A Knowledge Management Framework to Support the Automotive Systems Engineering Lifecycle

TIMOTHY SAUNDERS

FACULTY OF ENGINEERING AND SCIENCE

A thesis submitted in partial fulfilment of the requirements of the University of Greenwich for the Degree of Doctor of Philosophy

February 2017

DECLARATION

I certify that the work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy degree being studied at the University of Greenwich.

I also declare that this work is the result of my own investigations, except where otherwise identified by references and that the contents are not the outcome of any form of research misconduct.

Student Name: Timothy Saunders

Signature: …………………………………………. **Date:** ………………………….

Supervisor Name: Professor James Xiaoyu Gao

Signature: …………………………………………. **Date:** ………………………….

ACKNOWLEDGEMENTS

I would like to personally thank Professor James Gao whom I first met when I approached him on the subject of starting a part-time PhD in September 2011. As I left his office on that day he gave me a single word that has resonated in my mind every day of the +5 years it has taken to complete this PhD thesis, “Determination”. I will be forever grateful to James for the sustained support and encouragement.

I would also like to thank Dr. Caroline Tite for her time and support as my second supervisor, and additional thanks also go to the other members of the CiPDM research group at the University of Greenwich.

I owe a debt of gratitude to all the many engineers within Ford Motor Company that supported me with the necessary essential insights and information that forms the central core to this research project.

I would also like to show my appreciation to the managers at Ford Motor Company that have supported me in this endeavour and afforded me the time away from the office when needed. Particular thanks are extended to my Chief Engineer Tim Howard who always provided wise counsel, and Dr. Nigel King who supported my initial PhD application to the University.

I thank Liessa for her patience and support over such a long period, during which she also encountered a significant personal battle. I am eternally grateful for everything.

Finally, thanks to my three children Josh, Sophie and Ben who unknowingly provided me with the mental courage to continue and finish. I hope that one day the mere existence of this PhD thesis will give each of you similar courage to strive and overcome the seemingly insurmountable.

ABSTRACT

In recent decades global automotive companies have evolved into extended enterprises of geographically dispersed teams that collaborate simultaneously on the development of new product technologies and vehicle platforms. Furthermore, robust systems engineering design and high quality manufacturing are highly reliant on the valuable knowledge and experience embedded within company ICT systems, processes, documents and employees.

However, current knowledge management strategies are not well suited to effectively capture all the new Systems Engineering (SE) knowledge generated during continuous innovation, and then make it widely accessible to support the complete vehicle product lifecycle. This is particularly the case when new reliability failures emerge during vehicle operational service but the investigating team of engineers have no pathway to reference the system engineering knowledge associated with the original product development program.

This thesis reports the findings of an industrial investigation exploring the current Knowledge Management (KM) practices in a large-scale multinational automotive company. Although a wide spectrum of knowledge management tools are already in use there is a clear disadvantage caused through critical knowledge residing in discrete isolated silo's rather than in a central well-structured support tool that is accessible to all members of the global extended enterprise.

A significant number of powertrain reliability failure investigation reports are examined to establish a meta-knowledge classification scheme which is then used to form the central construct for the proposed new Knowledge Management (KM) framework. The framework is particularly focused on reliability failures that occur on vehicles in operational service and providing a mechanism to integrate new systems engineering knowledge into future multigenerational vehicle PD programs.

Finally, a prototype collaborative ICT support tool and user navigation guide are developed as an implementation of the KM framework and the proposition is then evaluated with industrial practitioners to assess the likelihood of user adoption.

LIST OF PUBLICATIONS

Journal Publications

Saunders, T., Gao, J. and Shah, S. (2014), ‘A case study to evaluate lean product development practices in the global automotive industry’, Int. J. Product Development, Vol. 19, Nos. 5/6, pp.307–327, ISSN 1477-9056, DOI:10.1504/IJPD.2014.064882

Conference Proceedings

Saunders, T., Gao, J. and Evans, R. (2015). Supporting Global Automotive Product Development Projects through the Integration of Systems Engineering Knowledge. Proceedings of the 13th International Conference on Manufacturing Research (ICMR 2015). University of Bath, Bath, UK, 08-10 September 2015, pages 159 – 163

Zammit, J., Gao, J. and Evans, R., Saunders, T. (2015). An Investigation into the use of Social Media and Video Sharing Tools to Improve Knowledge Management and Collaboration within a Testing Product Development Environment. Proceedings of the 13th International Conference on Manufacturing Research (ICMR 2015). University of Bath, Bath, UK, 08-10 September 2015.

Saunders, T., Gao, J. and Shah, S. (2012). A Framework for Effective Supplier Integration in Global Automotive Product Development Projects. Proceedings of the 10th International Conference on Manufacturing Research (ICMR 2012). Aston University, Birmingham, UK, 11-13 September 2012: Advances in Manufacturing Technology XXVI, Volume 2, pages 742 – 746, ISBN 9781905866601

CONTENTS

FIGURES

TABLES

ABBREVIATIONS

ABS	Affordable Business Structure
AIM	Automated Issues Matrix
AFR	Annual File Review
APDM	Analytical Powertrain Data Manager
AVBOM	Advanced Vehicle Bill of Material
BDCL	Base Design Checklist
BOM	Bill of Material
BOP	Bill of Process
BPMN	Business Process Modelling Notation
BPNO	Base Part Number
BRIC	Brazil, Russia, India & China
BSAQ	Balanced Single Agenda for Quality
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAX	Computer Aided ‘x’ (covers Design and Engineering)
CCC	Customer Concern Code
CDA	Content Delivery Application
CETP	Corporate Engineering Test Procedure
CFE	Chief Functional Engineer
CM	Configuration Management
CMA	Content Management Application
CMS	Content Management System
CPE	Chief Program Engineer
CPSCII	Corporate Product Systems Classification (II)
CSS	Common System Structures
DEC	Dunton Engineering Centre
DFMEA	Design Failure Mode Effects Analysis
DMAIC-R	Define, Measure, Analyse, Improve, Control, Replicate
DPA	Digital Pre-Assembly
DTC	Diagnostic Trouble Codes
DURIS	DURability Information System
DVP&R	Design Verification Plan & Report

E2KS	Enterprise Engineering Knowledge System
ECAT	Electronic Catalogue
ECM	Enterprise Content Management
EDMS	Electronic Data Management System
EE	Extended Enterprise
EFDVS	Electronic Ford Design Verification System
EKMS	Enterprise Knowledge Management Systems (Enterprise 2.0)
ERP	Enterprise Resource Planning
ES	Engineering Specification
EoL	End of Line (Manufacturing)
ESOW	Engineering Specification of Work
ETIS	Electronic Technical Information Services
FACTS	Ford And Competitor Technology System
FDJ	Final Data Judgement
FEA	Finite Element Analysis
FMA	Failure Mode Analysis / Avoidance
FNA	Ford North America
FOE	Ford of Europe
FSMS	Ford Standards Management System
GPDS	Global Product Development System
GUI	Graphic User Interface
HTML	Hyper Text Mark-up Language
ICT	Information Communication Technology
IHL	Institutes of Higher Learning
IMP	Integrated Master Plan
IMS	Integrated Master Schedule
IMVP	International Motor Vehicle Programme
INCOSE	International Council on Systems Engineering
IPO	Input, Process, Output
ISO	International Standards Organisation
JV	Joint Venture
KM	Knowledge Management
KMS	Knowledge Management System
LFMA	Lean Failure Mode Avoidance

LPD	Lean Product Development
LWB	Long Wheel Base
MAV	Multi Activity Vehicle
MCP	Manufacturing (Quality) Control Plan
MME	Mechanical and Manufacturing Engineering
MNC	Multinational Corporation
MNE	Multi National Enterprise
MR	Management Review
MS	Micro Soft
MSA	Measurement System Analysis
NPD	New Product Development
NVH	Noise, Vibration and Harshness
OEM	Original Equipment Manufacturer
OL	Organizational Learning
OM	Organizational Memory
OPD	Ongoing Product Development
PA	Program Approval
PADB	Part Address Database
PAF	Part Address Function
PCCN	Powertrain Calibration, Controls and NVH
PD	Product Development
PDP	Product Development Process / Perfect Drawing Plan
PDL	Product Description Letter
PDM	Product Data Management
PEBOD	Powertrain Electronic Bill of Design
PEC	Preliminary Engineering Completion
PFMEA	Process Failure Mode Effects Analysis
PLC	Product Life Cycle
PLM	Product Lifecycle Management
PMT	Programme Module Team
PPAP	Production Part Approval Process
PSC	Program Strategy Confirmation
PSM	Product Structure Management
PTC	Program Target Compatibility

PTAI	Power Train As-Installed
PTGCEF	Powertrain Global Core Engineering Foundation_documents
QCWF	Quality, Cost, Weight & Function
R&D	Research and Development
RCL	Robustness Checklist
RDM	Robustness Demonstration Matrix
RFQ	Request for Quotation
RLD	Road Load Data
RLIS	Research Library Information Services
RQT	Requirement
RRCL	Robustness and Reliability Checklist
SBD	Symptom Based Diagnostic
SCCAF	Significant Characteristic Communication and Agreement
SDS	System Design Specification
SE	Systems Engineering
SECI	Socialise, Externalise, Combine, Internalise
SME	Small & Medium Enterprise
SREA	Supplier Request for Engineering Approval
SST	Social Software Tool
SUV	Sport Utility Vehicle
SWB	Short Wheelbase
TCE	Team Centre Engineering
TDE	Transmission & Driveline Engineering
TVM	Team Value Management
UN	Underbody
UP	Upperbody
URL	Uniform Resource Locator
USD	United States Dollars
VEV	Vehicle Engineering and Verification
VFG	Vehicle Function Group
VSA	Variation Simulation Analysis
WBS	Work Breakdown Structure
WCR	Worldwide Customer Requirements
WERS	Worldwide Engineering Release Systems

THIS PAGE INTENTIONALLY LEFT BLANK

GLOSSARY

Term	Definition
5 Why's Statements	The 5 Whys is a technique used in the Analyse phase of the Six Sigma DMAIC (Define, Measure, Analyse, Improve, Control) methodology. The primary goal of the technique is to determine the root cause of a defect or problem by repeatedly asking the question "Why?" after each answer.
Benchmarking (Customer / Vehicle)	Benchmarking is a way of discovering what is the best performance being achieved – whether in a particular company, by a competitor or by an entirely different industry. This information can then be used to identify gaps in an organization's processes in order to achieve a competitive advantage.
Boundary Diagram	A boundary diagram is a graphical illustration of the relationships between the subsystems, assemblies, subassemblies, and components within the object as well as the interfaces with the neighbouring systems and environments. It defines the intended outputs as Functions, System interactions, and may help in identifying cause(s) of failure.
CAE / FEA Design Capacity Modelling	Computer-aided engineering (CAE) is the broad usage of computer software to aid in engineering analysis tasks. It includes finite element analysis (FEA), computational fluid dynamics (CFD), multibody dynamics (MBD), and optimization. The term encompasses simulation, validation, and optimization of products and manufacturing tools.
Cause and Effect Analysis (Ishikawa / Fishbone diagram)	Ishikawa diagram, in fishbone shape, showing factors of Equipment, Process, People, Materials, Environment and Management, all affecting the overall problem. Smaller arrows connect the sub-causes to major causes.
CTQ Transfer Function Analysis Y=f(X)	CTQ factors are the key measurable characteristics of a product or process whose performance standards or specification limits must be met in order to satisfy the customer. They align improvement or design efforts with stakeholder/customer requirements.
Design of Experiment (DoE)	Design of experiments (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. DoE is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output.

