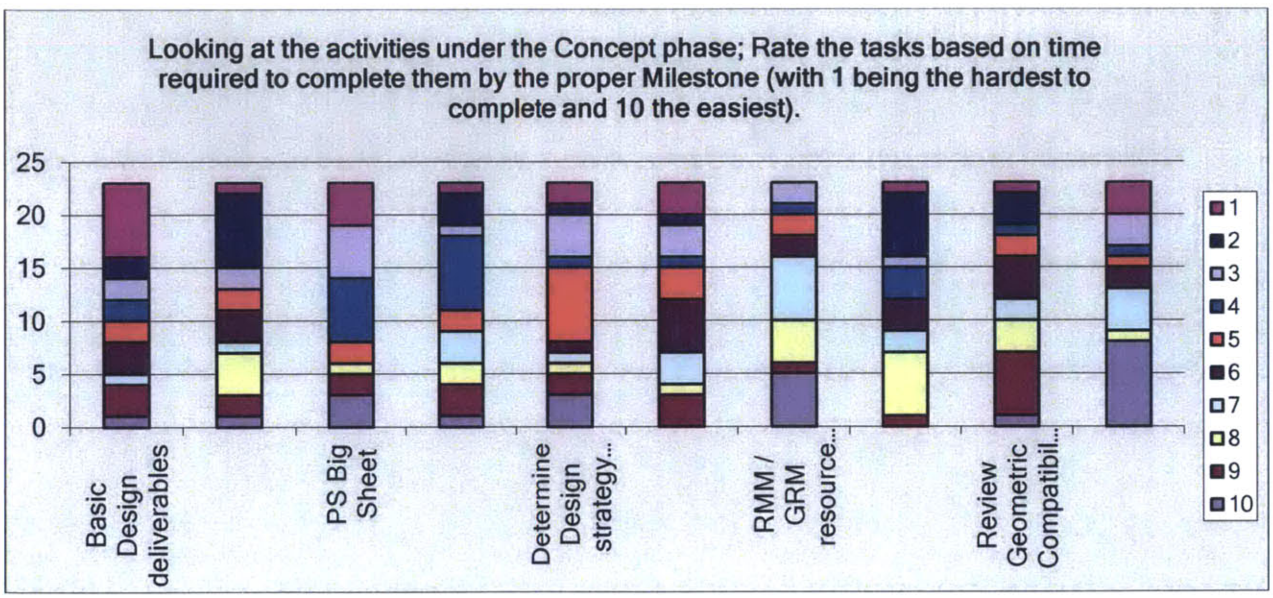


Concept Activities

Basic Design deliverables
Attachment D for each attribute
PS Big sheet
Perform PDB Market Study
Determine Design strategy (Full service supplier, In-House, Purchased services)
Design Source Selection Process
RMM / GRM resource assessment process
Purchase agreement, eSOW
Review Geometric Compatibility
Define PDB Strategy (Carryover, Minor/Mod changes, New)

Looking at the activities under the Concept phase; Rate the tasks based on time required to complete them by the proper Milestone (with 1 being the hardest to complete and 10 the easiest).

Answer Options	1	2	3	4	5	6	7	8	9	10	Response Count
Basic Design deliverables	7	2	2	2	2	3	1	0	3	1	23
Attachment D for each attribute	1	7	2	0	2	3	1	4	2	1	23
PS Big Sheet	4	0	5	6	2	0	0	1	2	3	23
Perform PDB Market Study	1	3	1	7	2	0	3	2	3	1	23
Determine Design strategy (Full service supplier, In-	2	1	4	1	7	1	1	1	2	3	23
Design Source Selection Process	3	1	3	1	3	5	3	1	3	0	23
RMM / GRM resource assessment process	0	0	2	1	2	2	6	4	1	5	23
Purchase agreement, eSOW	1	6	1	3	0	3	2	6	1	0	23
Review Geometric Compatibility	1	3	0	1	2	4	2	3	6	1	23
Define PDB Strategy (Carryover, Minor/Mod changes,	3	0	3	1	1	2	4	1	0	8	23
Other (please specify)											4
										answered question	23
										skipped question	22



Concept Activities

Basic Design deliverables
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PS Big sheet
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Determine Design strategy (Full service supplier, In-House, Purchased services)
Design Source Selection Process
RMM / GRM resource assessment process
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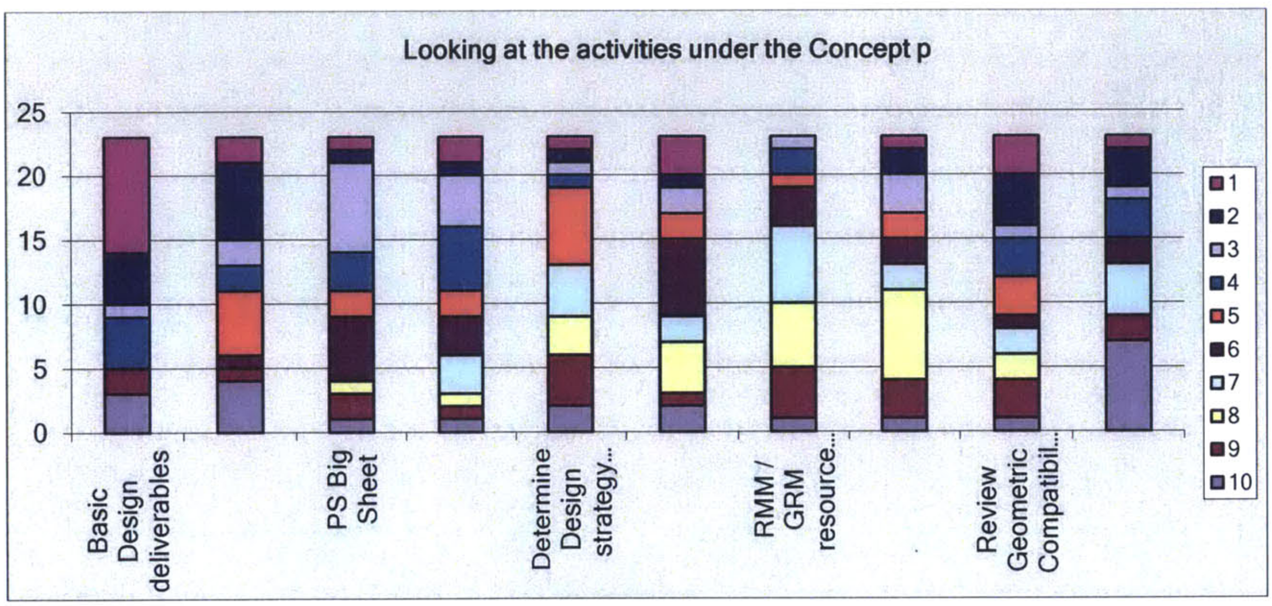
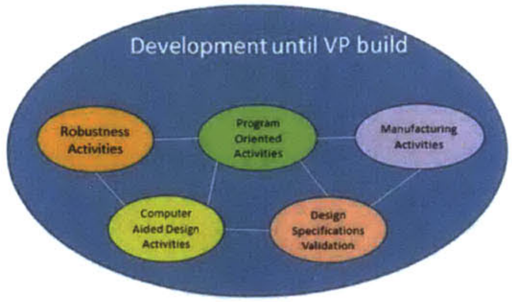
Review Geometric Compatibility
Define PDB Strategy (Carryover, Minor/Mod changes, New)

Looking at the activities under the Concept phase; Rate the tasks based in your opinion of which tasks depend more on information from cross functional areas in order for you to complete (With 1 being the task with more dependence on cross functional information and 10 the task with less dependence).

Answer Options	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Response Count**
Basic Design deliverables	9	4	1	4	0	0	0	0	2	3	23
Attachment D for each attribute	2	6	2	2	5	1	0	0	1	4	23
PS Big Sheet	1	1	7	3	2	5	0	1	2	1	23
Perform PDB Market Study	2	1	4	5	2	3	3	1	1	1	23
Determine Design strategy (Full service supplier, In-	1	1	1	1	6	0	4	3	4	2	23
Design Source Selection Process	3	1	2	0	2	6	2	4	1	2	23
RMM / GRM resource assessment process	0	0	1	2	1	3	6	5	4	1	23
Purchase agreement, eSOW	1	2	3	0	2	2	2	7	3	1	23
Review Geometric Compatibility	3	4	1	3	3	1	2	2	3	1	23
Define PDB Strategy (Carryover, Minor/Mod changes,	1	3	1	3	0	2	4	0	2	7	23
Other (please specify)											4
										answered question	23
										skipped question	22

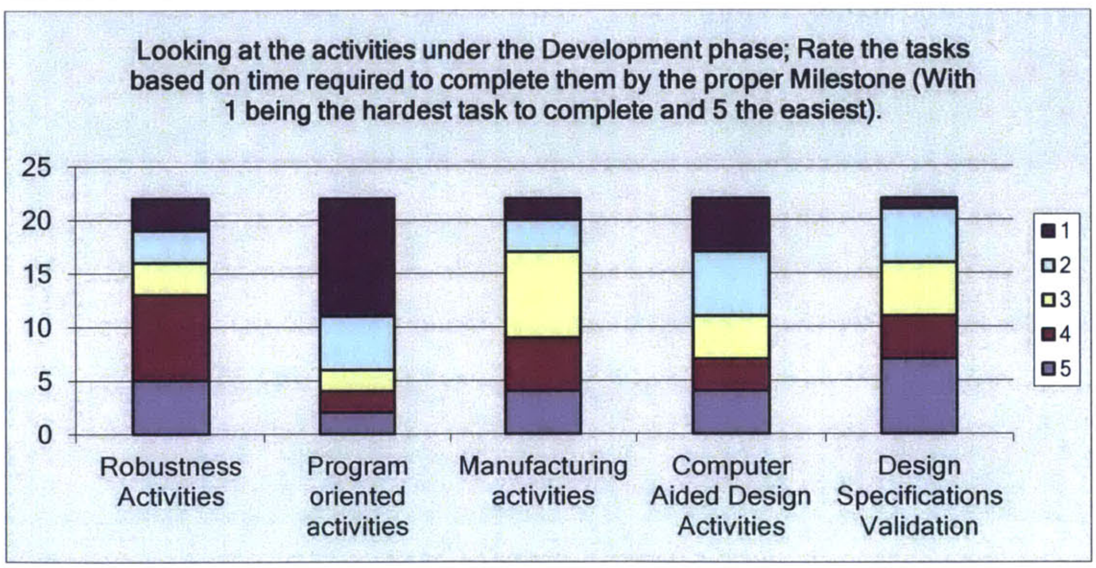


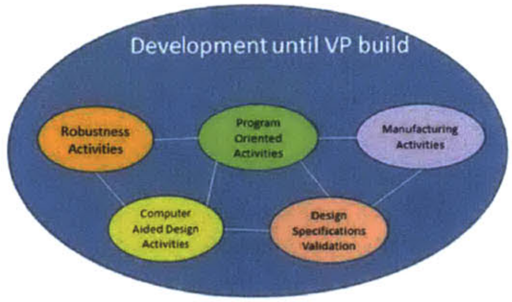


- **Robustness activities:**
  - FMA
  - DFMEA
  - SCCAF (LHS)
  - P-Diagrams
  - Reliability Checklist (RCL)
- **Computer Aid Design Activities**
  - Packaging studies
  - 3D CAD creation
  - DPA 0, 1 Resolution
  - DPA 2 Resolution (Craftsmanship)
  - DPA 3 Resolution (Ergonomics)
  - DPA 4 Resolution (Design for service)
  - DPA 5 Resolution (Assembly concerns)
  - DPA 6 Resolution
  - DIAS Studies
  - VRQA
  - CAE Analysis
- **Program Oriented Activities**
  - PDL Review
  - 2D Topology Completion
  - Logical & Physical schematics completion
  - M1 2D Prints creation
  - M1 Breadboard and Build support
  - Complexity Creation
  - Wire harness compatibility analysis
  - M1 & VP Illustrations generation
  - Deep Dive
  - RQA
  - Regulatory Compliance (Homologation, Emission, Safety)
  - AVBOM Release
  - EDS PDP
  - Breadboard Orders
  - Service documentation Delivery
  - FDJ Harnesses quotes
  - VP Build specs review
  - VP Bom validation
  - WERS P-Release
  - Circuit Bingo (Compatibility reviews, DT, Schematic, Print, Cutsheet)
  - Components(Connectors/Miscellaneous) PPAP Release & tracking
- **Manufacturing Activities**
  - 2D EDS Component Print Release
  - Harness Component Tool orders
  - PPAP On site visits
  - Design for Manufacturing Resolution
  - 2D Print plan & creation
  - Mater Sample Review
  - Update Prints from CAE
  - Components(Connectors/Miscellaneous)
  - PPAP process
- **Design Specifications Validation**
  - ECAR Phase I & III
  - EDS Design Rule assessment
  - SDS Assessment
  - Service parts release
  - Order & completion of Design Validations

Looking at the activities under the Development phase; Rate the tasks based on time required to complete them by the proper Milestone (With 1 being the hardest task to complete and 5 the easiest).