DFMEA	A DFMEA documents the key functions of a design, the primary potential failure modes relative to each function and the potential causes of each failure mode. The DFMEA method allows the design team to document what they know and suspect about a product's failure modes prior to completing the design, and then use this information to design out or mitigate the causes of failure.
Diagnostic / Fault Codes (DTC / CCC)	Diagnostic trouble codes (or fault codes) are codes that are stored by the on-board computer diagnostic system. These codes are stored when a sensor in the car reports a reading that is outside the normal/accepted range and provide a guide as to where a fault might be occurring within a car.
Fault Tree Analysis	Fault tree analysis (FTA) is a top down, deductive failure analysis in which an undesired state of a system is analysed using Boolean logic to combine a series of lower-level events.
Function Tree	In the theory of complex systems, a function tree is a diagram showing the dependencies between the functions of a system. It breaks a problem (or its solution) down into simpler parts.
Interface Matrix	Identifies system interfaces and both the effects of interfaces to the focused system and the interfacing system details.
IS / IS-NOT	Is/Is Not Analysis is a method of objectively defining and documenting a problem. It captures known facts to fully define the observed symptoms prior to root cause analysis.
ISO/IEC 15288	Systems Engineering standard covering processes and life cycle stages. The standard defines processes divided into four categories: Technical, Project, Agreement, and Enterprise. Each process is defined by a purpose, outcomes, and activities. ISO 15288 life cycle stages described in the document are: concept, development, production, utilization, support, and retirement.
ISO/TS 16949	ISO technical specification aimed at the development of a quality management system that provides for continual improvement, emphasizing defect prevention and the reduction of variation and waste in the automotive industry supply chain.
ISO 26262	A risk-based safety standard, where the risk of hazardous operational situations is qualitatively assessed and safety measures are defined to avoid or control; systematic failures, random hardware failures, or to mitigate the effects.
Knowledge-based view of the firm	The knowledge-based theory of the firm considers knowledge as the most strategically significant resource of a firm. Its proponents argue that because knowledge-based resources are usually difficult to imitate and socially complex, heterogeneous

	knowledge bases and capabilities among firms are the major determinants of sustained competitive advantage and superior corporate performance.
Measurement system analysis (MSA)	Measurement system analysis (MSA) is an experimental and mathematical method to determine the contribution to the overall process variability.
NVH measurements	Noise, vibration, and harshness (NVH), also known as noise and vibration (N&V), is the study and modification of the noise and vibration characteristics of vehicles, particularly cars and trucks.
Pareto / Histogram of Failures	The purpose of the Pareto chart is to highlight the most important among a (typically large) set of factors. In quality control, it often represents the most common sources of defects, the highest occurring type of defect, or frequent customer complaints.
P-Diagram	P-Diagram - identifies and documents the input signal(s), noise factors, control factors, and error states as associated with the ideal function(s).
PFMEA	A Process Failure Mode Effects Analysis (PFMEA) is a structured analytical tool used by an organization, business unit, or cross-functional team to identify the potential failures of a process.
Powertrain	Automotive Powertrains include the major torque transmitting technologies such as the engine, transmission, drive shaft, transfer case, and front and rear axles. The powertrain group of technologies also includes the engine air intake system, engine and transmission mounts, exhaust, cooling, vehicle sensors, engine management control system software and calibration.
Reliability Hazard Plot	Statistical tool used to help predict the number of potential future failures within a population based on the known rate of failures already experienced.
Statistical Process Control (SPC)	Statistical process control (SPC) is a method of quality control which uses statistical methods. SPC is applied in order to monitor and control a process.
System State Flow Diagram	State diagrams are used to give an abstract description of the behaviour of a system. This behaviour is analysed and represented as events that can occur in all possible states.
Variation Simulation Analysis	Variation Analysis (VSA) is a powerful dimensional analysis tool used to simulate manufacturing and assembly processes and predict the amounts and causes of variation.

1 INTRODUCTION

This initial chapter presents a general overview of the global automotive industry, the drivers for innovation, and some of the key challenges that are faced. The purpose of the research is then outlined through the initial problem statement and the underlying research questions. Finally the research aim and objectives are presented.

1.1 The Global Automotive Industry

The automotive industry is one of the single largest industrial sectors in the global economy that has truly shaped the lives of people and businesses around the world. In 2016 global light vehicle sales totalled 93 million units, and sales are set to exceed 100 million units by 2018, supported by a global extended enterprise that accounts for +60 million jobs worldwide (***Euler-Hermes*** 2014).

In recent decades global automotive industry growth opportunities have primarily centred on emerging market expansion across Brazil, Russia, India, and China (BRIC), underpinning financial projections for global automotive annual profits to exceed $80 billion by 2020 (***McKinsey*** 2015). Conversely, the long-time established key markets in the USA and Europe have been characterized by cyclic economic volatility, increasing competition for stagnant industry volume, and production overcapacity. Consequently, these factors have strongly driven strategic downsizing, re-location of manufacturing operations to reduce labour costs and overheads, and the optimisation of supply chains to drive down material costs.

Globalisation has also witnessed the largest automotive manufacturers expand well beyond the confines of the parent firm's geographical borders and evolve into complex multinational extended enterprises. This approach has enabled companies to gain a richer understanding of the local market customers, combine with local manufacturing companies, and attract a local skilled workforce.

Automotive manufacturing firms must also continuously update the vehicles they offer in order to satisfy evolving customer requirements. Leveraging the global network of specialist design partners and manufacturing suppliers are key features of the automotive industry, and have long been a reported as a source of competitive advantage (***Clark and Fujimoto*** 1991, ***Cusumano and Takeshi*** 1991, ***Wasti and Liker*** 1999). The supply chain must therefore also be aligned with each major OEM's business plan strategy so that products are designed and delivered to meet target cost, reliability and quality targets, and time to market (***Monczka et al.*** 2000, ***Johnsen*** 2009, ***Pero et al.*** 2010).

However, once OEM's have established the infrastructure to integrate suppliers it then requires a continuous sustained commitment to manage the long term relationship with the supplier network (***Ragatz et al.*** 1997, ***Wynstra et al.*** 2001, ***Petersen et al.*** 2005). Furthermore, although OEM's interact most directly with the immediate tier 1 suppliers in the PD process, it is of paramount importance to manage the complete supply chain tier structure to guarantee quality and timeliness of delivery to order.

Co-location is also no longer considered a necessary prerequisite to the formation of PD project teams, which can instead be replaced by non-collocated 'virtual' teams that are globally dispersed (***Ahmad et al.*** 2005). This approach can leverage and exploit the cross functional knowledge and multidisciplinary skills capability embedded in the firm throughout the extended enterprise.

1.2 Innovation in the Automotive Industry

Continuous innovation is a complex dynamic socio-technical phenomenon involving thousands of interactions and decisions that rely on the exchange of knowledge between the interrelated structures of product, process and organisation (***Danilovic and Browning*** 2006). Furthermore, in order to build a strong automotive brand it is essential to design and manufacture vehicles that provide an exceptional driving experience, meet the highest levels of customer satisfaction, and provide value for money. Consequently, the automotive industry is driven by the need to constantly innovate at a fast pace in order to satisfy many competing objectives:

i) Development of new technologies such as powertrain hybridisation and electrification to improve fuel economy and meet legislative requirements for reduced exhaust tailpipe emissions.

ii) Regular evolution of interior and exterior layout and styling for all models within the portfolio of vehicle platforms to maintain a perception of dealer showroom freshness and brand evolution (***Murphy*** 2009).

iii) Introduction of new marketable feature content such as digital integration of smart devices, active driver safety sensor and camera systems, and active park-assist to attract new customer interest with the latest technical innovations (***McMurran*** 2014).

The long standing pattern of traditional car ownership and use are now also being disrupted by the emerging business models for *Mobility-as-a-Service* and *Personalised-Transport-Services*. Embedded within these are app-based ride-sharing companies such as Uber, Curb, Lyft, and Didi Chuxing, which are targeting viable ‘cost effective’ alternatives to personal car ownership. These new emerging business models are also aimed at combating traffic congestion and reducing air pollution in large mega-cities (***MaaS_Alliance*** 2015, ***Schaeffer et al.*** 2015). Additionally, the accelerated pace of development for autonomous ‘driverless’ cars expects to see the first production units on the roads in the early part of the next decade (***Ford*** 2016).

However, by definition, continuous innovation also brings about significant changes and risks associated with the instability in design requirements and significant changes in manufacturing and production assembly facilities and processes. This challenges product development (PD) teams to perpetually achieve design robustness, and equally stretches manufacturing teams to continuously deliver high standards of build quality in the intense environment of high volume mass-production.

Today’s consumers are also far more informed regarding new vehicle build quality and reliability through unlimited access to online reports and surveys (***Motoring-Research*** 2016, ***Power*** 2016). The ‘voice-of-the-customer’ is equally far stronger since the advent of online social media which allows all aspects of customer dissatisfaction to be readily shared world-wide, which can be highly detrimental and quickly undermine brand image perception. It is therefore imperative that OEM’s continuously gather feedback regarding the ‘customer user-experience’, and prioritise engineering investigations that develop robust countermeasures as part of a systematic continuous improvement strategy.

However, it is highly impractical for any single firm to internally manage all the knowledge necessary for product innovation (***Rosell and Lakemond*** 2012), and so inter-organisational collaboration between manufacturers and suppliers of components and sub-assemblies is a proven solution to reduce the overall product development lead-time, improve product quality, and provide vital access to state-of-the-art technological developments (***van Echtelt et al.*** 2008, ***Wynstra et al.*** 2010).

When a firm lacks the resources or capabilities required to sustain competitive advantage they can be secured through inter-firm collaboration or strategic alliances *(**Doz and Hamel*** 1998). Strategic partnerships have been proven to be central to competitive success and are an empirically proven advantage for Automotive OEMs (***Oh and Rhee*** 2010). According to Amhad et al., collaboration is dependent on the integration of four key factors: Information, knowledge, people, and processes via the utilisation of optimised efficient technology (***Ahmad et al.*** 2005).

Furthermore, advances in Information Communication Technology (ICT) have been fundamental to increasing the effectiveness of enterprise collaboration in dispersed global environments (***Evans et al.*** 2012). An integrated enterprise now brings together all the firms involved in the value chain by coordinating their corporate strategies, resources and processes to behave as a coherent entity, and enabled through strongly networked ICT infrastructures that can bridge geographical boundaries.

As a point of departure, and to provide sufficient context to this research thesis proposition, the next sections present a general overview of each of the separate sub systems that collectively form the *Global Product Development System*. This is then followed by an introduction to the concept of knowledge management within the PD and manufacturing environments.

1.3 Global Product Development System

The enterprise environment within which automotive product development is conducted is highly complex and comprised of several sub-systems that coexist to form the overarching global PD system as discussed in the following sections.

1.3.1 Global PD as a 'System'

Over the decades several models have emerged to define the term 'product development system'. The first inception of the term, as directly applied to the auto industry, is synonymous with 'Lean' product development' which focused on; 'People/Organisation', 'Processes' and 'Tools & Technologies' as the cornerstones of the PD system (***Morgan and Liker*** 2006).

However, for a typical high-tech commercial systems integrator, such as automotive manufacturers, the Systems Engineering (SE) community defines 3 main periods and 10 sub-phases ISO/IEC 15288 (***ISO/IEC*** 2008) as shown in Table 1 below.

Study Period				Implementation Period			Operations Period		
User Requirements Definitions Phase	Concept Definition Phase	System Specification Phase	Acquire Preparation Phase	Source Selection Phase	Development Phase	Verification Phase	Deployment Phase	Operations and Maintenance Phase	Deactivation Phase

Table 1. System Lifecycle Periods and Phases (ISO/IEC 2008)

Furthermore, ***Browning et al.*** (2006) proposed that the overarching PD system is actually comprised of a suite of PD sub systems; 'Organisation System', 'Process System', 'Tool System', 'Product System'; plus 'Goal/Requirement System' and 'Project System'. The fundamental construct of the SE lifecycle model was later extended to incorporate the dimension of 'Knowledge System' (***Zhang et al.*** 2012).

The PD system is therefore a 'System-of-Systems', where the internal systems-of-interest are equally large scale interdisciplinary distributed sub systems (***INCOSE*** 2011).

In order to more fully explore and better define each of the key dimensions of the global PD System the following sections introduce each of the sub-elements of the adapted general PD system model shown in Figure 1.

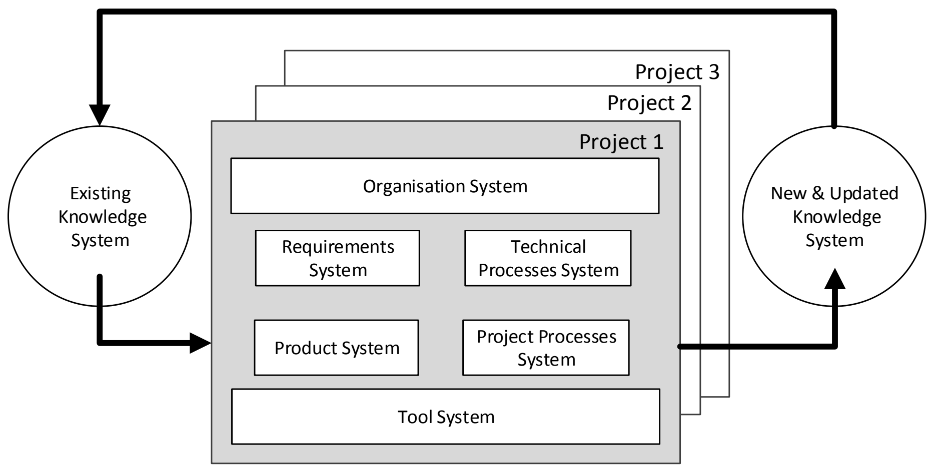


Figure 1. Adapted General PD System Model (Danilovic and Browning 2006)

1.3.2 Organisation System

The physical and logical organisation of large technically competent workforces of individuals within geographically dispersed teams, and the social interactions they engage in throughout the PD process, is highly complex (***Eppinger and Salminen*** 2001). The resourced-based view of organisations proposes that some organisations have a better mix of available resources than others, leading to sustained higher performance when the differentiating resources cannot be easily copied, acquired or substituted; and that knowledge management and the information contained therein is one of the major differentiating factors (***Zahay et al.*** 2004). The 'Organisation System' comprises the people assigned to perform the tasks, defined by the 'Technical Processes' system, to govern the development of the new product to be launched. This embodies all of the individuals, groups, teams and business units that collaborate throughout the PD process (***Browning et al.*** 2006).

Multinational Enterprises (MNE's) are able to extend their innovation activities by building networks of distributed Product Development centres, including joint venture partnerships or wholly owned R&D facilities in overseas locations (***Stonehouse et al.***

2001). This also extends access to market research on local customers, which in turn improves product success and competitiveness (***Karlsson et al.*** 2011). However, the global operations management of human capital for R&D, and fixed assets, also presents an array of complications in regard to strategy deployment, effective communications and optimization for efficient organisational interaction. In the past R&D followed two basic operating models (***Liviero and Kaminski*** 2009);

i. Highly autonomous region-specific PD centres for local market only programs, with very low levels of interaction and knowledge sharing with counterpart teams in the company located in other regions.

ii. Strongly centralized R&D only performed at company headquarters, with products either manufactured and exported, or manufactured locally in other regions.

However, the advent and subsequent vast improvement in ICT systems has greatly improved connectivity and intensified communication channels, which has enabled companies to evolve from simple local project teams into complex, globally dispersed, transnational projects teams (Figure 2).

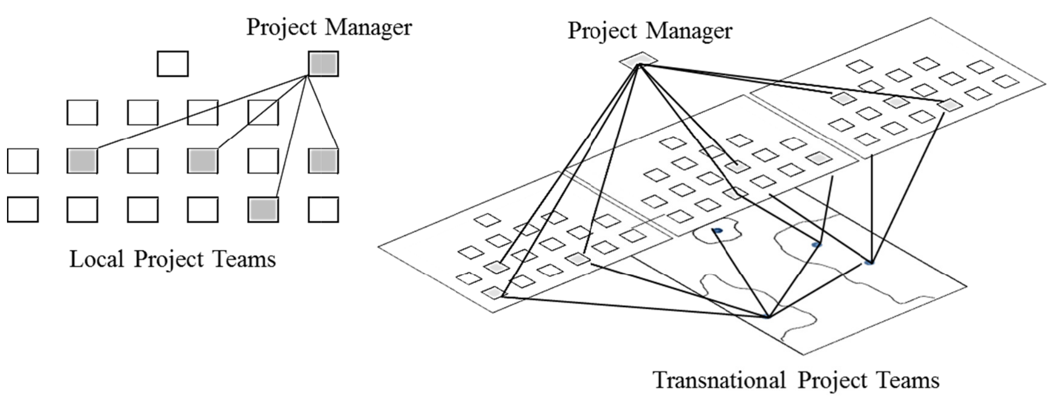


Figure 2. Local and Transnational project teams (Liviero and Kaminski 2009)

This has enabled large multinational companies to better connect the furthest out-reaches of their industrial empires and achieve greater levels of synergy, commonality and standardization through improved collaboration and elimination of unnecessary duplicate R&D activities (***Adenfelt and Lagerstrom*** 2005). This approach has also further enabled several optimization strategies to overcome the challenges of meeting higher quality demands, environmental and safety regulations, and increased competition through; streamlining resources, reduced R&D costs, shorter time to market, and platform engineering. However, the highly complex relational model of transnational project teams presents a multitude of alternate dilemmas that must instead be managed. Establishing an appropriate enterprise structure to integrate teams across multiple geographic locations that span different time zones, languages and cultures attracts a vast number of challenging issues. This is typified by the complicated network of factors that influence the type and nature of interactions that occur during global R&D (***Zedtwitz et al.*** 2004), as exemplified in Figure 3.

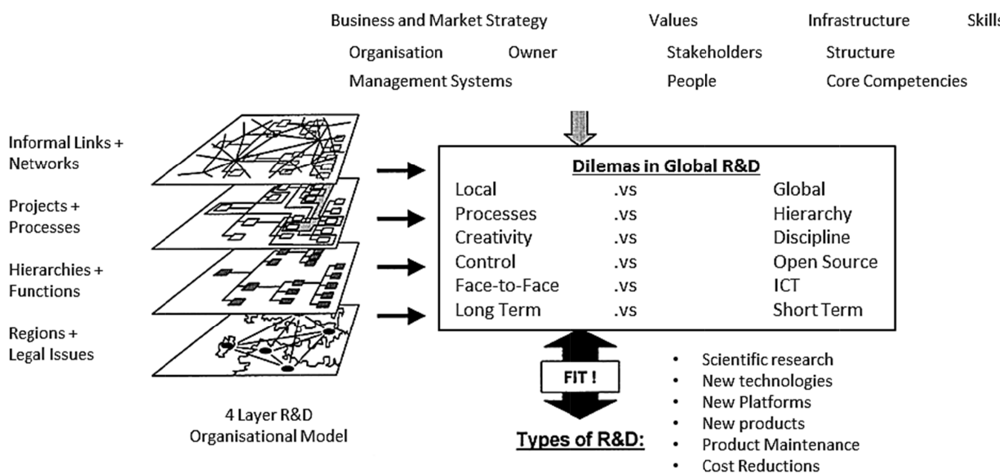


Figure 3. Global R&D Organisation (Zedtwitz *et al.* 2004)

It is therefore imperative that MNE's establish an organisational structure across all regional business units in order to maintain a worldwide Enterprise Architecture that partitions the divisional and departmental roles into clearly recognizable standard patterns of responsibility. This in turn allows interacting departments to work effectively, without overlap or duplication, whilst harnessing common global processes. This also enables MNE's to map the equivalent global ICT enterprise architecture with common software application tools accessible by all globally dispersed teams to allow knowledge intense organisations to more effectively engage in virtual collaborative innovation as a socio-technical phenomena (***Lytras and Pouloudi*** 2006). However, when the notional concept of an enterprise is stretched beyond the physical boundaries of the focal firm's operations, to also embrace the network of external suppliers and joint venture partners, the term 'extended enterprise' is appropriate. Murman et al. further define an Extended Enterprise as 'all of the entities along an organisations value chain, from its customer's customers to its supplier's suppliers, involved with the design, development, manufacture, certification, distribution and support of a product (***Murman*** 2002).

1.3.3 Requirements System

A system requirement is a statement that identifies a product or process operational, functional, or design characteristic (***ISO/IEC*** 2008). Typical stakeholders include system users/operators, organisation decision makers, regulatory bodies, and society at-large (***INCOSE*** 2011).

Stakeholder requirements are translated into engineering-orientated technical statements to define the system architecture design and function as well as system integration and verification activities to demonstrate the requirements are met (***Pyster et al.*** 2017). The 'Requirements System' (Figure 4) therefore embodies the collection of internal and external sources that drive the necessity for continuous innovation in order to sustain meeting stakeholder expectations.

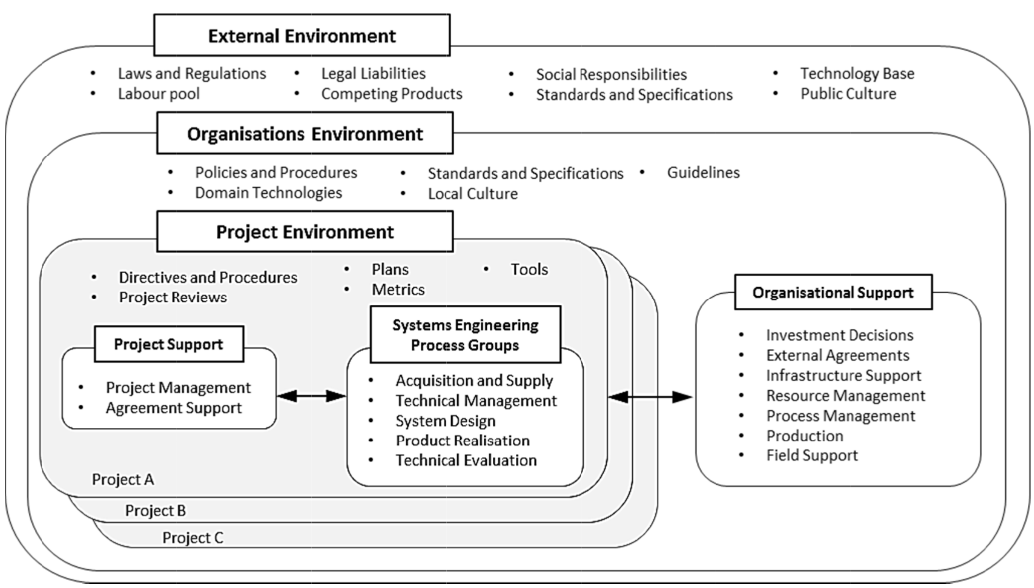


Figure 4. Requirements System (INCOSE 2011)

The evolving landscape of stakeholder requirements therefore has the greatest influence on the continued acceptance and competitiveness of current products, and equally dictates what must be addressed when developing future product portfolios.

1.3.4 Product System

In high value manufacturing the final end product to be marketed may be highly complex in terms of its function and integrated technologies. In automotive vehicles this dimension extends to include many thousands of individual components that comprise the diverse number of sub system functions, which are in turn integrated into higher level systems (***Oh***, 2008, ***Garza***, 2005). In the case of Systems Engineering in PD the structure is a hierarchical breakdown of the product into a tree structure (Figure 5) that facilitates decomposition from the top level product system into sub systems, and at the lowest level into the basic component elements (***INCOSE*** 2011, ***Pyster et al.*** 2017).

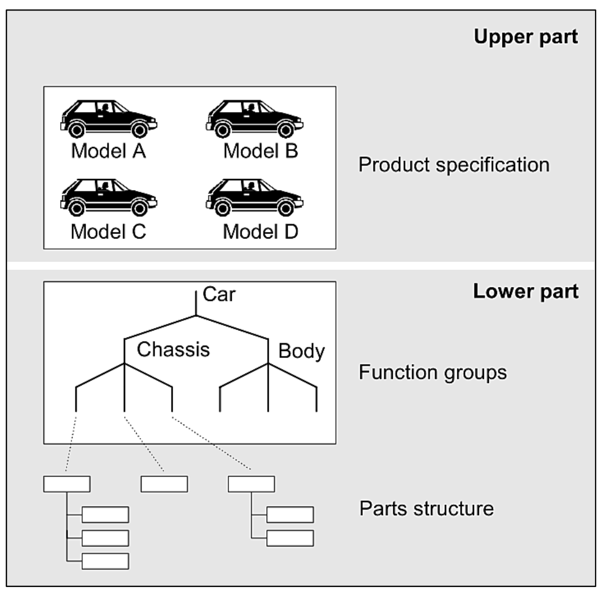


Figure 5. Product Design Structure (Svensson and Malmqvist 2000)

This partitioning enables organisations to segregate and align different responsibilities from functional, manufacturing and assembly process viewpoints, and is also a key enabler towards platform architecture engineering. The most common use of product structure within manufacturing is the Bill-of-Material (BoM), which enables Product

Structure Management (PSM) database systems to create logical product hierarchical configurations and manage product variant complexity (***Amann*** 2005). The BoM provides a common structured approach that ties together the product configuration in the PD domain with the Manufacturing Resource Planning (MRP) domain that links customer demand with manufacturing scheduling and material order demand (***Svensson and Malmqvist*** 2000).