Answer Options	1	2	3	4	5	Response Count
Robustness Activities	3	3	3	8	5	22
Program oriented activities	11	5	2	2	2	22
Manufacturing activities	2	3	8	5	4	22
Computer Aided Design Activities	5	6	4	3	4	22
Design Specifications Validation	1	5	5	4	7	22
Other (please specify)						0
					answered question	22
					skipped question	23





- **Robustness activities:**
  - FMA
  - DFMEA
  - SCCAF (LHS)
  - P-Diagrams
  - Reliability Checklist (RCL)

- **Computer Aid Design Activities**
  - Packaging studies
  - 3D CAD creation
  - DPA 0, 1 Resolution
  - DPA 2 Resolution (Craftsmanship)
  - DPA 3 Resolution (Ergonomics)
  - DPA 4 Resolution (Design for service)
  - DPA 5 Resolution (Assembly concerns)
  - DPA 6 Resolution
  - DIAS Studies
  - VRQA
  - CAE Analysis

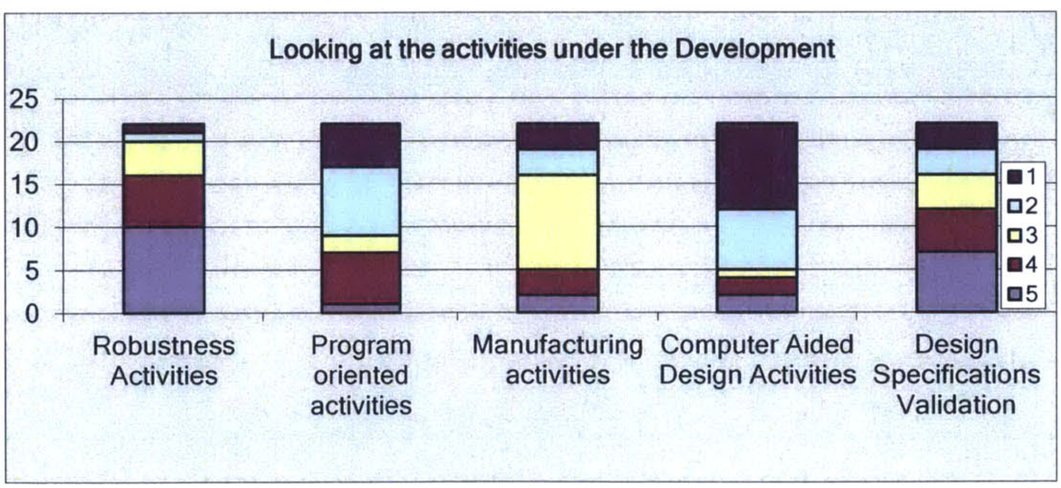
- **Program Oriented Activities**
  - PDL Review
  - 2D Topology Completion
  - Logical & Physical schematics completion
  - M1 2D Prints creation
  - M1 Breadboard and Build support
  - Complexity Creation
  - Wire harness compatibility analysis
  - M1 & VP Illustrations generation
  - Deep Dive
  - RQA
  - Regulatory Compliance (Homologation, Emission, Safety)
  - AVBOM Release
  - EDS PDP
  - Breadboard Orders
  - Service documentation Delivery
  - FDJ Harnesses quotes
  - VP Build specs review
  - VP Bom validation
  - WERS P-Release
  - Circuit Bingo (Compatibility reviews, DT, Schematic, Print, Cutsheet)
  - Components(Connectors/Miscellaneous) PPAP Release & tracking

- **Manufacturing Activities**
  - 2D EDS Component Print Release
  - Harness Component Tool orders
  - PPAP On site visits
  - Design for Manufacturing Resolution
  - 2D Print plan & creation
  - Mater Sample Review
  - Update Prints from CAE
  - Components(Connectors/Miscellaneous)
  - PPAP process

- **Design Specifications Validation**
  - ECAR Phase I & III
  - EDS Design Rule assessment
  - SDS Assessment
  - Service parts release
  - Order & completion of Design Validations

Looking at the activities under the Development phase; Rate the tasks based in your opinion of which tasks depend more on information from cross functional areas in order for you to complete (With 1 being the task with more dependence on cross

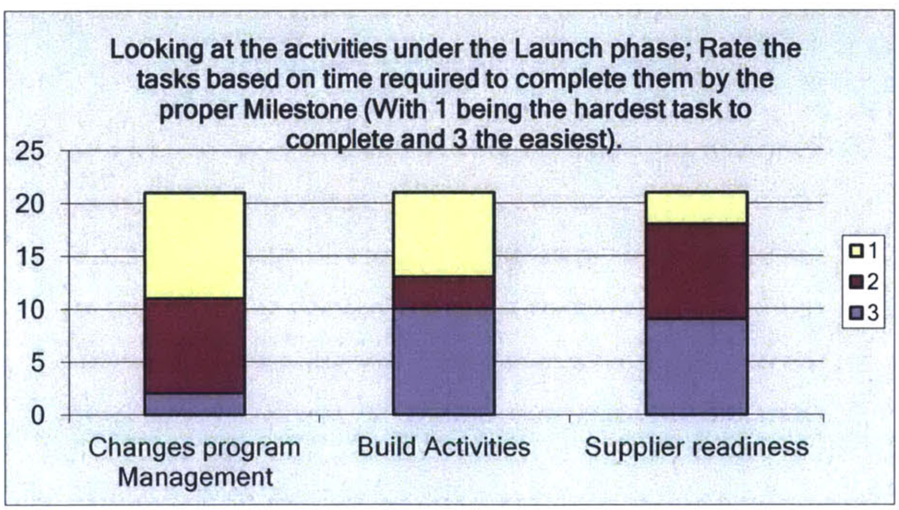
Answer Options	1	2	3	4	5	Response Count
Robustness Activities	1	1	4	6	10	22
Program oriented activities	5	8	2	6	1	22
Manufacturing activities	3	3	11	3	2	22
Computer Aided Design Activities	10	7	1	2	2	22
Design Specifications Validation	3	3	4	5	7	22
Other (please specify)						0
					answered question	22
					skipped question	23



- **Changes program management**
  - AVBOM Validation & updates
  - 2D Drafting Plan for TT and Beyond
  - PDL Review
  - Complexity Updates
  - Packaging Studies
  - DIAS Studies
  - DCRs creation
  - RFQ, 2-Pagers, Quest analysis
  - Wire Harness
  - Compatibility Analysis
  - Circuit Bingo (Compatibility reviews , DTs, Schematic, Print, Cutsheet)
  - 2D Print updates
  - WERS Release
- **Build Activities**
  - BOM Validation
  - Build Specs analysis
  - Build onsite support
  - Illustrations update
- **Supplier readiness**
  - SCCAF (RHS)
  - Control Plans
  - PFMEA
  - PV
  - Design for Manufacturing Resolution
  - Master Sample Order & Review
  - EDS PPAP On site visit
  - DV Testing

Looking at the activities under the Launch phase; Rate the tasks based on time required to complete them by the proper Milestone (With 1 being the hardest task to complete and 3 the easiest).

Answer Options	1	2	3	Response Count
Changes program Management	10	9	2	21
Build Activities	8	3	10	21
Supplier readiness	3	9	9	21
Other (please specify)				0
			answered question	21
			skipped question	24



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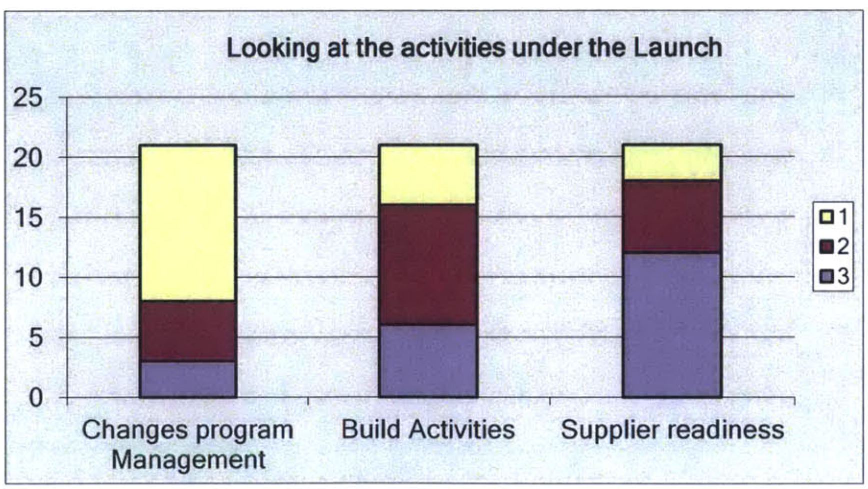
  - AVBOM Validation & updates
  - 2D Drafting Plan for TT and Beyond
  - PDL Review
  - Complexity Updates
  - Packaging Studies
  - DIAS Studies
  - DCRs creation
  - RFQ, 2-Pagers, Quest analysis
  - Wire Harness
  - Compatibility Analysis
  - Circuit Bingo (Compatibility reviews , DTs, Schematic, Print, Cutsheet)
  - 2D Print updates
  - WERS Release
- **Build Activities**
  - BOM Validation
  - Build Specs analysis
  - Build onsite support
  - Illustrations update
- **Supplier readiness**
  - SCCAF (RHS)
  - Control Plans
  - PFMEA
  - PV
  - Design for Manufacturing Resolution
  - Master Sample Order & Review
  - EDS PPAP On site visit
  - DV Testing

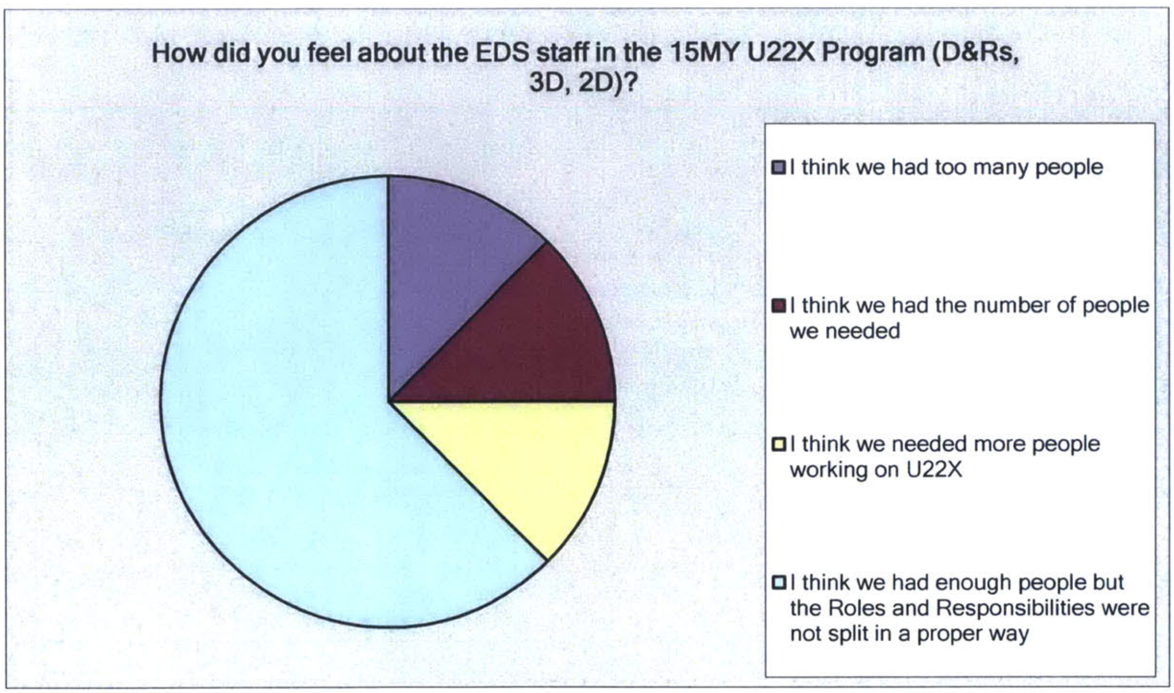
Looking at the activities under the Launch phase; Rate the tasks based in your opinion of which tasks depend more on information from cross functional areas in order for you to complete (With 1 being the task with more dependence on cross functional information and 3 the task with less dependence).

Answer Options	1	2	3	Response Count
Changes program Management	13	5	3	21
Build Activities	5	10	6	21
Supplier readiness	3	6	12	21
Other (please specify)				0
			answered question	21
			skipped question	24

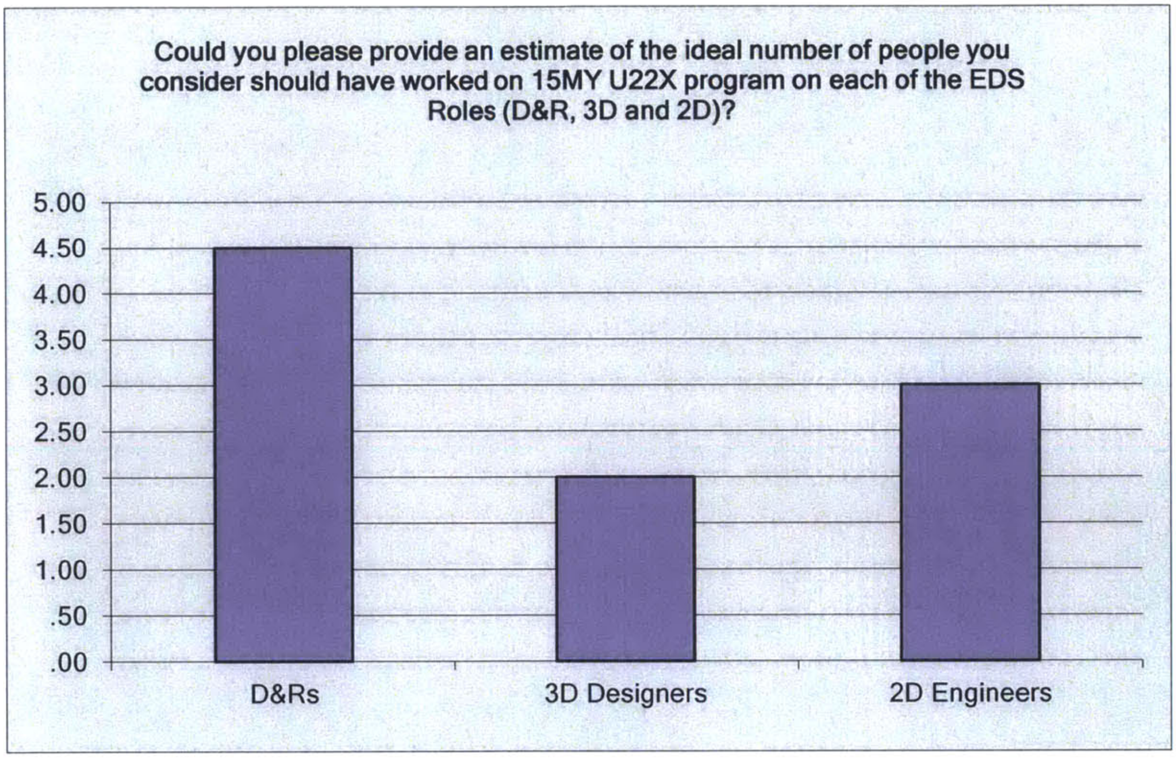


Appendix B - EDS SUV project team survey

How did you feel about the EDS staff in the 15MY U22X Program (D&Rs, 3D, 2D)?		
Answer Options	**Response Percent**	**Response Count**
I think we had too many people	12.5%	1
I think we had the number of people we needed	12.5%	1
I think we needed more people working on U22X	12.5%	1
I think we had enough people but the Roles and Responsibilities were not split in a proper way	62.5%	5
	answered question	**8**
	skipped question	**0**



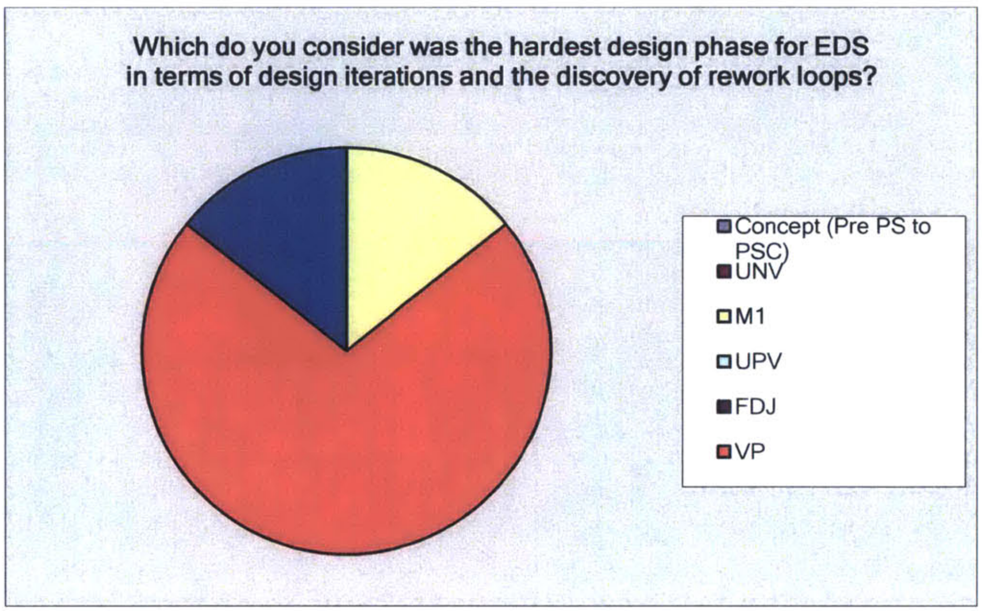
Could you please provide an estimate of the ideal number of people you consider should have worked on 15MY U22X program on each of the EDS Roles (D&R, 3D and 2D)?			
Answer Options	**Response Average**	**Response Total**	**Response Count**
D&Rs	4.50	36	8
3D Designers	2.00	16	8
2D Engineers	3.00	24	8
		answered question	8
		skipped question	0



Please describe briefly the 5 main EDS Design Issues that were critical during the 15MY U22X program	
Answer Options	**Response Count**
	7
answered question	7
skipped question	1

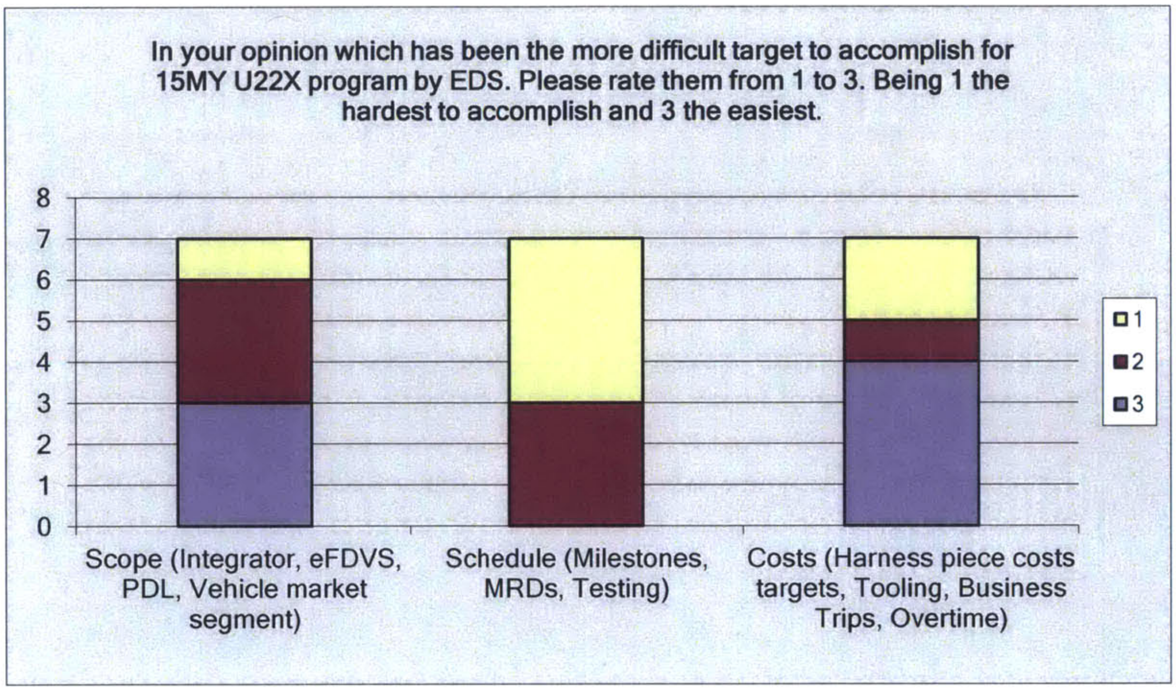
Number	Response Date	Response Text
1	jul 11, 2014 9:15 p.m.	Complexity not reviewed in detailed for AVBOM and WERS release, CCD, PEPS and ambient Light added late to the program, option tag issues and carry over content not implemented corectly at the builds due to lack of detail review, sections and views not on 2D or correct according to 2D and compability reviews missing.
2	jul 11, 2014 3:40 p.m.	BINGO review, DCR tracking and update, reworks tracking, responsibilities tracking, continuous job responsability update
3	jul 11, 2014 2:40 p.m.	-incorrect routing -incorrect selection of retainers -incorrect takeout lengths -incorrect views on prints leading to incorrerct retainer orientation
4	jul 11, 2014 3:52 a.m.	n/a
5	jul 10, 2014 9:36 p.m.	- Late changes required by the program. - Many additional features on an old platform. - New requirements of other systems that restrict EDS routing. - Considerable increase in bundle diameters. - As some components are c / o from other platforms, there is no opportunity to adapt them to U22X.
6	jul 10, 2014 4:54 p.m.	1. Communication (or lack there of) 2. Time Management 3. Feasibility 4. Resources 5. Establishing proper points of contact
7	jul 10, 2014 3:50 p.m.	8-way inline between Console and Body Interference with A/C Lines Drip loop deletion HVAC Mispinout Tail lamp inop sharp edge cutting B+ Touch with bolt in trasfer case

Which do you consider was the hardest design phase for EDS in terms of design iterations and the discovery of rework loops?		
Answer Options	**Response Percent**	**Response Count**
Concept (Pre PS to PSC)	0.0%	0
UNV	0.0%	0
M1	14.3%	1
UPV	0.0%	0
FDJ	0.0%	0
VP	71.4%	5
TT	14.3%	1
PP/MP1	0.0%	0
Other (please specify)		1
	answered question	7
	skipped question	1



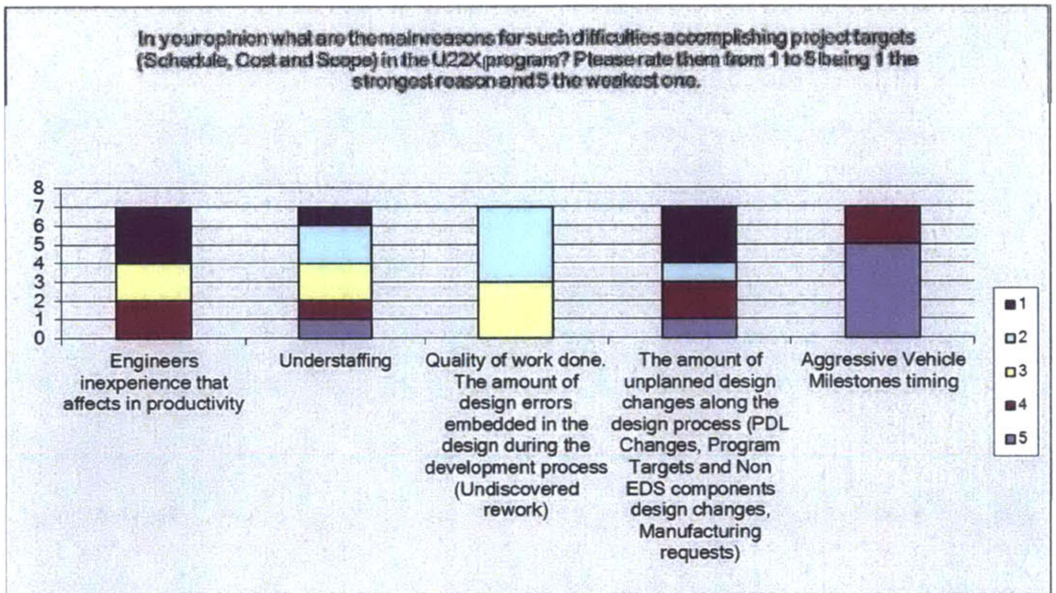
In your opinion which has been the more difficult target to accomplish for 15MY U22X program by EDS. Please rate them from 1 to 3. Being 1 the hardest to accomplish and 3 the easiest.