1.3.5 Project Processes System

The project management of large scale systems such as those delivered in the Aerospace, Military defence and Automotive industries requires structured coordination of the planning, tracking and execution of the technical development and manufacturing processes; against program time schedule and cost constraints (***DoD*** 2005). Projects and the systems they deliver are inseparable since the product to be developed, tested and delivered is determined by the system requirements, architecture, and design as stated in the project plan (***Sharon and Dori*** 2014). Highly complex products typically attract a vast number of systems engineering technical processes which are managed using predefined tasks that must be completed as series of events; engineering gateways or program milestones in a stage-gate approach (***da Silva and Rozenfeld*** 2007, ***Cooper*** 2008), as typified in Figure 6.

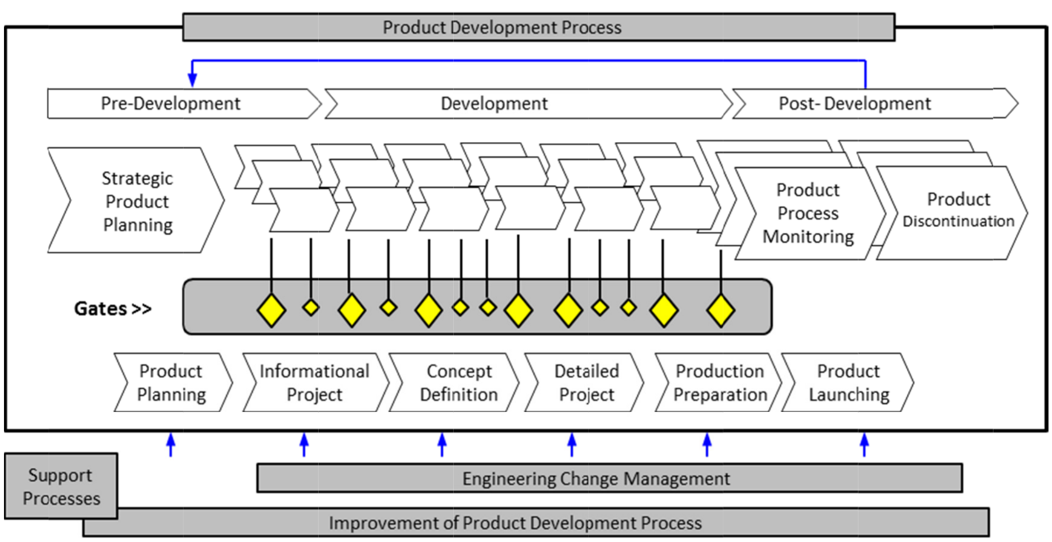


Figure 6. Systems Engineering Lifecycle Phases (Rozenfeld 2006)

Furthermore, many MNE's deliver multiple PD programs concurrently. This effectively creates an overlapping effect of simultaneous multigenerational projects running alongside each other, ranging from small to large scale in terms of new technology and modified design content, and at various stages of completion (***Odogwu*** 2002). Referring to Figure 6, the complete SE lifecycle comprises of three chronologically sequential phases; *i) Pre, ii) Main, iii) Post Development*;

i) Pre Development Phase – Aligns to the Requirements System and is primarily focused on market research activities to establish the customer wants/needs, and enables companies to establish a portfolio of innovative products which incorporates latest technology developments and complies with future regulatory requirements. The individual projects that emerge from this phase form part of the overall business cycle plan to ensure a continuous stream of new products to maintain competitiveness. The predevelopment phase also considers critical planning aspects such as competitive strategies and capacity utilisation of product development and manufacturing resources.

ii) Main Development Phase – Once the content of the new project has been defined the SE development engineers progressively work through the complex series of SE processes from concept to launch. The scale of the project is dictated by the level of new technology and design change, which in turn drives developmental lead time for engineering, testing and manufacturing. The engineering teams then work towards robust completion of the systems engineering disciplines at each successive program gateway (***Chang et al.*** 2012).

iii) Post Development Phase – This phase within the Product Lifecycle is concerned with the continuous production in manufacturing to meet customer demand, and the subsequent operational service of the product with the customer. Continuous monitoring of product integrity via quality and warranty data metrics, and customer feedback that the product meets expectations, are an essential part of feeding new knowledge back into the manufacturing plants to correct and error-proof mistakes, and to also update design rules and requirements into the next generation replacement products as part of continuous improvement (***ISO*** 2009, ***ISO*** 2015).

1.3.6 Technical Processes System

The technical engineering work to be performed is often highly complex in nature and involves a vast number of structured processes, activities and tasks, which take many years to be fully understood and internalised by Systems Engineering practitioners (***INCOSE*** 2011, ***Oppenheim*** 2011, ***Pyster et al.*** 2017). ISO/IEC 15288:2008 defines the Technical Processes System as the set of processes used to define the stakeholder (i.e. internal and/or external customer), regulatory and legislative requirements for the system of interest and then transform those requirements into an effective end product that conforms with the expectations for product functionality and performance, reliability and quality, usability, manufacturability and serviceability (***ISO/IEC*** 2008).

The pace and complexity of innovation in the automotive industry has also increased dramatically in the last decades. However, continuous innovation leads to instability through regular changes in product design and manufacture processes that affects all the many sub subsystems, both mechanical hardware and electronic control systems. This instability must be managed within the PD innovation process through the rigorous application of Quality Management System techniques and tools (***ISO*** 2015).

Quality Management Systems uphold two key tenets aimed at improving design robustness and preventing mistakes which are two distinct but complementary efforts in Failure Mode Avoidance (***Henshall and Campean*** 2009). Central to the FMA effort in the automotive industry is the 'Design Failure Mode Effects Analysis' (DFMEA) which details the potential *Design* failure modes related to the system primary functions and interface functions. The 'Process Failure Mode Avoidance (PFMEA) is the equivalent logical approach to identify and evaluate the potential failure modes associated with manufacturing and assembly *Processes*.

1.3.7 PD Tool Systems

The ***PD tool system*** represents the collective suite of Information Communications Technologies (ICT) harnessed by organisations to manage the PD processes that lead to the successful launch of the new product (***Browning et al.*** 2006). This can also be further defined as the wide array of ICT applications that support the PD engineering teams in the management of the large volume of systems engineering knowledge

(***Karlsson et al.*** 2011). The R&D and product innovation processes, which traditionally take many years to transform complex knowledge and technology into commercially viable end products, have been greatly compressed as information and data is now more rapidly created and exchanged via PLM systems (***Baughey*** 2011b).

These state-of-the-art PLM systems have encouraged the emergence of stronger collaborative patterns between all divisions of the global extended enterprise including; marketing, design, engineering, testing, manufacture and the global network of specialist suppliers (***Ming et al.*** 2008). Fundamentally triggered by the genesis of the internet, enterprise 2.0 tools have also now evolved to include web-based applications that both facilitate and intensify communication channels between globally dispersed PD teams and inform group decision making (***De Hertogh and Viaene*** 2012).

1.4 Knowledge Management in Product Development

Global Product Development may be characterized as the sharing of knowledge between multiple globally dispersed knowledge centres (***Karlsson et al.*** 2011). 'Knowledge' is the intellectual capital that resides within organisations and across enterprises. It enables all levels within companies to behave in an informed way to perform tasks, solve problems, make decisions, plan and innovate. Knowledge therefore 'embodies the combination of know-how, experience, emotion, beliefs, values, intuition, curiosity, motivation, behaviours, attitudes, capabilities, trust, social skills, and entrepreneurial spirit to result in a valuable asset which can be used to improve the capacity to act and support decision making' (***CEN*** 2004a). Knowledge comprises a broad array of individual components, and is equally defined by the interactions and combinations of these components in varying contexts to result in further new knowledge;

- Ideas & Concepts
- Theories & Hypotheses
- Principles and Practices
- Experience and Observations
- Analyses and Investigations
- Results and Outcomes

Knowledge is distinctly separate from pure data which comprises simple facts and figures, which in turn is distinct from information which comprises data with meaning and context. Knowledge is therefore superior to data and information as it combines both together with 'expert opinion, skills and experience and therefore may be explicit and/or tacit, individual and/or collective' (***CEN*** 2004a)

1.4.1 Knowledge Epistemology

The epistemology of knowledge is broadly categorised by four types;

i) Situational knowledge recognises the combination of events or situations within a particular domain, including the consideration for cause-and-effect, which can explain the series of events that may have led to a situation as presented, and equally the various permutations of outcomes and risks associated with the potential next decision or action.

ii) Conceptual knowledge is built on facts, concepts and principles that apply within a certain domain and may be used as additional information towards solving problems or making decisions and taking actions when contemplating a situational knowledge scenario.

iii) Procedural knowledge contains actions or steps that will reliably move a situation from its present state to an intended alternate state, possibly whilst concurrently integrating conceptual knowledge.

iv) Strategic knowledge centres on the ability to intuitively integrate situational, conceptual and procedural knowledge with superior insight and experience.

Knowledge types can then be further sub-divided into two further categories;

Explicit knowledge can be captured and codified, and as such can then in turn be represented in a formal systematic language that is easily stored, transferred and shared. There are two further layers within explicit knowledge that create further important distinctions;

Structured knowledge is typically codified in such a way that it conforms with predefined taxonomies and is stored within content management systems within well-defined structured hierarchies, thus making the storage location intuitive to whomever may wish to retrieve the knowledge document in the future.

Unstructured knowledge, conversely, lacks defined data types and rules to enforce where the data is stored, and is created across a broad cross section of end users and stored in user-defined directories, beyond the reach of enterprise rules (***McKendrick*** 2011). Unstructured knowledge types include electronic files such as Microsoft Office documents (MS Word.doc reports, MS Excel.xls spreadsheets, and MS Powerpoint.ppt presentations), Adobe Acrobat.pdf, and transient dialogue via online social media and instant messaging systems.

Tacit knowledge is generally unstructured knowledge that cannot be easily articulated because it has become internalised. It represents a level of understanding that cannot be easily externalised because it is buried in subconscious mind and difficult to retrieve to the consciousness mind.

Ikujiro Nonaka and Hirakata Takeuchi proposed the four phase 'SECI' model of knowledge creation and conversion (***Nonaka and Takeuchi*** 1995) – Socialization, Externalization, Combination and Internalization (Figure 7);

Tacit to Tacit knowledge transfer is known as ***'Socialization'***. Social interaction and face-to-face dialogue enable knowledge transfer through shared experiences. Tacit knowledge is considered difficult to formalize.

Tacit to Explicit knowledge transfer is known as ***'Externalization'***. Publishing concepts, images, and written documents can support articulating this kind of interaction. When tacit knowledge is made explicit, knowledge is captured formally, thus allowing it to be shared with others, and it becomes the basis of new knowledge. Concept creation in new product development is an example of this knowledge conversion process (***du Plessis*** 2007).

Explicit to Explicit knowledge transfer is known as ***'Combination'***. Explicit knowledge is collected from inside or outside the organisation and then combined, edited or processed to form new knowledge. The new explicit knowledge is then disseminated among the members of the organisation as learning via training courses and formalised processes and procedures.

Explicit to Tacit knowledge transfer is known as ***'Internalization'***. Learning and acquiring new tacit knowledge in practice via 'learning by doing'. Explicit knowledge becomes an intrinsic part of an individual's knowledge, and they in turn become a knowledge asset for an organisation.

From/To	**Tacit**	**Explicit**
Tacit	***Socialisation*** Creates sympathised knowledge through the sharing of experiences, and the development of mental models and technical skills.	***Externalisation*** Creates conceptual knowledge through articulation using language. Dialogue and collective reflection needed.
Explicit	***Internalisation*** Creates operational knowledge through learning by doing. Explicit knowledge studied from text books or manuals, or verbal stories.	***Combination*** Creates systemic knowledge through the systemising of ideas. Involves different media, and leads to new knowledge by adding, combining and categorising.

Figure 7. The SECI knowledge Conversion Cycle (Nonaka and Takeuchi 1995)

1.4.2 Knowledge Management Concepts

The concept of 'Knowledge management' (KM) is defined as the management of activities and processes for leveraging knowledge to enhance competitiveness through better use and creation of individual and collective knowledge resources' (***CEN*** 2004a). 'Knowledge Management is the collective discipline that enables individuals, teams, organisations and communities to systematically capture, store, share and apply their knowledge'***(Knowledge-Management-Online*** 2014). Additionally, ***Jennex and Addo*** (2005), cited within ***Grundstein*** (2005), define Knowledge Management as 'The process of selectively applying knowledge from previous experiences of decision making to current and future decision making activities with the express purpose of improving the organisations effectiveness'.

They propose the goals of Knowledge Management as follows;

- Identify and acquire critical knowledge in a knowledge base
- Share and apply the critical knowledge to appropriate situations
- Monitor and optimize the effectiveness of using the applied knowledge

Knowledge Management is one of the most popular approaches for improving collaborative innovation in all organisations from small to large extended enterprises (***An et al.*** 2014). There is equal wide recognition that KM is an essential part of managing large scale complexity in highly technical organisations that continuously generate large volumes of data as part of delivering daily business operations (***McKendrick*** 2011). KM encourages effective collaboration between employees in all parts of the enterprise, supports process standardisation and creates shared context between participants in product development teams (***Ramesh and Tiwana*** 1999).

The PD process is a structured framework that defines the order and schedule of work that should be completed by all involved parties from concept to final production launch. However, the socio-technical dimension of participants exchanging and converting knowledge through the SECI cycle results in 'thousands of minor independent decisions, conducted in a context of constant technological and market change that can affect the products future launch' (***Rozenfeld*** 2006)

The PD process draws together cross functional teams to work on design solutions to overcome technical obstacles, which in turn generates new knowledge for future projects. 'It expands the participation of clients and suppliers, improves the integration and coordination of the projects activities and stimulates the creation, accumulation and circulation of new knowledge in the company' (***da Silva and Rozenfeld*** 2007). Due to the extensive knowledge utilised and generated in the PD process it has long been considered one of the best disciplines to study KM as a research problem (***Drucker*** 1988, ***da Silva and Rozenfeld*** 2007).

Global knowledge management refers to the set of KM activities that cover the processes and strategies that govern the PD interactions between distributed non collocated departments both within companies and across the extended enterprise between suppliers and OEM's. Global Knowledge management introduces a number of additional considerations due to the influence of barriers and challenges such as time-zones, culture, language and communication, organisational competences and lack of standardized or harmonized KM tools (***Pawlowski and Bick*** 2012).

1.4.3 Knowledge Management Systems

Enterprise content management (ECM) systems are the technologies, tools and methods that facilitate the creation, management, distribution and exchange of large volumes of rich and primarily unstructured content, within and beyond the enterprise to customers, between employees, partners and suppliers (***EMC*** 2006). ECM is concerned with content, documents, details and records related to the organisational processes of an enterprise. ECM systems include features such as document and records management, content taxonomies, auditing, check-in/check-out, workflow controls and security (***Fowler*** 2008).

Product lifecycle management (PLM) is the process of managing the entire lifecycle of a product from its conception, through design and manufacture, to service and disposal. The core of PLM is in the creation and central management of all product data and the technology used to access this information and knowledge. Compared to ECM which is primarily directed at managing an organisation's *unstructured* information content, the core purpose of PLM is to manage *structured* product data. Both classes of systems are managing content with the key distinction between structured and unstructured data types.

Meta-knowledge classification deals with 'knowledge about knowledge'. Many Knowledge Managements Systems (collectively ECM, PLM and CMS) provide the in-built facility to include meta-knowledge, which should then simplify the task of systematically viewing or sharing a specific topic or problem. Ontologies also provide a unified framework within an organization that reduces the terminological confusion arising from different contexts or viewpoints for a particular domain (***Menzies et al.*** 2000). The meta-knowledge within any ontology therefore allows KMS's to be searched with a greater degree of accuracy and a higher chance of successful retrieval.

1.5 Initial Problem Statement

It is generally accepted that engineering design, product development, and manufacturing processes rely heavily on the vast and complex body of knowledge held within company processes and documents. It is through the internalisation of this knowledge, and then subsequent externalisation, that employees become valuable intellectual assets. Effective management, reuse and exploitation of the knowledge capital embedded in the experience and skills of the workforce are therefore critical success factors towards achieving and sustaining competitive advantage.

However, in the high-tech / high-value manufacturing sectors, such as the automotive industry, the body of knowledge is extremely dynamic as technologies and products are perpetually replaced over short production life cycles. Consequently, the annual volume of new unstructured knowledge stored digitally by enterprises is growing and becoming increasingly more complex to manage.

The majority of valuable knowledge is also generally distributed across enterprises rather than in well-organised central repositories, and is created in a variety of unstructured electronic file formats that include email, word processed documents, data spreadsheets, reports and presentations. The lack of associated context and metadata is also adding to the information explosion. It is estimated that a typical enterprise with 1,000 knowledge workers wastes as much as $3 million per year searching for non-existent information, failing to find existing information, or recreating information that can’t be found (***Gantz and Reinsel*** 2010).

The relatively modern phenomena of global platform programs has also proliferated the complexity of part design information to be managed by regional Product Development (PD) teams that now interface with many more geographically dispersed engineering and manufacturing personnel around the globe.

Accordingly, to successfully drive New Product Development (NPD), an enormous volume of intellectual capital in the form of critical design and manufacturing knowledge documents are exchanged daily across the virtual boundaries of these extended enterprises, challenging both MNE’s and SME’s to better understand how they should better manage and protect these intellectual assets more effectively.

Commercial Product Lifecycle Management (PLM) software systems have long addressed the need to maintain structured databases for 2D drawings, integrated 3D models, manufacturing bill of materials, and material ordering and purchasing systems. However, less formal *unstructured* knowledge, which is also routinely generated as part of the SE design process, has received far less attention. In this respect the ability to navigate intuitively and search for information within unstructured databases is generally ineffective, and the inability to efficiently relocate critical SE design knowledge quickly when needed causes frustration ***(Demidova et al.*** 2010).

Therefore, if future knowledge management practices could also improve the organisation and integration of *unstructured knowledge*, there is vast potential for increasing business effectiveness (***Global-Graphics*** 2014). This notion stretches much further than the just the individual stages within new product development only, but rather across complete lifecycle of multi-generational vehicle platform programs from initial design concept proposal, through to design integration and development, and onwards to final production launch, and beyond into operational service.

Crucially, it is also envisaged that improved KM practices within the Automotive PD environment could help strengthen the organisational ability to deliver and maintain the intended functional integrity and reliability on new vehicle programs, bolstering the corporate brand image and quality perception. In this respect, a well-structured KM support tool could also help engineering teams with vital historical knowledge to help investigate unanticipated reliability failures more efficiently, and develop more effective design and manufacturing countermeasures.

1.6 Research Questions

The underlying proposition that guides this research inquiry is that global product development is highly complex in terms of; product technologies, design engineering, and manufacturing processes, and the proliferation of people that collaborate throughout the extended enterprise to generate the vast body of *unstructured SE knowledge* involved in bringing new products to market. Furthermore, modern vehicles are typically designed to last a minimum of 150,000 miles / 10 years on the road. So, the team of engineers tasked with understanding and resolving any product reliability failures on vehicles in operational service are invariably not the same group of design engineers that delivered the original vehicle PD program.

The overarching research question is therefore as follows;

What are the requirements for a knowledge management framework and tool to support the automotive systems engineering lifecycle?

The overarching research question provokes a further five sub questions;

i. *What are the key KM challenges encountered across the extended enterprise within a typical large automotive MNE?*

ii. *What 'new' SE knowledge is generated during the investigation of powertrain reliability failures on vehicles in operational service?*

iii. *How could the 'new' SE knowledge learned from powertrain reliability failure investigations be captured and shared more effectively?*

iv. *What are the requirements for an automotive SE lifecycle KM framework to enhance knowledge capture, sharing and re-use capabilities?*

v. *How might the KM framework be implemented, including appropriate methods and enabling tools, to realise the benefits?*

The remainder of this thesis seeks to explore the challenges and complexities in respect to the above research questions and how each may be addressed.

1.7 Aim and Objectives

Based on the overarching research question in the previous section, the aim of this research may be summarised as follows;

To investigate and then specify the requirements for a KM framework and support tool to improve the systematic capture of automotive SE knowledge for re-use across future multigenerational vehicle programs.

The set of defined research objectives to achieve the above aim are as follows.

1. Conduct an exploratory industrial investigation with Automotive PD practitioners focusing on the real-world application of systems engineering knowledge.

2. Propose an automotive enterprise architecture model to represent the knowledge transactions across the extended enterprise throughout the SE lifecycle.

3. Identify the different types, nature and importance of automotive SE knowledge generated during vehicle operational service, focusing on un-structured knowledge.

4. Propose a KM framework to support the capture, sharing and future re-use of automotive SE lifecycle knowledge, focusing on the integration of new SE knowledge learned from powertrain reliability failure investigations on vehicles in operational service.

5. Develop a functional prototype ICT support tool as an implementation of the KM framework construct, including the provision of an appropriate user-guide, and evaluate with automotive PD practitioners.

1.8 Scope of the Research

The scope of this research is primarily confined to investigating the systems engineering knowledge focusing on un-structured knowledge associated with developing robust design solutions for the installed mechanical assemblies and electro-mechanical functions related to the Powertrain group of technologies within automotive PD.

The continuous improvement of product quality and reliability, including the use of failure mode avoidance tools and structured problem solving approaches, are referenced extensively. However, this research makes no claims towards redefining or improving any of these well-established tools and techniques, but rather seeks to investigate how improved KM practices could better support these quality processes within the automotive industry.

This research also makes no attempt to address any of the issues inherent in commercial Product Lifecycle Management (PLM) ICT systems that handle structured data and information such as; Product Data Management (PDM) for BoM lifecycle version control, Configuration Management (CM) software systems for handling 2D/3D CAD, or Engineering Resource Planning (ERP) systems pertaining to supplier/vendor and cost/price information.

Finally, the research is limited to a single large multinational automotive OEM and a number of its sub suppliers, and therefore the results cannot be generalised across the complete automotive industry. However, since the focus is systems engineering knowledge, the methodologies developed within the research may be considered extensible across other automotive OEM's, as well as a wide range of other manufacturing industries.

General reference is made to 'ISO 9001 / TS 16949 Quality Management Systems' (***ISO*** 2009) and 'ISO/IEC 15288 Systems Engineering – Systems Lifecycle Processes' (***ISO/IEC*** 2008). However, 'ISO 26262 – Road Vehicles Functional Safety' (***ISO*** 2011) is considered outside the scope of this present research.

1.9 Thesis Structure

This thesis is organised into a number of chapters to provide a coherent flow through the research project as follows;

Chapter 1 of the thesis introduces the scale and magnitude of the global automotive industry and the key drivers for innovation. The chapter then proceeds to frame the research context by introducing the various sub elements of the product development system and the main concepts involved in knowledge management. The initial problem statement that underlies the motivation for the research project is then presented, and the subsequent overarching research question, project aim and objectives are advanced as the point of departure.

Chapter 2 provides a review of the wide array of different methodologies available to applied research. The chosen Design Research Methodology (DRM) is then advanced and justified in the context of the research aim and objectives. The project stages and process steps are then outlined through the provision of the research design map.

Chapter 3 presents the critical analysis of the current extant body of published literature that most informed the research direction, particularly in the fields of systems engineering and collaborative innovation within large multinational extended enterprises where knowledge management was the main unit of analysis. The initial DRM reference and impact models are developed to describe the current *undesirable* 'as-is' situation, and future *desirable* 'to-be' situation.

Chapter 4 outlines the five stage investigative approach adopted for an exploratory industrial investigation at a major Automotive Manufacturing OEM. The findings of the initial four stages are then used as the foundation for a large scale multinational PD survey. The developed Automotive Extended Enterprise Architecture Model is then presented to describe the major knowledge transactions between the different PD domains and interfacing operations. The DRM *final* reference model to describe the refined understanding of the current *undesired* 'as-is' situation is then also presented.

Chapter 5 then focuses on the detailed examination of a significant number of historical powertrain functional reliability failure investigations which facilitated establishing a KM meta-knowledge classification scheme. The DRM *final* impact model to describe the refined understanding of the potential *desired* 'to-be' future situation is then presented.

Chapter 6 initially develops the requirements for the proposed KM framework that incorporates the key findings from chapter 4 and 5. The key elements of the complex framework are then explained in close detail to assist the reader in connecting together the main knowledge generating PD activities in each phase of the automotive systems engineering lifecycle. The KM framework is then validated via an example real-world PD vehicle program which provides a detailed account of a longitudinal case study.