Answer Options	1	2	3	Response Count
Scope (Integrator, eFDVS, PDL, Vehicle market segment)	1	3	3	7
Schedule (Milestones, MRDs, Testing)	4	3	0	7
Costs (Harness piece costs targets, Tooling, Business Trips, Overtime)	2	1	4	7
Other (please specify)				0
			answered question	7
			skipped question	1

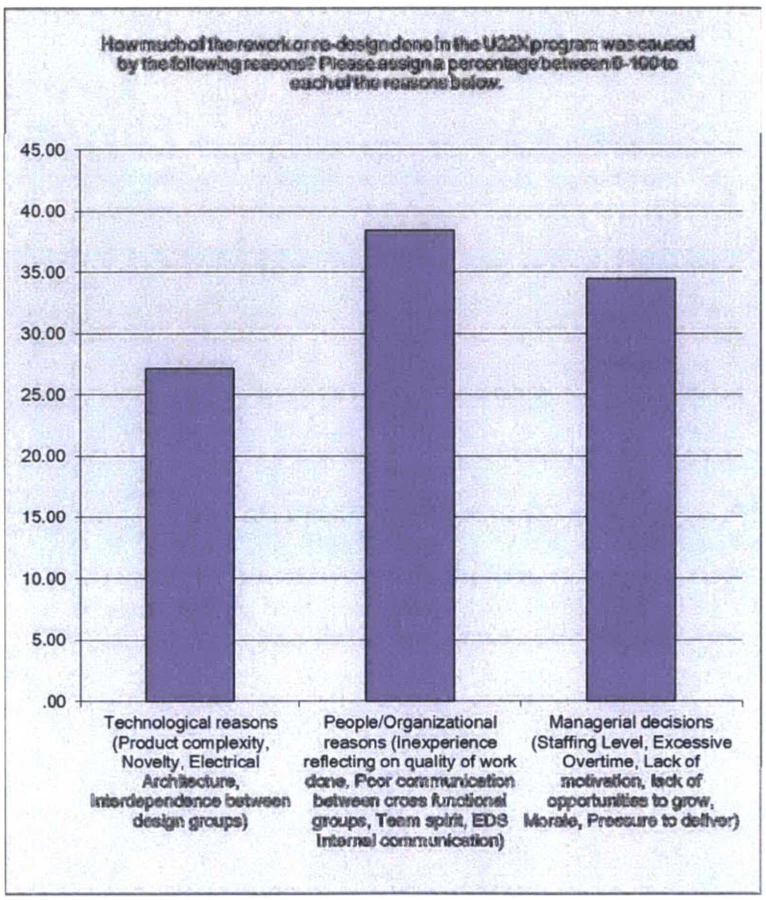


In your opinion what are the main reasons for such difficulties accomplishing project targets (Schedule, Cost and Scope) in the U22X program? Please rate them from 1 to 5 being 1 the strongest reason and 5 the weakest one.

Answer Options	1	2	3	4	5	Response Count
Engineers inexperience that affects in productivity	3	0	2	2	0	7
Understaffing	1	2	2	1	1	7
Quality of work done. The amount of design errors	0	4	3	0	0	7
The amount of unplanned design changes along the	3	1	0	2	1	7
Aggressive Vehicle Milestones timing	0	0	0	2	5	7
Other (please specify)						1
					answered question	7
					skipped question	1

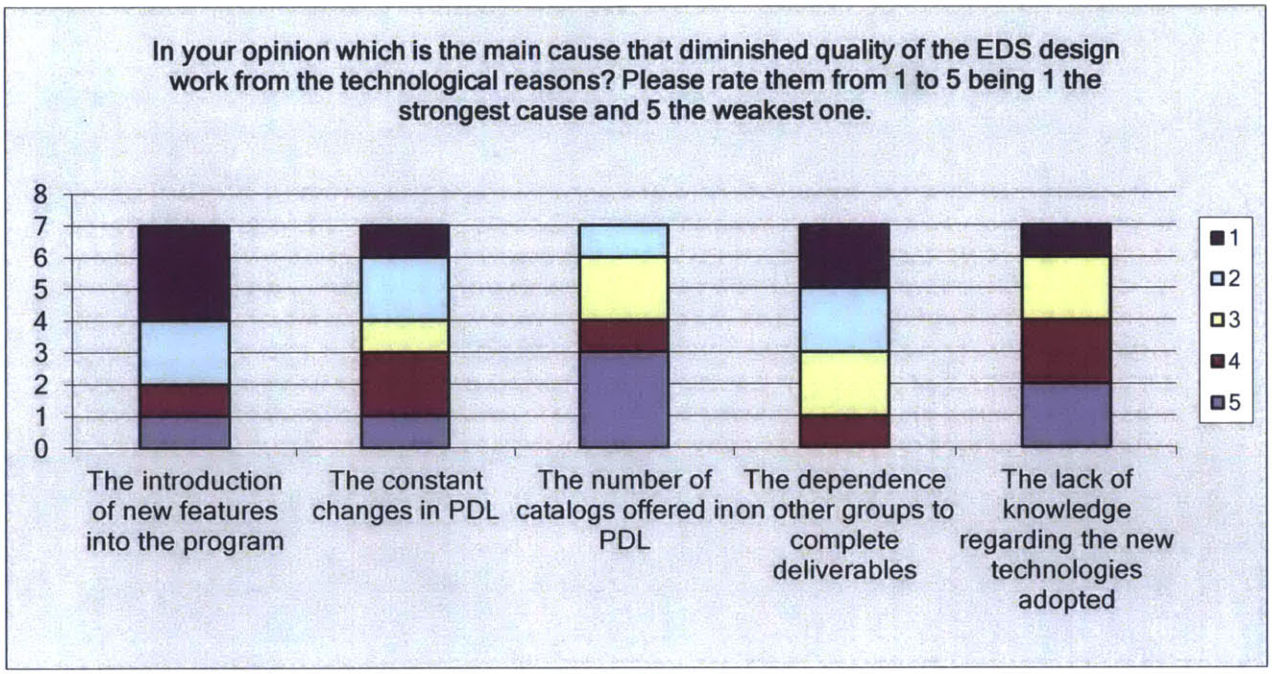


How much of the rework or re-design done in the U22X program was caused by the following reasons? Please assign a percentage between 0-100 to each of the reasons below.			
Answer Options	**Response Average**	**Response Total**	**Response Count**
Technological reasons (Product complexity, Novelty, Electrical Architecture, Interdependence between design groups)	27.14	190	7
People/Organizational reasons (Inexperience reflecting on quality of work done, Poor communication between cross functional groups, Team spirit, EDS Internal communication)	38.43	269	7
Managerial decisions (Staffing Level, Excessive Overtime, Lack of motivation, lack of opportunities to grow, Morale, Pressure to deliver)	34.43	241	7
		answered question	7
		skipped question	1

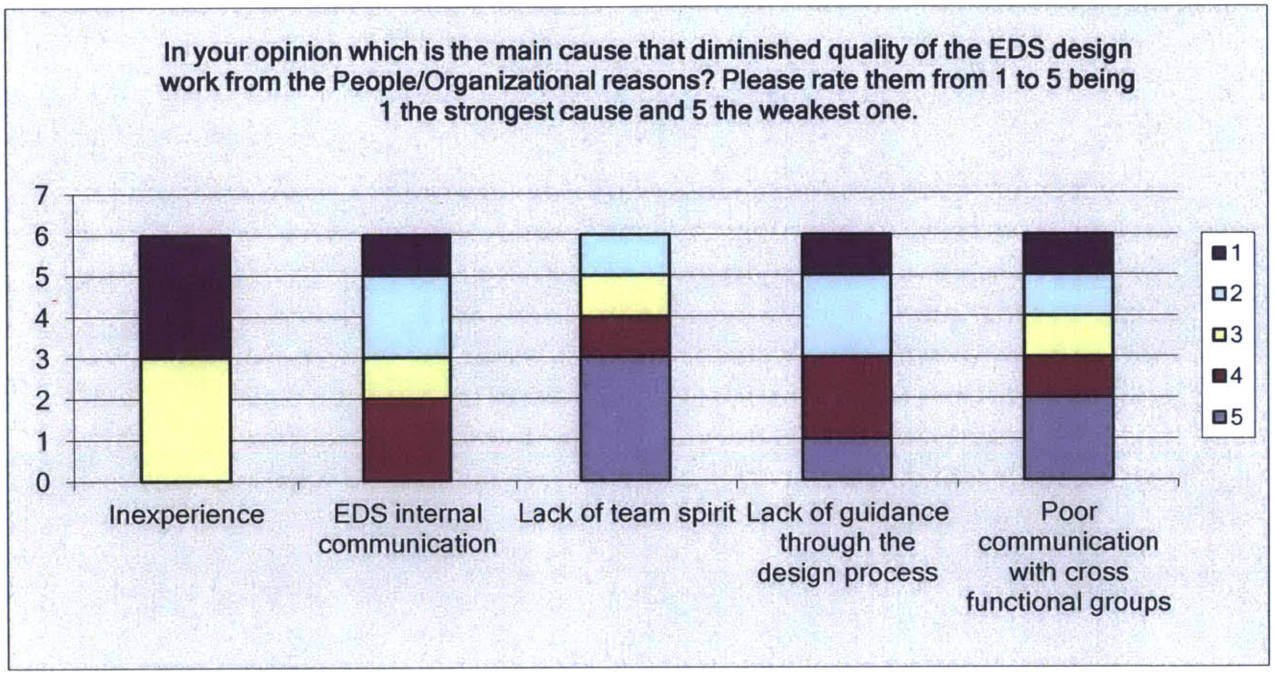


In your opinion which is the main cause that diminished quality of the EDS design work from the technological reasons? Please rate them from 1 to 5 being 1 the strongest cause and 5 the weakest one.

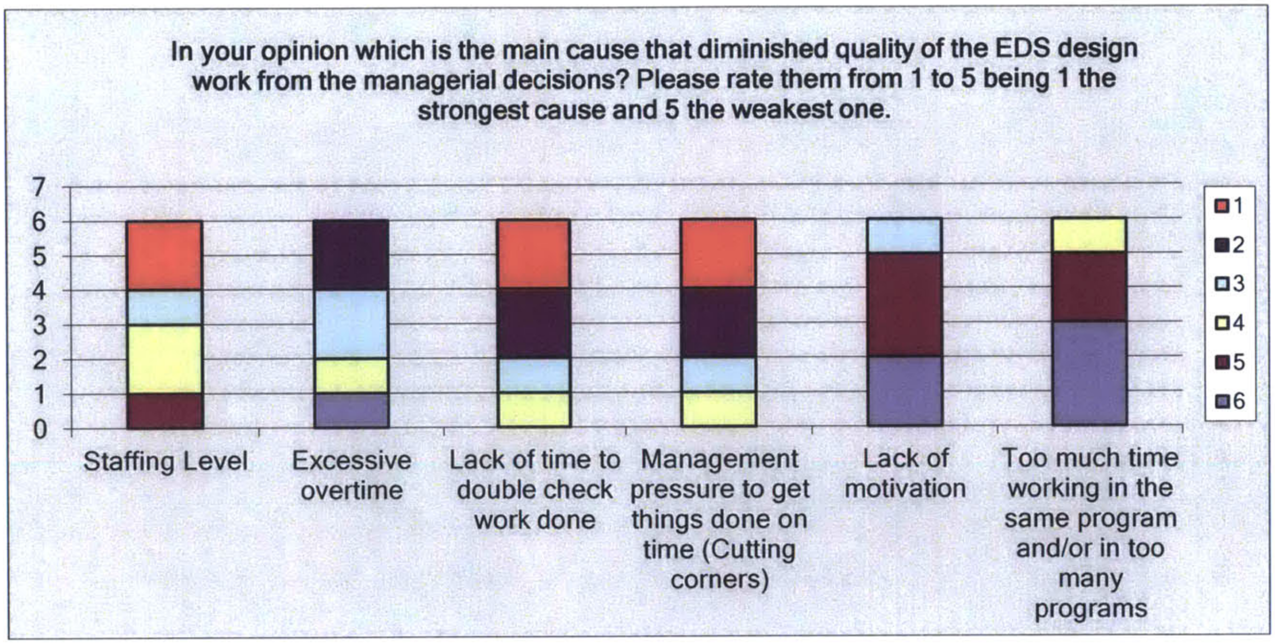
Answer Options	1	2	3	4	5	Response Count
The introduction of new features into the program	3	2	0	1	1	7
The constant changes in PDL	1	2	1	2	1	7
The number of catalogs offered in PDL	0	1	2	1	3	7
The dependence on other groups to complete	2	2	2	1	0	7
The lack of knowledge regarding the new	1	0	2	2	2	7
Other (please specify)						0
					answered question	7
					skipped question	1



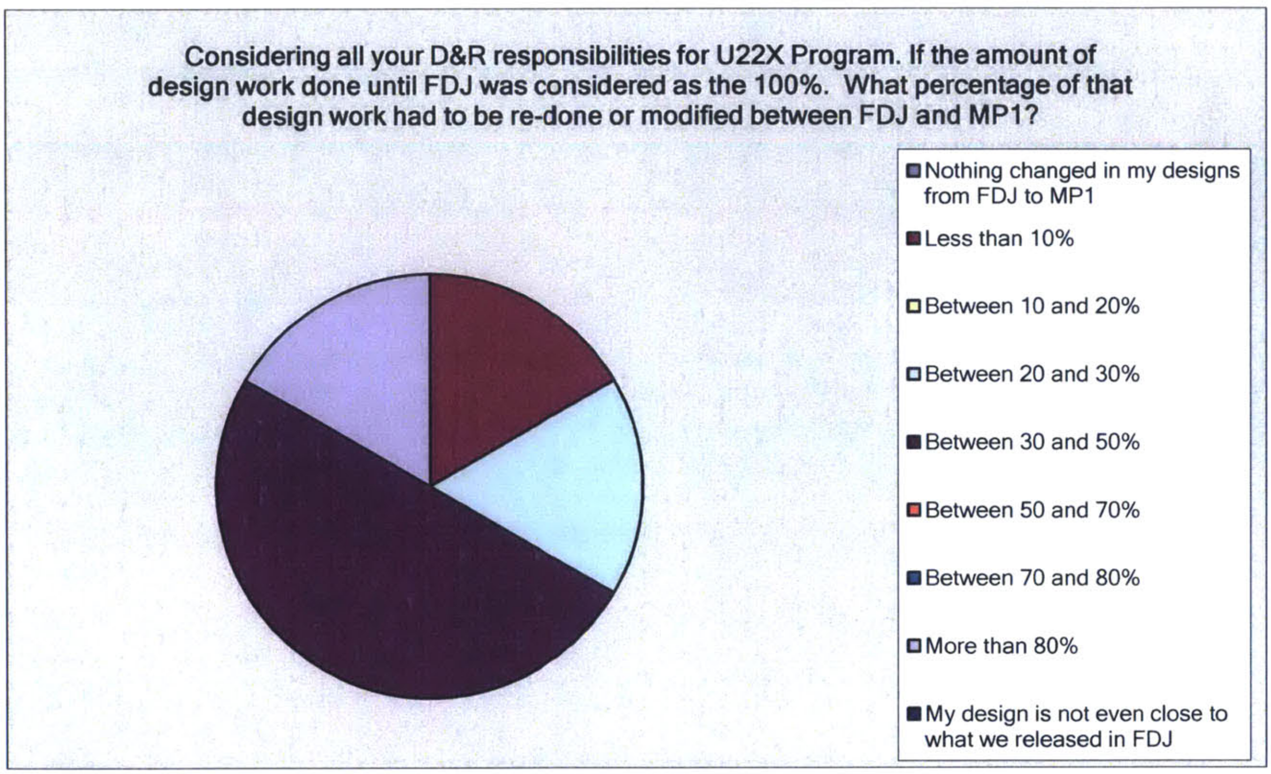
In your opinion which is the main cause that diminished quality of the EDS design work from the People/Organizational reasons? Please rate them from 1 to 5 being 1 the strongest cause and 5 the weakest one.						
Answer Options	**1**	**2**	**3**	**4**	**5**	**Response Count**
Inexperience	3	0	3	0	0	6
EDS internal communication	1	2	1	2	0	6
Lack of team spirit	0	1	1	1	3	6
Lack of guidance through the design process	1	2	0	2	1	6
Poor communication with cross functional groups	1	1	1	1	2	6
Other (please specify)						0
					answered question	6
					skipped question	2



In your opinion which is the main cause that diminished quality of the EDS design work from the managerial decisions? Please rate them from 1 to 5 being 1 the strongest cause and 5 the weakest one.							
Answer Options	1	2	3	4	5	6	Response Count
Staffing Level	2	0	1	2	1	0	6
Excessive overtime	0	2	2	1	0	1	6
Lack of time to double check work done	2	2	1	1	0	0	6
Management pressure to get things done on time	2	2	1	1	0	0	6
Lack of motivation	0	0	1	0	3	2	6
Too much time working in the same program and/or in	0	0	0	1	2	3	6
Other (please specify)							0
						answered question	6
						skipped question	2



Considering all your D&R responsibilities for U22X Program. If the amount of design work done until FDJ was considered as the 100%. What percentage of that design work had to be re-done or modified between FDJ and MP1?		
Answer Options	**Response Percent**	**Response Count**
Nothing changed in my designs from FDJ to MP1	0.0%	0
Less than 10%	16.7%	1
Between 10 and 20%	0.0%	0
Between 20 and 30%	16.7%	1
Between 30 and 50%	50.0%	3
Between 50 and 70%	0.0%	0
Between 70 and 80%	0.0%	0
More than 80%	16.7%	1
My design is not even close to what we released in FDJ	0.0%	0
	answered question	6
	skipped question	2



What actions do you think we could have implemented in the EDS Design and Development process for U22X Program to reduce iteration loops and avoid the need of reworks during later phases of the design?	
Answer Options	**Response Count**
	6
answered question	6
skipped question	2

Number	Response Date	Response Text
1	jul 11, 2014 9:30 p.m.	To add more people since the begining of the program for all areas and reviwe it during it to remove once it is getting better considering changes may become as use to happen and pushing to have supplier doing the same to allow complete all proceeses and reviews on time before start building.
2	jul 11, 2014 3:46 p.m.	BINGO REVIEWS!!!!!
3	jul 11, 2014 2:48 p.m.	review complexity against PDL and have al full complexity update to create prints
4	jul 11, 2014 3:54 a.m.	AS
5	jul 10, 2014 5:04 p.m.	Better communication and documentation of issues. More team work and less pointing fingers. It is more effective to realize a problem and fix it than it is to figure who is at fault before addressing the solution. Also, team members cannot be afraid to admit that a mistake was made on their behalf. It is also important to push back on the changes when it is clear that it will affect the timing and quality of the product and could ultimately affect the flow of the build.
6	jul 10, 2014 3:55 p.m.	More time between milestones Change TDR process to a go no go decision Assign more experience engineers to the program Train properly the Supervisor in charge

Appendix C – System Dynamics Model equations

Total Project Finish Switch = Downstream Finish*(1-Project Finished Switch)

Units: Dimensionless

Costed OT before build starts = Cost Rate Before Build*Fraction of Effort to Design*Planned Staff*(1+IF THEN ELSE (Overtime<=Trigger for Double Time, (Overtime-1)*1.5, (Trigger for Double Time-1)*1.5+Max (0,(Overtime-Trigger for Double Time))*2))*(1-Switch to Start Build)

Units: $/Week

Actual Cumulative THD Design Effort= INTEG (Downstream Effort,0)

Units: Person*Weeks

Downstream Effort = Effective Staff Allocated to Top Hat Design*(1-Downstream Finish)

Units: People

Current Costed Effort = Cost Rate*Planned Staff*Fraction of Effort to Design*(1+IF THEN ELSE(Overtime <= Trigger for Double Time, (Overtime-1)*1.5, Trigger for Double Time*1.5+Max(0,(Overtime-Trigger for Double Time))*2))

Units: $/Week

Costed OT after build starts = (Cost Rate after Build*Planned Staff*Fraction of Effort to Design*(1+IF THEN ELSE (Overtime<=Trigger for Double Time, (Overtime-1)*1.5, (Trigger for Double Time-1)*1.5+Max (0, (Overtime-Trigger for Double Time))*2))*Switch to Start Build)*Project Finished Switch

Units: $/Week

Cost Rate after Build = 1625

Units: $/(Week*Person)

Breakdown: Hotel --> 400

Rental Car --> 350

Per diem --> 275

OT --> 600

Cumulative cost after build starts = INTEG (Costed OT after build starts,0)

Units: $

Cumulative Cost before Build = INTEG (Costed OT before build starts,0)

Units: $

Total OT Cost = Cumulative cost after build starts+Cumulative Cost before Build

Units: $

Cost Rate Before Build = 600

Units: $/(Week*Person)

Effect of Work Intensity on Top Hat Progress = 1+(Work Intensity-1)*(1-Sensitivity for Effect of Intensity on Rework)

Units: Dimensionless

Priority to Platform Design = 1

Units: Dimensionless

Cost Rate = 1

Units: $/Week/Person

Productivity Before OOS and Intensity Effects = Productivity Before OOS Effects/Effect of Intensity on Productivity

Units: Task/(Week*Person)

Cumulative Costed Effort = INTEG (Current Costed Effort,0)

Units: $

Fraction of Effort to Design = MIN (1,Priority to Platform Design*Indicated Staff/Max(1e-005,Priority to Platform Design*Indicated Staff+Top Hat People Needed))

Units: Fraction

Effect of Fatigue on Top Hat Progress = Real Effect of Fatigue on productivity*Effect of Fatigue on Fraction Correct

Units: Dimensionless

Overtime = MIN (Maximum Overtime, 1 + Willingness to Use Overtime * Table for Overtime (Work Schedule Pressure))

Units: Dimensionless

Perceived Productivity Before OOS Effects = SMOOTHI (Productivity Before OOS and Intensity Effects, Time to Perceive Productivity, Normal Productivity)

Units: Task/(Week*Person)

Total Staff Needed = Indicated Staff+Top Hat People Needed

Units: People

Trigger for Double Time = 1.25

Units: Dimensionless

Work Schedule Pressure = Total Staff Needed/Planned Staff

Units: Fraction

Effective Downstream Effort = Effective Staff Allocated to Top Hat Design*Effect of Fatigue on Top Hat Progress*Effect of Work Intensity on Top Hat Progress*(1-Downstream Finish)

Units: People

Table for Overtime ([(0,0)-(3,2)],(0,0),(1,0),(1,0),(1.1,0.1),(1.2,0.2),(1.3,0.275),(1.4,0.35),(1.5,0.4),(1.6,0.45),(1.7,0.475),(1.8,0.49),(1.9,0.5),(2,0.5),(3,0.5))

Units: Dimensionless

Linear Table [(0,0)-(3,2)],(0,0),(1,0),(1,0),(1.1,0.1),(1.2,0.2),(1.3,0.3),(1.4,0.4),(1.5,0.5),(1.6,0.6),(1.7,0.7),(1.8,0.8),(1.9,0.9),(2,1),(3,2)[(0,0)-(3,2)],(0,0),(1,0),(1,0),(1.1,0.1),(1.2,0.2),(1.3,0.275),(1.4,0.35),(1.5,0.4),(1.6,0.45),(1.7,0.475),(1.8,0.49),(1.9,0.5),(2,0.5),(3,0.5)

Multiplier on Design Errors Leading to Build Rework = 0

Units: Fraction

Maximum Technical Work Rate on Original Work at Original Sequence = Max(0,Total OW Tasks That Could Be Worked On at Original Sequence-Original Work Completed)/Average Time to Accomplish an Original Work Task

Units: Tasks/Week

Build Rework Discovery Fraction = Design Rework Discovery Fraction*Multiplier on Design Errors Leading to Build Rework

Units: Fraction/Week

Original Work Completed = Total Scope-Original Work to Do

Units: Tasks

Fraction of Tasks Available to Work On Given Design Progress = Table for Fraction of Tasks Available to Work On Given Design Progress (Fraction Reported Complete)

Units: Fraction

Build Rework Discovery = Build Work Done*Build Rework Discovery Fraction

Units: Tasks/Week

Design Rework Discovery Fraction = Design Rework Discovery/Max(1e-005,Work Believed Done Correctly)

Units: Fraction/Week

Total OW Tasks That Could Be Worked On at Original Sequence = Total Scope*Fraction of Tasks Available to Work on Given Progress on Original Work

Units: Tasks

Fraction of Tasks Available to Work on Given Progress on Original Work = MIN(1,(Table for Fraction of Tasks to Work on City Car(Fraction of Original Work Complete)))

Units: Fraction

Build Work to Do = INTEG (Build Rework Discovery-Build Work Being Accomplished,Initial Build Work to Do)

Units: Tasks

Build Work Done = INTEG (Build Work Being Accomplished-Build Rework Discovery,0)

Units: Tasks

Estimated Fraction to Technical Factors = Estimated Effect of Technical Factors/Total Estimated Effect