Chapter 7 then proceeds with the development and evaluation of the ICT support tool in accordance with the DRM final Impact model (Figure 48). The requirements for the tool are fundamentally based on the KM framework (Figure 49) presented in chapter 6. The requirements are then used to construct the sitemap architecture for a prototype web-based ICT groupware. The groupware user guide is then used to explain the navigation within the support tool. Finally, the demonstration of the groupware to a small group of industrial PD practitioners and subsequent evaluation through the use of a short questionnaire is discussed.

Chapter 8 then draws together the overall conclusions for the research project in the context of whether the findings satisfied the original aim and objectives, and addressed the original research questions. The proposed key contributions to new knowledge in the field of knowledge management are also discussed.

Chapter 9 finally reflects on the main limitations within the scope of this research project and proposes some additional directions for future research that may be considered to further extend and widen the knowledge in this field of research.

2 RESEARCH METHODOLOGY

The successful delivery of this research project should be founded on the adoption of a proven and rigorous scientific methodology. This chapter reviews the array of methodologies available, discusses the numerous distinctions, and then presents the methodology that was eventually adopted.

2.1 Introduction

The term 'Methodology' provokes much debate in the context of numerous conflicting and alternate definitions and terminologies (***Baxter*** 2007). Furthermore, the wide spectrum of available research philosophies, ideologies and respective interpretations of approaches and methods is an equally complex introspective field. The complex array of available choices is typified by the six level research process 'onion' model (Figure 8) that draws on the eclectic crossover between pure and applied research; Philosophies, Approaches, Strategies, Choices, Time Horizons, Techniques and procedures (***Saunders et al.*** 2002).

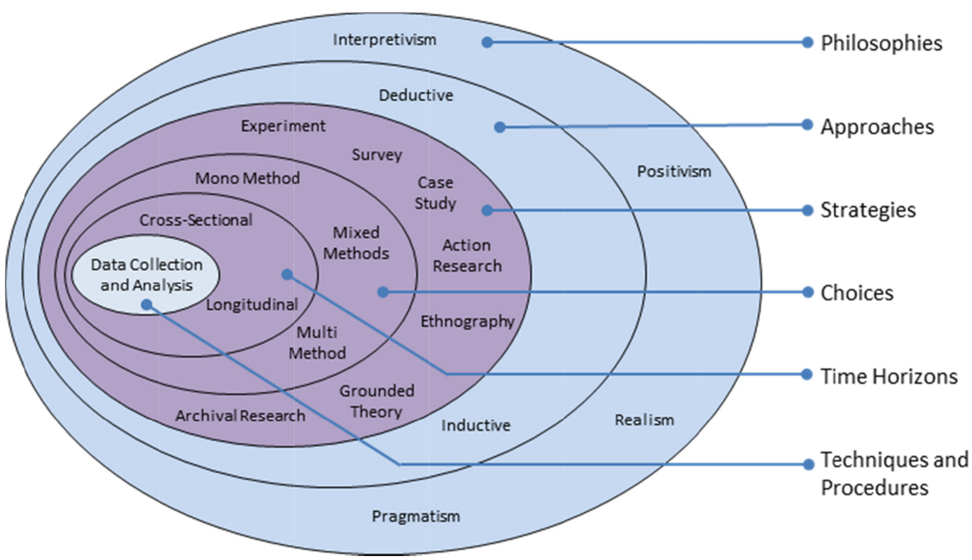


Figure 8. The 'Research Process Onion' (Saunders *et al.* 2002)

As the nature of this research investigation is firmly grounded in the domain of *'Applied'* research, rather than *'Pure'* research, a brief outline of the distinction between the two approaches is first presented.

2.2 Research Definitions

Pure research, sometimes referred to as basic research, aims to formulate and test hypotheses, theories and laws through the analysis of phenomena and observable facts. Robson defines pure research as residing within controlled environments, such as laboratory experiments, where 'closed-loop' conditions permit the researcher to predefine the parameters and variables to be studied (***Robson*** 2002). Equally critical to the definition of pure research is the lack of any particular intent to utilise the results of the research in any practical application (***OECD*** 2015).

Applied research is a form of systematic enquiry which involves the practical application of science and generally employs empirical methodologies to solve real world practical problems. Applied research quite often accesses the accumulated theories, knowledge, methods and techniques developed in the pure research domain; and then extends the practical application of these to solve issues identified in the business enterprise and industrial sectors (***OECD*** 2015). Applied research is frequently conducted by practitioner-researchers and is therefore often found to be synonymous with the phrase 'real world research or enquiry' (***Robson*** 2002). It generally lays the foundation to the subsequent experimental development and operational form of new or improved products, processes and services.

Research Philosophy

There are three main dimensions when considering research philosophies;

- ***Epistemology*** – The factors that constitute towards what is deemed to be acceptable knowledge in the research domain. As such it is important that the researcher considers if they are independent or embedded and interact with the subject matter of the research (***Creswell*** 1994). There are four main sources of knowledge;
    - Intuitive knowledge – based on faiths, beliefs, feelings
    - Authoritarian knowledge – secondary sources such as publications
    - Logical knowledge – newly created via logical reasoning
    - Empirical knowledge – objective and demonstrable facts
- ***Ontology*** – the nature of social phenomena as entities.
    - ***Objectivism*** holds that social entities exist external to the social actors.
    - ***Subjectivism*** views social phenomena as derived from social actors.

- ***Axiology*** – the philosophical judgement of the personal values attached to justifying the field of research and research methods to be employed. Value-free and unbiased research is more embedded in quantitative research, whereas value-laden and biased research is more aligned to qualitative research (***Creswell*** 1994).

There now follows a brief description of the four main philosophical stances generally adopted within the field of applied research;

Positivism adheres to the paradigm that only objective factual knowledge gained through direct observation, using scientific methods such as testing and measurement is quantifiable and trustworthy. Theory is deduced through explanation that establishes causal relationships between variables. Positivists generally adopt a deductive research approach and quantitative methodologies. ***Post-Positivism*** acknowledges that the theories, hypotheses, background knowledge and values of the researcher influence what is observed (***Robson*** 2002).

Realism in the field of applied research is also known as ***Scientific Realism*** and holds the ***Objectivist*** views that only the world as described by science is the real world. Scientific realists assert the possibility to make reliable claims about the unobservable as having the same ontological status as the observable.

Interpretivism (***Schwandt*** 1994), is also known as ***Constructivism***. This philosophical stance adopts the concept that the task of the researcher is to understand the multiple social constructs of knowledge and meaning using methods such as interviews and observation. The research participants play a vital role in constructing the 'reality' (***Robson*** 2002).

Pragmatism holds the belief that the key determinant of the epistemology, ontology and axiology is the research 'question'. If the research question cannot strictly adhere to either a positivist or interpretivist philosophy then the pragmatist philosophy holds firm belief that it is possible to conduct research which may alternate between both.

Research Purpose

There are three critical types of research purpose, which may be adopted either in isolation or in combination with each other, and primarily dependant on the specific research questions being addressed and the intent of the overall research outcome; ***Explanatory*** research is employed when "how" or "why" questions are being posed. ***Exploratory*** research is typified when the research question focuses on "what", and ***Descriptive*** research is associated with "who" and "where" inquiry (***Yin*** 2013).

Research Approaches

There are two main research approaches; a ***deductive*** approach first develops the theory and hypothesis, and then research strategy is designed to test the hypothesis. As such deductive theory may be considered a 'top-down' approach where the research starts out from a wide generalization and works towards specific confirmation (***Burney*** 2008). Conversely, an ***inductive*** approach first collects data which is then analysed to develop the theory (***Saunders et al.*** 2002), and as such is considered more of a 'bottom-up' approach that starts from specific observations and where the research then works towards validating broader generalizations and theories (***Burney*** 2008).

Quantitative and Qualitative Research Methods

It is imperative that the research strategy adopted is suited to the nature of the applied research to be conducted as it strongly influences both the methods of data collection and the likelihood of successful outcome. There are generally two widely accepted paradigms that are followed, namely quantitative (fixed) and qualitative (flexible) inquiry, or the combination of both in mixed methods research. ***Quantitative research*** is generally ***deductive*** and is defined as; 'The inquiry process of understanding a social or human problem, based on testing a theory composed of variables, measured with numbers, and analysed with statistical procedures, in order to determine whether the predictive generalizations of the theory hold true' (***Creswell*** 1994). ***Qualitative research*** is generally ***inductive*** and is defined as; 'The inquiry process of understanding a social or human problem, based on building a complex, holistic picture, formed with words, reporting detailed views of informants, and conducted in a natural setting' (***Creswell*** 1994).

Research Strategies

The choice of research strategy should be guided by the research questions and objectives, extent of existing knowledge in the field of research and philosophical stance. The research strategies available span all forms of research purpose; exploratory, descriptive and explanatory and therefore switch between deductive and inductive approaches. A brief description of each strategy now follows;

i. ***Experimental research*** is performed with the objective of verifying or rejecting the validity of a tested hypothesis. Controlled experiments provide insight into cause-and-effect by demonstrating what outcome occurs when particular parameters or variables are manipulated. Controlled experiments rely on repeatable procedure and logical analysis of the results and therefore tend to be employed in exploratory and explanatory research to answer 'how' and 'why' type questions (***Saunders et al.*** 2002).

ii. ***Survey strategies*** such as questionnaires consist of a predetermined set of questions that are given to a sample that is representative of the larger population of interest. The data collected then enables the researcher to generalize the findings from the smaller sample as applicable to the larger population (***Creswell*** 1994). Surveys types include ***face-to-face interviews, telephone interviews and self-completion questionnaires*** (***Robson*** 2002). ***Face-to-face intervie*****ws** are flexible since they may be conducted at ant chosen location. Extra care must be taken in soliciting, storing and sharing any personal details which may be necessarily required in order to create taxonomies within the results. However, self-completion surveys are notorious for low return rate and are frequently ignored by companies due to lack of available time due business pressures (***Blessing and Chakrabarti*** 2009).

iii. ***Ethnography*** is an ***inductive*** research approach which explores cultural phenomena where the researcher observes society, in a natural setting over a prolonged period of time, from the point of view of the subject of the study. The resulting field study or a case report reflects observational data and knowledge on the lives of a cultural group. Ethnography, as the empirical data on human societies and cultures, was pioneered in the biological, social, and cultural branches of anthropology but has also become popular in the social sciences in general. The research process typically evolves contextually as part of the shared experiences in the field environment (***Creswell*** 2003).

iv. ***Grounded Theory*** is a systematic methodology involving the discovery of theory through the analysis of data in the social sciences (***Glaser and Strauss*** 1967). Grounded theory is an ***inductive*** research approach which starts with the first step of data gathering through a variety of methods, which is then codified. The codes are grouped into similar *concepts* from which *categories* are formed, which are the basis for the creation of a *theory*. The approach is therefore also employed in the development of conceptual frameworks (***Jabareen*** 2009).

v. ***Phenomenological studies*** and philosophies originate from the abstract works of ***Edmund Husserl*** (1859 – 1938), and are strongly tied to human and social science studies including sociology and psychology, and is the field of study that is interested in how ordinary members of society both constitute and understand everyday life (***Creswell*** 1998).

vi. ***Case study research*** is 'an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident' (***Yin*** 2013). Case study strategies are most often employed in explanatory and exploratory research to answer 'why' and 'how' type research questions. Data collection techniques interviews, observation, documentary analysis questionnaires, which poses the dilemma in overlap with survey strategy (***Saunders et al.*** 2002). However, case studies strongly reinforce the possibility to triangulate multiple sources of data and improve both the internal and external validity of results through cross reference of results between different methods such as qualitative data from semi structured interviews with quantitative data from questionnaires (***Bradfield*** 2007). Case studies may be ***'single'*** where the observations are considered typical and can be justified as suitable for extending into theoretical generalizations, or ***'multiple'*** where cross case analysis is required to validate the existence of common theory between boundaries of different case types (***Yin*** 2013). A further dimension to case study research is whether there is a single or multiple units of analysis. In the case where only a single unit of analysis is of concern the study is conceived to be ***'holistic'***, or conversely if various logical sub units are to be considered, such as different departments or work groups, then the research would be conceived as an ***'embedded'*** case study (***Yin*** 2013).

vii. ***Action Research*** is conducted where the research itself is intended to influence or change some aspect of the focus of the research. The researcher intervenes in the environment being studied in order improve the current practices or gain an improved understanding from the practitioners. Action research is normally conducted as a longitudinal study and poses serious threats to the validity of the research findings due to impartial involvement of the researcher and perceived lack of rigour (***Robson*** 2002)

Research Time Horizons

Cross sectional studies are the result of research conducted to observe the incidence of phenomena during a fixed period in time. This type of research frequently employs survey strategies and interview questionnaires. ***Longitudinal studies*** are appropriate for studying change in phenomena over time, but are only employed where the research is not cost or time constrained (***Saunders et al.*** 2002).