Units: Fraction

Total Rework Due to People Factors = INTEG (Rework Due to People Factors,0)

Units: Tasks

Rework Due to People Factors = Rework Being Generated*Estimated Fraction to People Factors

Units: Tasks/Week

Rework Due to Tech Factors = Rework Being Generated*Estimated Fraction to Technical Factors

Units: Tasks/Week

Estimated Effect of People Factors = ((1-Normal Fraction of Work Correct)*(1-Split of Normal to Technical Factors))+(1-Effect of People Factors on FWC)

Units: Dimensionless

Estimated Effect of Technical Factors = ((1-Normal Fraction of Work Correct)*Split of Normal to Technical Factors)+(1-Effect of Technical Factors on FWC)

Units: Dimensionless

Estimated Fraction to People Factors = 1-Estimated Fraction to Technical Factors

Units: Fraction

Total Rework Due to Technical Factors = INTEG (Rework Due to Tech Factors,0)

Units: Tasks

Estimated Fraction Total Rework Due to People Factors = Total Rework Due to People Factors/Max(1e-005,Total Rework Generated)

Units: Fraction

Estimated Fraction Total Rework Due to Technical Factors = Total Rework Due to Technical Factors/Max(1e-005,Total Rework Generated)

Units: Fraction

Split of Normal to Technical Factors = 0.5

Units: Fraction

Effect of Technical Factors on FWC = Effect of Rework on Fraction Correct*Effect of Undiscovered Rework on Fraction Correct*Effect on Fraction Correct of OOS Work

Units: Dimensionless

Total Estimated Effect = Estimated Effect of Technical Factors+Estimated Effect of People Factors

Units: Dimensionless

Total Rework Generation Check = Total Rework Due to People Factors+Total Rework Due to Technical Factors

Units: Tasks

Effect of People Factors on FWC = Effect of Fatigue on Fraction Correct*Effect of Intensity on Fraction Correct

Units: Dimensionless

Cumulative PD Effort = "Cumulative Effort Pre-Build"+Cumulative effort after Build start

Units: Tasks

Pre Build effort = (Original Work Done Correctly+Rework Generation on Original Work+Rework Done Correctly)*(1-Switch to Start Build)

Units: Task/Week

Build effort = (Rework Done Correctly+Rework Generation on Rework+Rework Generation on Original Work)*Switch to Start Build

Units: Task/Week

Indicated Work Intensity = Max (1,Indicated Staff/Max(1e-005,Effective Staff Allocated to Design))

Units: Dimensionless

Effective Staff = Planned Staff*Overtime

Units: People

Effective Staff Allocated to Design = Effective Staff*Fraction of Effort to Design

Units: People

Effective Staff Allocated to Top Hat Design = Effective Staff-Effective Staff Allocated to Design

Units: People

Staff = Effective Staff Allocated to Design*Project Finished Switch * (1-Switch to Use Indicated Staff) + Switch to Use Indicated Staff*MIN (Indicated Staff, Maximum Staff)*Project Finished Switch

Units: People

Minimum Time To Finish = 1

Units: Weeks

Top Hat Design0 Planned Effort = 183

Units: Weeks*Person

Scheduled Finish of Top Hat 0 = 28

Units: Week

"Top Hat Design 1 & 2 Planned Effort" = 346

Units: Weeks*Person

Top Hat Effort Needed = (Top Hat Design0 Planned Effort+"Switch to Top Hat 1 & 2"*"Top Hat Design 1 & 2 Planned Effort")-Cumulative THD Design Effort

Units: Weeks*Person

Cumulative Effort Needed to Finish = Top Hat Design0 Planned Effort+"Top Hat Design 1 & 2 Planned Effort"

Units: Person*Weeks

"Switch to Top Hat 1 & 2"= IF THEN ELSE (Time>=Scheduled Finish of Top Hat 0, 1, 0)

Units: Dimensionless

Top Hat People Needed = Max (0,(Top Hat Effort Needed)/(Time Remaining on Top Hat 0*(1-"Switch to Top Hat 1 & 2")+"Switch to Top Hat 1 & 2"*Time Remaining))

Units: People

Time Remaining = Max (Minimum Time To Finish, Scheduled Completion Date-Time)

Units: Weeks

Time Remaining on Top Hat 0 = Max (Minimum Time To Finish, Scheduled Finish of Top Hat 0-Time)

Units: Weeks

Planned Staff = (Normal Planned Staff+Extra Staff After Build Start*Switch to Start Build)*(1-Switch for Endogenous Staff)+Switch for Endogenous Staff*Staff Needed to Meet Schedule

Units: People

Time for Fatigue to Effect Work = 16

Units: Weeks

Time for Pressure to Effect Fraction Correct = 16

Units: Weeks

Buffer for Finishing Rework = 5

Units: Weeks

Real Effect of Fatigue on productivity = WITH LOOKUP (Lagged Extra Hours for Productivity,

([(1,0)-(3,1)],(1,1),(1.1,0.91),(1.2,0.833),(1.3,0.77),(1.4,0.715),(1.5,0.67),(1.6,0.625),(1.7,0.59),(1.8,0.555),(1.9,0.525),(2,0.5),(2.1,0.475),(2.2,0.455),(2.3,0.435),(2.4,0.417),(2.5,0.4),(2.6,0.385),(2.7,0.37),(2.8,0.355),(2.9,0.345),(3,0.333)))

Units: Dimensionless

Extra Staff After Build Start = 4

Units: People

Productivity Before OOS Effects = Normal Productivity*Effect of Rework on Productivity*Effect of Undiscovered Rework on Productivity*Real Effect of Fatigue on productivity*Effect of Intensity on Productivity

Units: Task/(Week*Person)

Time Remaining to Finish Rework = Max (1, Time Remaining-Buffer for Finishing Rework)

Units: Weeks

Build Staff = Switch to Start Build*Normal Build Staff*(1-Build Finished Switch)

Units: People

Phase in of Minimum at Project End = WITH LOOKUP (Fraction Really Complete,

([(0,0)-
(1,1)],(0,0),(0.7,0),(0.75,0),(0.8,0),(0.85,0),(0.9,0),(0.95,0),(0.96,0),(0.97,0),(0.99,0.85),(0.995,0.9),(1,1)))

Units: Dimensionless

Fraction of Original Work Believed Complete Adjusted For Change Impacts = (Work Believed Done Correctly*(1-Switch for Changes*Fraction of Design Already Complete Impacted by Changes))/Total Scope

Units: Fraction

Lagged Extra Hours for Productivity = SMOOTH3I (Overtime, Time for Fatigue to Effect Work , 1)*Sensitivity for Effect of Extra Hours on Productivity+(1-Sensitivity for Effect of Extra Hours on Productivity)

Units: Dimensionless

Lagged Intensity for productivity = SMOOTH3I (Work Intensity, Time for Pressure to Effect productivity , 1)*Sensitivity for effect of Intensity Hours on Productivity+(1-Sensitivity for effect of Intensity Hours on Productivity)

Units: Dimensionless

Downstream Finish = IF THEN ELSE (Cumulative THD Design Effort>=Cumulative Effort Needed to Finish, 1, 0)

Units: Dimensionless

Time for Pressure to Effect productivity = 8

Units: Weeks

Effect of Progress on Time to Accomplish Rework = WITH LOOKUP (Fraction Reported Complete,

([(0,0)-
(1,1)],(0,0),(0.9,0),(0.91,0.1),(0.92,0.25),(0.93,0.5),(0.94,0.75),(0.95,0.9),(0.96,1),(0.97,1),(0.98,1),(0.99,1)
,(1,1)))

Units: Dimensionless

Fraction of Work Correct = Normal Fraction of Work Correct*Effect of Rework on Fraction Correct*Effect of Undiscovered Rework on Fraction Correct*Effect of Fatigue on Fraction Correct*Effect of Intensity on Fraction Correct*Effect of Late Stage Work on Normal Fraction Correct*(Effect on Fraction Correct of OOS Work*Switch to Include OOS Effects+1-Switch to Include OOS Effects)

Units: Fraction

Cumulative THD Design Effort = INTEG (Effective Downstream Effort,0)

Units: Person*Weeks

Effect of Fatigue on Fraction Correct = MIN (1,(1+(Lagged Extra Hours for Fraction Correct-1)*(1-Sensitivity for Effect of Extra Hours on Rework))/Lagged Extra Hours for Fraction Correct)

Units: Dimensionless

Maximum Overtime = 1.5

Units: Dimensionless

Sensitivity for Effect of Intensity on Rework = 0.4

Units: Dimensionless

Sensitivity for Effect of Extra Hours on Rework = 0.4

Units: Dimensionless

Sensitivity for effect of Intensity Hours on Productivity = 0.5

Units: Dimensionless

Maximum Effect of Rework on Productivity ([(0,0)-(1,1)],(0,1),(0.1,0.9),(0.2,0.8),(0.3,0.7),(0.4,0.6),(0.5,0.5),(0.6,0.4),(0.7,0.3),(0.8,0.2),(0.9,0.1),(1,0.05))

Units: Dimensionless

Effect of Intensity on Fraction Correct = MIN (1,(1+(Work Intensity-1)*(1-Sensitivity for Effect of Intensity on Rework))/Work Intensity)

Units: Dimensionless

Time to Finish a Rework Task = Average Time to Accomplish a Rework Task*(1-Effect of Progress on Time to Accomplish Rework)+Effect of Progress on Time to Accomplish Rework*Time Remaining to Finish Rework

Units: Weeks

Effect of Intensity on Productivity = Work Intensity

Units: Dimensionless

Willingness to Use Work Intensity = 1

Units: Dimensionless

Productivity = Productivity Before OOS Effects*(Switch to Include OOS Effects*Effect on Productivity of OOS Work+1-Switch to Include OOS Effects)

Units: Task / (Person * Week)

Lagged Extra Hours for Fraction Correct = SMOOTH3I (Overtime,Time for Fatigue to Effect Work,1)

Units: Dimensionless

Sensitivity for Effect of Extra Hours on Productivity = 0.3

Units: Dimensionless

Work Intensity = Max (1,(1+(Indicated Work Intensity-1)*Willingness to Use Work Intensity))

Units: Dimensionless

Willingness to Use Overtime = 1

Units: Dimensionless

Normal Work intensity Extra Hours Ratio = 1

Units: Dimensionless

Priority to Rework = IF THEN ELSE (Switch to Start Build>=1, 1 , "Pre-build Priority to Rework")

Units: Dimensionless

"Pre-build Priority to Rework"= 1

Units: Dimensionless

Fraction of Staff on Rework = Max (0,MIN (1,Maximum Work Rate Based on Rework Tasks Available*Relative Effort Required for Rework*Priority to Rework/Max(1e-005,(Maximum Work Rate Based on Rework Tasks Available*Relative Effort Required for Rework*Priority to Rework+Maximum Work Rate Based on Original Work Available))))

Units: Fraction

Cumulative effort after Build start = INTEG (Build effort,0)

Units: Task

Build Start = IF THEN ELSE(Time Remaining <= Trigger to Start Build, 1/TIME STEP, 0)* IF THEN ELSE (Switch to Start Build >= 1, 0, 1)

Units: Dimensionless/Week

"Cumulative Effort Pre-Build" = INTEG (Pre Build effort, 0)

Units: Tasks

Design Undiscovered Rework Discoverable by Build = INTEG (Design Rework Generation To Be Discovered by Build-Design Rework Discovered By Build, 0)

Units: Tasks

Build Finished Switch = IF THEN ELSE (Build Work Done >= Fraction Complete to Finish Project*Initial Build Work to Do, 1, 0)

Units: Dimensionless

Design Rework Generation To Be Discovered by Build = Design Rework Generation*Normal Fraction of Design Rework Discovered by Build Work

Units: Tasks/Week

Design Rework Generation To Be Discovered by Design = Design Rework Generation*Normal Fraction of Design Rework Discovered by Design Work

Units: Tasks/Week

Surplus Design Staff = Planned Staff-Staff

Units: People

Design Undiscovered Rework Discoverable by Design = INTEG (Design Rework Generation To Be Discovered by Design-Design Remaining Rework Discovered by Build-Design Rework Discovered By Design,0)

Units: Tasks

Dedicated Build Staff = 10

Units: People

Maximum Technical Build Work Rate = Max (0,New Build Work Tasks Available to Work On/Build Minimum Time to Complete a Task)

Units: Tasks/Week

Effective Design Rework Discovery Time =MIN (40, Design Time to Discover Rework/Max(1e-005,Fraction Design Rework Discovered))

Units: Weeks

Design Rework Discovered By Build = Design Undiscovered Rework Discoverable by Build*Fraction of Design Rework Discovered by Build Work/Design Time to Discover Rework

Units: Tasks/Week

Build Fraction Complete = Build Work Done/Initial Build Work to Do

Units: Fraction

Build Minimum Time to Complete a Task = 0.25

Units: Weeks

Build Productivity = 1

Units: Task/(Week*Person)

Build Work Being Accomplished = MIN (Build Work Rate Based on Staff, Build Work Rate Based on Tasks Available)

Units: Tasks/Week

Build Work Rate Based on Staff = Build Staff*Build Productivity

Units: Tasks/Week

Build Work Rate Based on Tasks Available = MIN (Maximum Technical Build Work Rate, Build Work to Do/Build Minimum Time to Complete a Task)

Units: Tasks/Week

Normal Fraction of Design Rework Discovered by Build Work = 0.2

Units: Fraction

Check Design Undiscovered Rework = Undiscovered Rework-Design Undiscovered Rework by Type

Units: Tasks

Effect of Design Progress on Design Rework Discovery = WITH LOOKUP (Fraction of Original Work Complete,([(0,0)-(1,1)],(0,0),(0.1,0),(0.2,0),(0.2263,0),(0.3,0),(0.4,0),(0.5,0),(0.6,0),(0.7,0),(0.8,0),(0.91,0),(0.92,0),(0.93,0),(0.97,0.98),(0.98,0.99),(0.99,1),(1,1)))

Units: Dimensionless

Rework Discovery = Design Rework Discovery

Units: Tasks/Week

Switch to Start Build = INTEG (Build Start,0)

Units: Dimensionless

Fraction Rework Discovered By Build = Rework Discovered By Build/Max(1e-005,Total Rework Discovered)

Units: Fraction

Design Effect of Build Work on Rework Discovery = WITH LOOKUP (Build Fraction Complete,

([(0,0)-(1,1)],(0,0),(0.1,0),(0.2,0),(0.3,0.1),(0.4,0.25),(0.5,0.5),(0.6,0.75),(0.7,0.9),(0.8,1),(0.9,1),(1,1)))

Units: Dimensionless

Design Effect of Design Work on Rework Discovery = Effect of Design Progress on Design Rework Discovery*Effect of Work Rate on Rework Discovery*Fraction of Design Rework Discovered by Design Work

Units: Fraction

Fraction Rework Discovered by Design as Fraction of Max = MIN (1,Fraction Rework Discovered by Design/Normal Fraction of Design Rework Discovered by Design Work)

Units: Fraction

Design Remaining Rework Discovered by Build = Design Undiscovered Rework Discoverable by Design*Fraction of Design Rework Discovered by Build Work/Design Time to Discover Rework

Units: Tasks/Week

Design Rework Discovered By Design = Design Undiscovered Rework Discoverable by Design*Design Effect of Design Work on Rework Discovery/Design Time to Discover Rework

Units: Tasks/Week

Design Rework Discovery = Design Rework Discovered By Design+Design Rework Discovered By Build+Design Remaining Rework Discovered by Build

Units: Tasks/Week

Design Rework Generation = Rework Generation on Original Work+Rework Generation on Rework

Units: Tasks/Week

Undiscovered Rework = INTEG (Rework Generation on Original Work+Rework Generation on Rework-Rework Discovery, 0)

Units: Tasks

Trigger to Start Build = 16

Units: Week

Design Time to Discover Rework = 1

Units: Weeks

Design Undiscovered Rework by Type = Design Undiscovered Rework Discoverable by Design+Design Undiscovered Rework Discoverable by Build

Units: Tasks

Total Rework Discovered = Rework Discovered by Design+Rework Discovered By Build

Units: Tasks

Required Staff = Indicated Staff

Units: People

"Effect of Build/Test Work Rate on Design Rework Discovery" = WITH LOOKUP (Build Work Being Accomplished/Max(1e-005,Build Work Rate Based on Staff),([(0,0)-(1,1)],(0,0),(0.1,0.25),(0.2,0.5),(0.3,0.75),(0.4,0.9),(0.5,1),(0.6,1),(0.7,1),(0.8,1),(0.9,1),(1,1)))

Units: Dimensionless

Normal Fraction of Design Rework Discovered by Design Work = 0.8

Units: Fraction

Rework Discovered by Design = INTEG (Design Rework Discovered By Design, 0)

Units: Tasks

Fraction Design Rework Discovered = Design Effect of Design Work on Rework Discovery+Fraction of Design Rework Discovered by Build Work

Units: Fraction

Table for Fraction of Tasks Available to Work On Given Design Progress([(0,0)-(1,1)],(0,0),(0.75,0),(0.8,0.2),(0.85,0.4),(0.9,0.6),(0.95,0.8),(0.96,0.85),(0.97,0.9),(0.98,0.95),(0.99,0.99),(0.995,1),(1,1))

Units: Fraction

Fraction of Design Rework Discovered by Build Work = Design Effect of Build Work on Rework Discovery*"Effect of Build/Test Work Rate on Design Rework Discovery"

Units: Fraction

Fraction of Design Rework Discovered by Design Work = 0.2

Units: Fraction

Rework to Do = INTEG (Changes+Rework Discovery-Rework Done Correctly-Rework Generation on Rework, 0)

Units: Tasks

Effect of Work Rate on Rework Discovery = MIN (1,Staff/Max(0.0001,Required Staff))

Units: Fraction

New Build Work Tasks Available to Work On = Max (0,Total Build Tasks That Could Be Worked On- Build Work Done)

Units: Tasks

Initial Build Work to Do = 320

Units: Tasks

Total Build Tasks That Could Be Worked On = Initial Build Work to Do*Fraction of Tasks Available to Work On Given Design Progress

Units: Tasks

Normal Build Staff = 20

Units: People

Rework Discovered By Build = INTEG (Design Remaining Rework Discovered by Build+Design Rework Discovered By Build, 0)

Units: Tasks

Fraction Rework Discovered by Design = Rework Discovered by Design/Max(1e-005,Total Rework Discovered)

Units: Fraction

Indicated Staff = (Indicated Staff on Original Work+Indicated Staff on Rework)*Project Finished Switch

Units: People

Maximum Technical Work Rate On Original Work at Planned Sequence = Max (0,New Original Work Tasks Available to Work On/Average Time to Accomplish an Original Work Task)

Units: Tasks/Week

Fraction of Tasks Available to Work On Given Progress = MIN (1,(Table For Fraction of Tasks to Work On Given Progress Linear(Fraction of Original Work Believed Complete Adjusted For Change Impacts)+Linear Buffer of Tasks Available)*(1-Switch for City Car)+Switch for City Car*Table for Fraction of Tasks to Work on City Car (Fraction of Original Work Believed Complete Adjusted For Change Impacts))

Units: Fraction

New Original Work Tasks Available to Work On = Max (0,Total Original Work Tasks That Could Be Worked On-(Work Believed Done Correctly+Rework to Do))

Units: Tasks

Maximum Staff = 40

Units: People

Effect of Rework on Productivity = Maximum Effect of Rework on Productivity(Fraction of Staff on Rework)*Sensitivity of Productivity to Rework+(1-Sensitivity of Productivity to Rework)

Units: Dimensionless

Total Scope = INTEG (Increase in Total Scope, Initial Work to Do)

Units: Tasks

Time of Changes = 10

Units: Week

Original Work to Do = INTEG (Scope Growth-Original Work Done Correctly-Rework Generation on Original Work, Initial Work to Do)

Units: Task

Changes = STEP (Magnitude of Changes*Work Done/Duration of Changes, Time of Changes)-STEP (Magnitude of Changes*Work Done/Duration of Changes, Time of Changes+Duration of Changes)

Units: Tasks/Week

Cumulative Changes = INTEG (Changes, 0)

Units: Tasks

Cumulative Design Impacts = INTEG (Design Impacts, 0)

Units: Tasks*Weeks

Fraction of Original Work Complete = (Total Scope-Original Work to Do)/Total Scope

Units: Fraction

Project Finished Switch = INTEG (IF THEN ELSE(Work Believed Done Correctly>Fraction Complete to Finish Project*Total Scope,-1/TIME STEP,0)*IF THEN ELSE(Project Finished Switch = 0, 0, 1),1)

Units: Dimensionless

Design Impacts = Work Believed Done Correctly*Switch for Changes*Fraction of Design Already Complete Impacted by Changes

Units: Tasks

Duration of Changes = 5

Units: Weeks

Duration of Scope Growth = 5

Units: Weeks

Scope Growth = STEP (Magnitude of Scope Growth*Initial Work to Do/Duration of Scope Growth, Time of Scope Growth)-STEP (Magnitude of Scope Growth*Initial Work to Do/Duration of Scope Growth, Time of Scope Growth+Duration of Scope Growth)

Units: Tasks/Week

Increase in Total Scope = Scope Growth

Units: Tasks/Week

Fraction Really Complete = Work Done/Total Scope

Units: Fraction

Fraction Reported Complete = Work Believed Done Correctly/Total Scope

Units: Fraction

Magnitude of Changes = 0

Units: Fraction

Time of Scope Growth = 10

Units: Week

Magnitude of Scope Growth = 0

Units: Fraction

Total Original Work Tasks That Could Be Worked On = Total Scope*Fraction of Tasks Available to Work On Given Progress

Units: Tasks

Work Done = INTEG (Original Work Done Correctly+Rework Done Correctly-Changes, 0)

Units: Task

Fraction Complete to Start Increase in Normal Fraction Correct = 0.9

Units: Fraction

Effect of Late Stage Work on Normal Fraction Correct = IF THEN ELSE(Fraction Really Complete > Fraction Complete to Start Increase in Normal Fraction Correct, 1 +((1-Normal Fraction of Work Correct)/Normal Fraction of Work Correct)*(Fraction Really Complete-Fraction Complete to Start Increase in Normal Fraction Correct)/(1-Fraction Complete to Start Increase in Normal Fraction Correct), 1)

Units: Dimensionless

Perceived Productivity on Rework = SMOOTHI (Productivity on Rework, Time to Perceive Productivity, Normal Productivity)

Units: Task/(Week*Person)

Phase out of Sensitivity at End of Project = WITH LOOKUP (Fraction Really Complete,

([(0,0)-(1,1)],(0,1),(0.9,1),(0.925,0.9),(0.95,0.5),(0.975,0.1),(0.99,0),(1,0)))

Units: Dimensionless

Indicated Staff on Rework = Maximum Work Rate Based on Rework Tasks Available/Perceived Productivity on Rework

Units: People

Maximum Sensitivity of Fraction Correct to Undiscovered Rework = 0.95

Units: Dimensionless

Time to Perceive Productivity = 1

Units: Week

Maximum Sensitivity of Productivity to Undiscovered Rework = 0.4

Units: Dimensionless

Staff Needed to Meet Schedule = (Work Remaining/Time Remaining)/Perceived Productivity Before OOS Effects

Units: People

Sensitivity of Fraction Correct to Undiscovered Rework = Maximum Sensitivity of Fraction Correct to Undiscovered Rework*(1-Fraction of Rework Discovered)

Units: Dimensionless

Maximum Sensitivity of Productivity to Rework = 0.25

Units: Dimensionless

Sensitivity of Productivity to Rework = Maximum Sensitivity of Productivity to Rework*Phase out of Sensitivity at End of Project

Units: Dimensionless

Sensitivity of Productivity to Undiscovered Rework = Maximum Sensitivity of Productivity to Undiscovered Rework*Fraction of Rework Discovered

Units: Dimensionless

Indicated Staff on Original Work = Maximum Work Rate Based on Original Work Available/Perceived Productivity Before OOS Effects

Units: People

Minimum Time to Accomplish a Rework Task = 0.5

Units: Weeks

Staff on Rework = Staff*Fraction of Staff on Rework

Units: People

Maximum Work Rate Based on Rework Tasks Available = Rework to Do/Time to Finish a Rework Task

Units: Tasks/Week

Rework Being Accomplishmed = MIN (Staff on Rework*Productivity on Rework,Maximum Work Rate Based on Rework Tasks Available)

Units: Tasks/Week

"'Hardness' of Precedence Constraints" = Normal 'Hardness' of Precedence Constraint+Increase in 'Hardness' with Progress

Units: Dimensionless

Increase in 'Hardness' with Progress = Table for Increase in 'Hardness' with Progress(Fraction Reported Complete)*(1-Normal 'Hardness' of Precedence Constraint)*Switch to Increase 'Hardness'

Units: Dimensionless

Average Time to Accomplish an Original Work Task = 1

Units: Weeks

Productivity on Rework = Productivity Before OOS Effects/Relative Effort Required for Rework

Units: Task/(Week*Person)