In order to better inform and guide the research pathway through the available choices of methodology, a review of specifically selected prior PhD research projects was conducted. The projects were selected from the fields of collaborative product development, design and manufacture, on the basis that each research project focused on the empirical study of the challenges in industry in the real-world context. The findings are summarised **Appendix A**.

2.3 Design Research Methodology (DRM)

In justifying the selected research methodology it is first imperative to summarise the intended research approach, purpose, strategy and methods. As there is no clearly defined theory from the outset an ***inductive approach*** is required in order to form generalized theory from the study of particular contemporary phenomena, rather than to develop a theory and then test hypotheses as would be the case with a deductive approach. As the *research purpose* is essentially ***Exploratory*** a ***flexible*** *research strategy* is required as the objectives are likely to evolve as the research progresses. Therefore, the research methodology adopted is broadly based on the 'Design Research Methodology' (DRM) advanced by ***Blessing and Chakrabarti*** (2009), and as outlined in Figure 9.

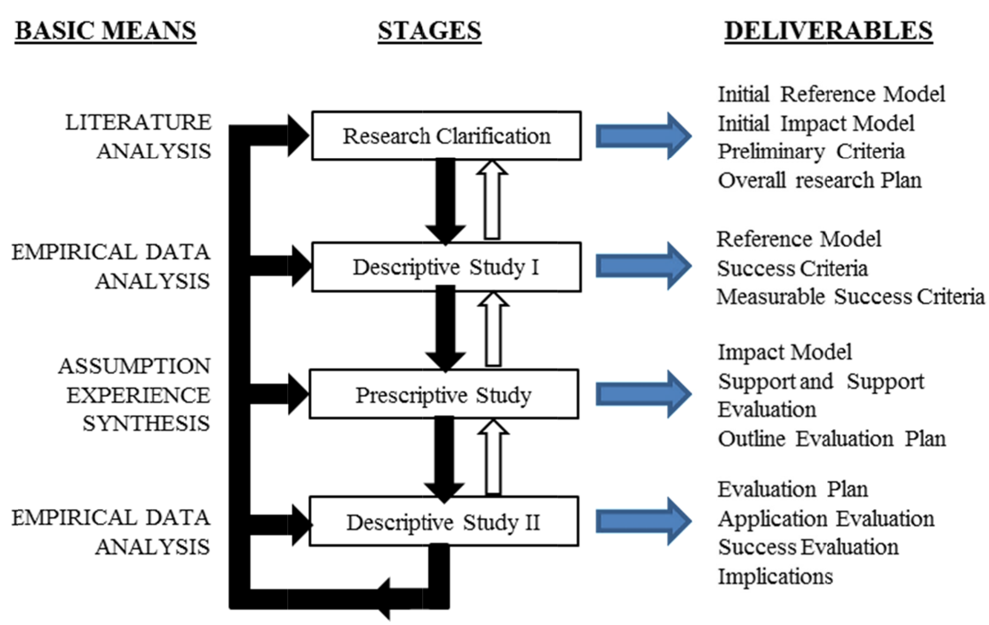


Figure 9. DRM Framework (Blessing and Chakrabarti 2009)

The main thrust of the DRM may be summarised as follows;

(1) Develop a reference model and theory of the existing situation.

(2) Propose a vision (model or theory) of the desired situation, and an initial impact model of the key factors and attributes that can influence the existing situation.

(3) Develop a vision of the support that is likley to change the existing situation into the desired situation, evaluation of the support and the implications to sustaining it.

The Design Research Methodology advocates that a *reference* model which describes the current (as-is) situation, and an *impact* model which describes the desired (to-be) situation which is to be achieved through the outcome of the research, are established using the prescribed DRM modelling notation.

The DRM modelling notation designates that each circled factor is assigned a measurable attribute and value. The sign convention of the attribute value then depicts the influence on the causal link between any two adjacent factors, as described in Figure 10 below.

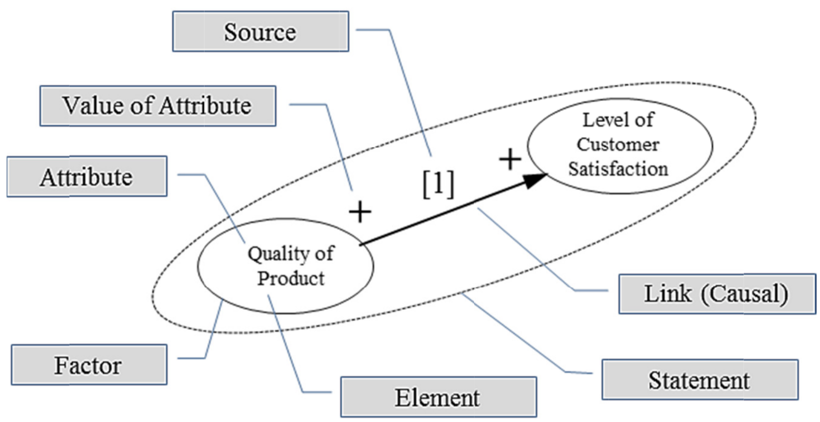


Figure 10. Graphical Model Notation (Blessing and Chakrabarti 2009)

The value of attribute signs ('+' and '-') may be influenced subjectively by introducing the implied changes through the improvement actions sought when comparing the *reference* model which describes the current (undesirable) situation to the *impact* model which describes the future (improved) situation.

The above notation and sign convention is then employed to develop the *initial* DRM reference and impacts models based on the combined findings of literature review and the identified research gaps, and augmented with real-world experience in the context of the initial problem statement and research aim.

The initial models are then refined through the course of the ***Descriptive Study I*** phase to establish the final ***Reference Model***, and through the ***Prescriptive Study*** phase to develop the final ***Impact Model*** (Figure 9).

2.4 Research Objectives aligned to DRM deliverables

The research objectives and sub tasks are aligned to the Design Research Methodology (DRM) deliverables in Table 2.

<table>
<tr><th>Research Objective</th><th>Sub-task</th><th>DRM Deliverable</th></tr>
<tr><td rowspan="3">1. Conduct an exploratory industrial investigation with Automotive PD practitioners focussing on the real-world application of systems engineering knowledge.</td><td>1.1 Define the common problems when;
i. Capturing/storing new SE knowledge
ii. Relocating existing SE knowledge</td><td rowspan="5">Initial Reference Model.

Initial Impact Model.

Preliminary Criteria.

Overall Research Plan.

Reference Model.</td></tr>
<tr><td>1.2. Investigate the adequacy of current KM practices and ICT support tools, and how each aspect of the SE knowledge lifecycle is supported.</td></tr>
<tr><td>1.3. Establish and compare the current alternate KM taxonomies employed by PD practitioners to classify different knowledge types for the different phases of the automotive SE lifecycle.</td></tr>
<tr><td rowspan="2">2. Propose an automotive extended enterprise architecture model to depict the SE knowledge lifecycle.</td><td>2.1. Capture the various knowledge transactions that occur between the different sub-organisational functional teams in the automotive EE.</td></tr>
<tr><td>2.2. Model the SE knowledge transactions between the various actors throughout the EE at different phases of the SE lifecycle.</td></tr>
<tr><td rowspan="2">3. Identify the different types, nature and importance of SE knowledge generated during vehicle operational service.</td><td>3.1. Identify the knowledge utilised during automotive powertrain reliability failure investigations.</td><td rowspan="2">Success Criteria.

Measurable Success Criteria.

Impact Model.</td></tr>
<tr><td>3.2. Establish an appropriate meta-knowledge classification scheme for the capture of new knowledge learned during vehicle operational service.</td></tr>
<tr><td rowspan="2">4. Propose a KM framework to support the Automotive SE Lifecycle.</td><td>4.1 Define the requirements for an integrated KM framework and establish a coherent graphical representation.</td><td rowspan="4">Support.

Support Evaluation.

Outline Evaluation Plan.

Evaluation Plan.</td></tr>
<tr><td>4.2 Validate the proposed SE KM framework with a real-world case study.</td></tr>
<tr><td rowspan="2">5. Develop a working prototype KM support tool and evaluate with auto PD practitioners.</td><td>5.1. Select an appropriate software platform and develop a functional prototype ICT support tool.</td></tr>
<tr><td>5.2. Evaluate the prototype support ICT tool with industrial practitioners.</td></tr>
<tr><td rowspan="2">6. Summarise the findings from all research stages, conclusions and future work.</td><td>6.1 Synthesis of practitioner feedback from ICT tool demonstration.</td><td rowspan="2">Application Evaluation.

Success Evaluation. Implications.</td></tr>
<tr><td>6.2 Reflection on overall success of the research project and contribution to new knowledge in the field.</td></tr>
</table>

Table 2. Research Objectives, and sub tasks, aligned to the DRM Deliverables

2.5 Research Design – Aligned to DRM Stages

The overall research design and pathway through the different phases and steps is outlined below in Figure 11. Each element is additionally aligned to the respective stage of the DRM framework (Figure 9); such that the deliverables should then satisfy the objectives and achieve the overall aim of the research project.

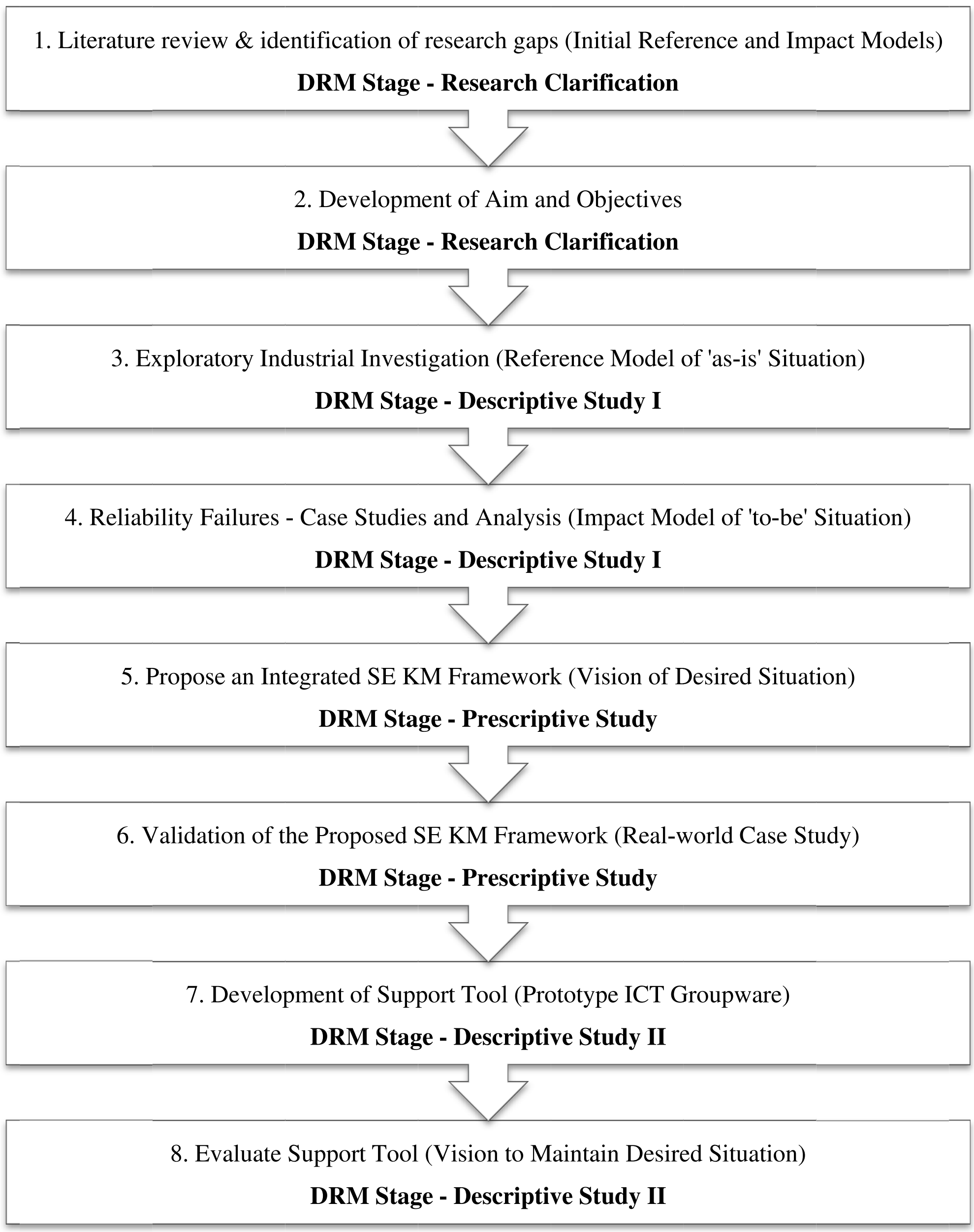


Figure 11. Research Design Steps - Aligned to DRM Framework

3 LITERATURE REVIEW

This chapter presents the findings of the detailed literature review that examined the inter-linkages between the key themes most pertinent to the overarching research question posed in chapter 1. Prior academic and industrial practitioner publications based on empirically informed research investigations, specific to knowledge management as the unit of analysis, in the context of automotive systems engineering and collaborative innovation within extended enterprises were deemed most relevant as shown in Figure 12.