Effect of Rework on Fraction Correct = Maximum Effect of Rework on Fraction Correct(Fraction Rework In Upstream Work Products)*Sensitivity of Fraction Correct to Rework+(1-Sensitivity of Fraction Correct to Rework)

Units: Dimensionless

Effect of Undiscovered Rework on Fraction Correct = Maximum Effect of Undiscovered Rework on Fraction Correct (1-Fraction Undiscovered Rework in Upstream Work Products)*Sensitivity of Fraction Correct to Undiscovered Rework+(1-Sensitivity of Fraction Correct to Undiscovered Rework)

Units: Dimensionless

Effect of Undiscovered Rework on Productivity = Maximum Effect of Undiscovered Rework on Productivity (1-Fraction Undiscovered Rework in Upstream Work Products)*Sensitivity of Productivity to Undiscovered Rework+(1-Sensitivity of Productivity to Undiscovered Rework)

Units: Dimensionless

Maximum Effect of Undiscovered Rework on Fraction Correct ([(0,0)-(1,1)],(0,0.05),(0.1,0.1),(0.2,0.2),(0.3,0.3),(0.4,0.4),(0.5,0.5),(0.6,0.6),(0.7,0.7),(0.8,0.8),(0.9,0.9),(1,1))

Units: Dimensionless

Effect on Fraction Correct of OOS Work = Maximum Effect of OOS on Fraction Correct*Effect on Productivity of OOS Work+(1-Effect on Productivity of OOS Work)

Units: Dimensionless

Effect on Productivity of OOS Work = 1-Precedence Constraint Effect on Incremental Productivity

Units: Dimensionless

Table for Phase out of Precedence Effect ([(0,0)-(1,1)],(0,1),(0.9,1),(0.91,1),(0.92,1),(0.93,1),(0.94,1),(0.945,0.9),(0.95,0.75),(0.955,0.5),(0.96,0.25),(0.965, 0.1),(0.97,0),(0.975,0),(0.98,0),(0.985,0),(0.99,0),(0.995,0),(1,0))

Units: Dimensionless

Fraction of Design Already Complete Impacted by Changes = Table for Fraction of Design Impacted by Changes (Time)

Units: Dimensionless

Sensitivity of Fraction Correct to Precedence Effects = 0.25

Units: Dimensionless

"Fraction of Work Being Done Out-of-Sequence" = IF THEN ELSE(Indicated Work Rate on Original Work Based on Staff Available>0,Max(0,Phase Out of Precedence Effect*(Indicated Work Rate on Original Work Based on Staff Available-Maximum Technical Work Rate On Original Work at Planned Sequence)/Indicated Work Rate on Original Work Based on Staff Available),0)

Units: Fraction

Fraction of Work Done Correct and Complete = Max (1e-006,Work Done)/Max(1e-006,Work Believed Done or Awaiting Rework)

Units: Fraction

Switch for City Car = 1

Units: Dimensionless

Soft Precedence Constraint Effect on Incremental Productivity = Table for Soft Precedence Effect ("Fraction of Work Being Done Out-of-Sequence")*Sensitivity of Productivity to Precedence Effects

Units: Dimensionless

Fraction Rework and Undiscovered Rework in Upstream Work Products = Fraction Rework In Upstream Work Products+Fraction Undiscovered Rework in Upstream Work Products

Units: Fraction

Fraction Rework In Upstream Work Products = Rework to Do/Max(1e-006,Work Believed Done or Awaiting Rework)

Units: Fraction

Fraction Undiscovered Rework in Upstream Work Products = Undiscovered Rework/Max(1e-006,Work Believed Done or Awaiting Rework)

Units: Fraction

Hard Precedence Constraint Effect on Incremental Productivity = IF THEN ELSE(Project Finished Switch = 0, 1, MIN(1,"Fraction of Work Being Done Out-of-Sequence"))

Units: Dimensionless

Switch for Changes = 0

Units: Dimensionless

Maximum Effect of OOS on Fraction Correct = Table for Effect of OOS on Fraction Correct("Fraction of Work Being Done Out-of-Sequence")*Sensitivity of Fraction Correct to Precedence Effects+(1-Sensitivity of Fraction Correct to Precedence Effects)

Units: Dimensionless

Maximum Effect of Rework on Fraction Correct ([(0,0.4)-(0.5,1)],(0,1),(0.05,0.95),(0.1,0.9),(0.15,0.85),(0.2,0.8),(0.25,0.75),(0.3,0.7),(0.35,0.65),(0.4,0.6),(0.45,0.55),(0.5,0.5))

Units: Dimensionless

Indicated Work Rate on Original Work Based on Staff Available = Staff on Original Work*Productivity Before OOS Effects

Units: Tasks/Week

Linear Buffer of Tasks Available = 0.04

Units: Fraction

Table for Soft Precedence Effect ([(0,0)-(1,1)],(0,0),(0.05,0.025),(0.1,0.05),(0.15,0.075),(0.2,0.1),(0.25,0.125),(0.3,0.15),(0.35,0.175),(0.4,0.2),(0.45,0.225),(0.5,0.25),(0.6,0.325),(0.7,0.45),(0.8,0.625),(0.9,0.8),(1,1))

Units: Dimensionless

Maximum Technical Work Rate Based on Task Sequence = Maximum Technical Work Rate On Original Work at Planned Sequence*(1-Weight on Unadjusted Sequence)+Maximum Technical Work Rate on Original Work at Original Sequence*Weight on Unadjusted Sequence

Units: Tasks/Week

Table for Fraction of Tasks to Work on City Car ([(0,0)-(1,1)],(0,0.028),(0.028,0.052),(0.052,0.075),(0.075,0.099),(0.099,0.122),(0.122,0.144),(0.144,0.174),(0.174,0.196),(0.196,0.201),(0.201,0.218),(0.218,0.255),(0.255,0.285),(0.285,0.315),(0.315,0.342),(0.342,0.364),(0.364,0.385),(0.385,0.41),(0.41,0.429),(0.429,0.439),(0.439,0.445),(0.445,0.471),(0.471,0.498),(0.498,0.53),(0.53,0.562),(0.562,0.588),(0.588,0.611),(0.611,0.631),(0.631,0.652),(0.652,0.672),(0.672,0.683),(0.

683,0.694),(0.694,0.704),(0.704,0.714),(0.714,0.733),(0.733,0.772),(0.772,0.803),(0.803,0.826),(0.826,0.848),(0.848,0.874),(0.874,0.904),(0.904,0.933),(0.933,0.951),(0.951,0.98),(0.98,1),(1,1))

Units: Fraction

Maximum Effect of Undiscovered Rework on Productivity ([(0,0)-(1,1)],(0,0.05),(0.1,0.1),(0.2,0.2),(0.3,0.3),(0.4,0.4),(0.5,0.5),(0.6,0.6),(0.7,0.7),(0.8,0.8),(0.9,0.9),(1,1))

Units: Dimensionless

Maximum Work Rate Based on Original Work Available = Maximum Technical Work Rate Based on Task Sequence

Units: Tasks/Week

Phase Out of Precedence Effect = Table for Phase out of Precedence Effect(Fraction of Original Work Complete)*Switch for Phase Out of Precedence Effect+(1-Switch for Phase Out of Precedence Effect)

Units: Dimensionless

Weight on Unadjusted Sequence = 1

Units: Fraction

Normal Productivity = 1

Units: Task/(Week*Person)

Table for Effect of OOS on Fraction Correct ([(0,0)-(1,1)],(0,1),(0.05,0.95),(0.1,0.9),(0.15,0.85),(0.2,0.8),(0.25,0.75),(0.3,0.7),(0.35,0.65),(0.4,0.6),(0.45,0.55),(0.5,0.5),(0.9,0.1),(1,0.05))

Units: Dimensionless

Normal 'Hardness' of Precedence Constraint = 0

Units: Dimensionless

Normal Fraction of Work Correct = 0.95

Units: Fraction

Switch to Increase 'Hardness' = 0

Units: Dimensionless

Precedence Constraint Effect on Incremental Productivity = "'Hardness' of Precedence Constraints"*Hard Precedence Constraint Effect on Incremental Productivity +(1-"'Hardness' of Precedence Constraints")*Soft Precedence Constraint Effect on Incremental Productivity

Units: Dimensionless

Work Believed Done or Awaiting Rework = Work Believed Done Correctly+Rework to Do

Units: Tasks

Switch for Phase Out of Precedence Effect = 1

Units: Dimensionless

Table for Increase in 'Hardness' with Progress ([(0,0)-(1,1)],(0,0),(0.4,0),(0.5,0.1),(0.6,0.3),(0.7,0.5),(0.8,0.7),(0.9,0.9),(1,1))

Units: Dimensionless

Sensitivity of Fraction Correct to Rework = 0.5

Units: Dimensionless

Table for Fraction of Design Impacted by Changes ([(0,0)-(100,0.3)],(0,0),(1,0),(2,0.025),(3,0.05),(4,0.1),(5,0.15),(6,0.225),(7,0.25),(8,0.25),(9,0.225),(10,0.15),(11,0.1),(12,0.05),(13,0.025),(14,0),(15,0),(100,0))

Units: Fraction

Switch to Include OOS Effects = 1

Units: Dimensionless

Sensitivity of Productivity to Precedence Effects = 1

Units: Dimensionless

Table For Fraction of Tasks to Work On Given Progress Linear ([(0,0)-(1,1)],(0,0),(0.1,0.1),(0.2,0.2),(0.3,0.3),(0.4,0.4),(0.5,0.5),(0.6,0.6),(0.7,0.7),(0.8,0.8),(0.9,0.9),(1,1))

Units: Fraction

Switch to Use Indicated Staff = 0

Units: Dimensionless

Average Time to Accomplish a Rework Task = 0.5

Units: Weeks

Normal Planned Staff = 16

Units: People

Scheduled Completion Date = 60

Units: Week

Switch for Endogenous Staff = 0

Units: Dimensionless

Work Remaining = Original Work to Do+Relative Effort Required for Rework*Rework to Do

Units: Tasks

Staff on Original Work = Staff-Staff on Rework

Units: People

Original Work Being Accomplishmed = MIN (Staff on Original Work*Productivity,Maximum Work Rate Based on Original Work Tasks Available)

Units: Tasks/Week

Work Backlog Check = Undiscovered Rework+Work Done+Work to Do

Units: Tasks

Fraction Complete to Finish Project = 0.995

Units: Fraction

Fraction of Rework Discovered = WITH LOOKUP (Fraction of Original Work Complete,

([(0,0)-(1,1)],(0,0.03),(0.1,0.03),(0.2,0.035),(0.3,0.04),(0.4,0.045),(0.5,0.055),(0.6,0.075),(0.7,0.125),(0.8,0.2),(0.9,0.4),(1,1)))

Units: Fraction

Cumulative Effort = INTEG (Current Effort, 0)

Units: Person*Weeks

Current Effort = Staff

Units: People

Work to Do = Original Work to Do+Rework to Do

Units: Tasks

Original Work Done Correctly = Fraction of Work Correct*Original Work Being Accomplished

Units: Task / Week

Rework Done = Rework Done Correctly+Rework Generation on Rework

Units: Tasks/Week

Tasks Being Done = Rework Generation on Original Work+Original Work Done Correctly+Rework Generation on Rework+Rework Done Correctly

Units: Tasks/Week

Rework Done Correctly = Fraction of Work Correct*Rework Being Accomplished

Units: Tasks/Week

Total Rework Generated = INTEG (Rework Being Generated, 0)

Units: Tasks

Rework Being Generated = Rework Generation on Original Work+Rework Generation on Rework

Units: Tasks/Week

Rework Generation on Rework = (1-Fraction of Work Correct)*Rework Being Accomplished

Units: Tasks/Week

Relative Effort Required for Rework = 0.5

Units: Fraction

Total Rework Done = INTEG (Rework Done, 0)

Units: Tasks

Rate of Work Being Accomplished = Original Work Being Accomplished+Rework Being Accomplished

Units: Tasks/Week

Minimum Time to Finish an Original Work Task = 0.25

Units: Week

Maximum Work Rate Based on Original Work Tasks Available = Original Work to Do/Minimum Time to Finish an Original Work Task

Units: Tasks/Week

Rework Generation on Original Work = (1-Fraction of Work Correct)*Original Work Being Accomplished

Units: Task / Week

Initial Work to Do = 663

Units: Tasks

Work Believed Done Correctly = Undiscovered Rework+Work Done

Units: Tasks

Cumulative Tasks Done = INTEG (Tasks Being Done,0)

Units: Tasks

FINAL TIME = 100

Units: Week

INITIAL TIME = 0

Units: Week

SAVEPER = TIME STEP

Units: Week

TIME STEP = 0.0625

Units: Week