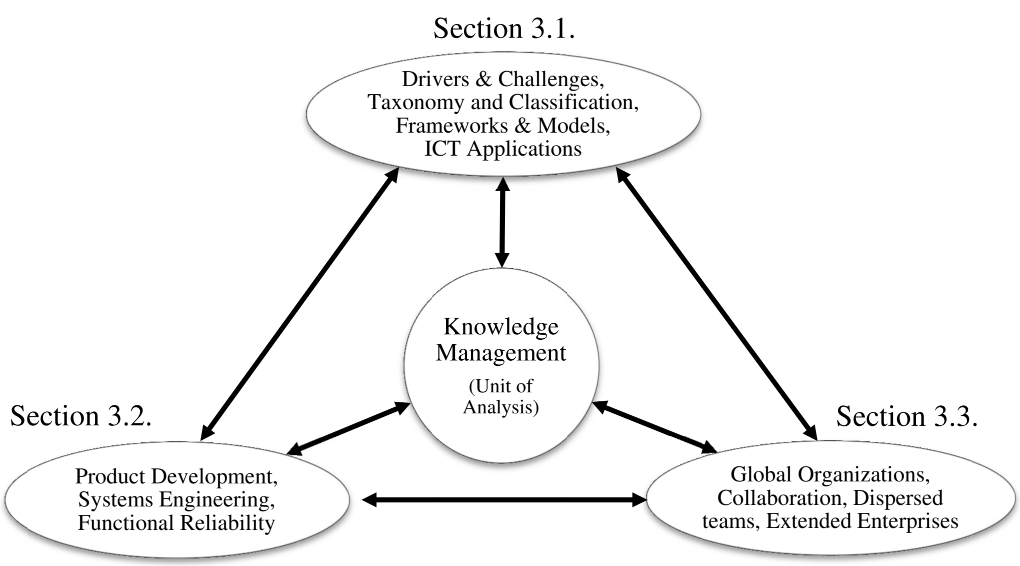


Figure 12. Literature Search Strategy to Support Critical Analysis

Section 3.1 initially analyses prior knowledge management research related to the challenges and drivers for improving future knowledge management practices. Publications that advance theory on the implications of taxonomies and classification systems, frameworks or models, or propose ICT solutions are examined. Section 3.2 then presents a critical analysis of prior publications specifically linked to knowledge management within the fields of product development, systems engineering management, and product quality and reliability practices. Finally, section 3.3 takes a detailed look at the implications of geographically dispersed teams and the wider perspective of the extended enterprise in conjunction with knowledge management as the main unit of analysis.

3.1 KM Practices and Approaches

The next sections present the general concepts and principles associated with the practical application of different knowledge management approaches.

3.1.1 Drivers and Challenges for KM

The risks posed by non-existent or ineffective knowledge management have been well documented over the years, but the loss of corporate knowledge caused by the exodus of employees through retirement, forced downsizing, or voluntarily leaving to work elsewhere still remains a common threat (***Pryce-Jones*** 2013).

Early propositions towards combating these threats centred on strategies to extract and document the tacit knowledge residing within aging work forces to make corporate knowledge assets available for future generations (***Carter*** 2005). Centralising access to knowledge and creating intelligent enterprises by building corporate knowledge bases that facilitate collaboration has also been a long standing motivation (du Plessis 2005). Crucially though, the motivation and fundamental tenet of knowledge capture and transfer, first asserted in these early publications, continues to underpin the philosophy of modern KM approaches. Many of today's KM strategies still aspire to extract the buried forms of tacit and implicit knowledge and transform them into retrievable explicit knowledge.

However, ***Rusu et al.*** (2013) recognised that much knowledge within organisations exists as unstructured and semi structured data, which is by its very nature typically unorganised and therefore, since there are no formal mechanisms by which it may be retrieved, it generally resides redundant in isolated 'silos'. They define unstructured knowledge as information that lacks any definition about its type or any rules that enforce where and how it is stored. The research team proposed a conceptual theory and ICT tool 'KDD' (Knowledge Discovery in Databases) and outlined the usefulness of its general real-world application. The underlying proposition is that companies are overwhelmed by the continued growth rate of 'Big Data' and that viable solutions to combat the problem are needed. The research proposed a set of sequential conceptual steps required to convert unstructured and semi structured data into potentially useful knowledge; Initial data selection and extraction, pre-processing of the target data by syntactic and semantic analysis, transformation of the pre-processed data through data classification, enable data mining of the transformed data by adding inference rules, re-representation of the data into structured format through interpretation and evaluation of patterns within the transformed data. However, the research lacked any proposition for an application tool that could validate the proposal through a real world case study.

According to ***Irani et al.*** (2009) organisational learning (OL) and organisational memory (OM) are both commonly cited drivers for improved knowledge management approaches. The manufacturing case study concluded that organisational learning from corporate memory embedded with knowledge management systems can be realised, but is more likely to be effective if coupled with an incentive reward system to promote OL.

This view is supported by the findings of the grounded theory research conducted by ***Lakshman*** (2007) who analysed 37 in-depth interviews with company CEO's to understand the role of leaders in promoting knowledge management in order to positively impact and maximize organisational performance and effectiveness. The analysis included interview material collected from Jacque Nasser, the then CEO at Ford Motor Company, quoting; *"Spreading knowledge is part of it (teaching). There is no better, faster way to distribute knowledge than through teaching"*.

It is therefore inferred that a 'top-down' approach is not only required to initially conceive and implement a suitable KM system, but the subsequent adoption and successful long term sustained use must also be actively promoted by management to prevent KMS redundancy. This in turn will then promote a 'self-teaching' organisation that can readily access, retrieve and learn from a well-structured and organised knowledge management system.

3.1.2 KM taxonomies and classification approaches

The organisation of knowledge is critical to ensure that it is accurate and widely available within large companies. In the research study on complex knowledge organisation within Institutes of Higher Learning (IHL), ***Basaruddin et al.*** (2013)

advanced that formal taxonomies provide the mechanism to map the knowledge domain and provide a standard and common understanding of where knowledge resides through the grouping of knowledge artefacts so they can be systematically developed, stored and reused.

In a separate analysis and characterization of 157 sources across 55 different companies in 16 different industry sectors ***Barnett et al.*** (2009) developed a classification system for the solution space of KM tools and methods used in Mechanical and Manufacturing Engineering (MME) organisations. In total, a spectrum of 19 different KM solution types were identified with most acting as support tools during the course of conducting business rather than solely aimed at the specific capture of explicit knowledge related to product development artefacts. This highlighted that certain key tools support dynamic decision making, and as such the information and knowledge handled may be transient and therefore not apparent in the final artefact such as; collaborative discussion forums, problem solving tools, and historical lessons learnt that help steer decision making.

Cross and Sivaloganathan (2007) conducted a 3 year study at a UK based capital equipment manufacturer to reinforce that NPD is a complex process that requires industry-specific knowledge to produce commercially viable solutions, and that it is that specialist knowledge that provides the differentiating competitive advantage. The findings of the study advanced 10 different categories of specialist knowledge aligned across 7 different phases of product development lifecycle. Many of the categories are considered as ‘metadata’ or knowledge about knowledge since, as in findings of ***Barnett et al.*** (2009), they provide crucial insights about information and data that influence decision making; country or market specific requirements, best practices, product specific parameters, interactions and trade-offs, knowledge contacts, legislation, manufacturing process capability and available materials, stakeholder behaviour and stakeholder requirements. The researchers also recognised that although it is impractical to record every piece of product knowledge during development, the capture of knowledge within the proposed specialist categories is a manageable and pragmatic approach.

3.1.3 KM Frameworks and Models

Heisig's thorough analysis of 160 knowledge management frameworks, retrieved from published works in the fields of; science, KM practitioners and Standardization bodies, sought to reveal the underlying consensus of categories used to describe KM activities (***Heisig*** 2009). The study recognised that 117 frameworks were explicitly designated to handling actual knowledge, and uncovered a total of 29 discrete categories with the majority centred on implicit/tacit to explicit knowledge transfer and the transformation of individual knowledge into organisational/collective knowledge. The study concluded that 4 key factors are considered critical to the success of KM; Culture and leadership, Organisational process and structure, technology infrastructure and applications, and Management strategies and goals. The research findings did not venture that any one of the particular 160 frameworks was supreme, but the mere existence of so many independent frameworks is highly suggestive that no single generic framework is holistically applicable.

In fact, the more holistic frameworks that provide broad general guidance on KM practices (***CEN*** 2004a, ***CEN*** 2004b, ***CEN*** 2004c) possess very limited insight on the practical steps required to construct KM systems. The research conducted by ***Pawlowski and Bick*** (2012) goes someway to filling this void by extending the considerations to include geographically dispersed teams, communications across time zones, and cultural factors. The proposed 'Global Knowledge Management Framework' (GKMF) references the earlier published works of ***Heisig*** (2009) and ***CEN*** (2004) and also integrates the complicated intrinsic views of ***Maier's*** KM architecture framework which draws on key factors at the Strategic, Design, and Operational levels within organisations (***Maier*** 2007). The combined model is the result of a litany of considerations beneath 5 core areas; business processes, stakeholder characteristics and business environment context, the knowledge held within companies and how it is used, instruments and interventions that realize the knowledge processes, and finally the knowledge that results from business operations.

The 'Model for Global Knowledge Management within the Enterprise' (MGKME), advanced by ***Grundstein*** (2005) ventured that 'core' knowledge is embodied inside people's heads. Thus, their social interactions through networked communication, combined with the *output from the core value-add business processes* should form two key components of any effective knowledge management system since they both govern the sociotechnical environment.

These equally valid, yet juxtaposed views sit at opposite ends of the KM spectrum, one end highly generalised and the other end extremely specific. However, it is envisaged that the KM infrastructure required for large scale global industry, with associated high product variant complexity and change driven by continuous innovation should possess both breadth and depth.

3.1.4 KM and ICT Application Tools

Recent research conducted by ***Pirkkalainen and Pawlowski*** (2013) focused on the implications of Social Software Tools (SST's) when considered in the context of global knowledge management. The study adopted the stance of identifying and mapping SST's to 7 stages of the knowledge management lifecycle; create, organize, formalize, distribute, identify, apply, evolve. The SST's identified were believed to provide an effective means of dynamic communication between geographically dispersed individuals located across large multinational global enterprises. The array of SST's include; wiki's, social networking, instant messaging, message boards, blogs, discussion forums, and online conferencing tools which were all identified as targeted ways of improving both communication and collaboration across enterprises. The study looked at multiple sources of prior secondary research to establish the major barriers and challenges for wide-scale adoption of SST's. This approach and findings are equally supported by recent research by ***Evans*** which examined the growing popularity of social media tools in supporting tacit knowledge transfer through the course of PD in the aerospace and defence industry (***Evans et al.*** 2012, ***Evans*** 2013).

A similar research stance was adopted by ***Louw and Mtsweni*** (2013) in their qualitative case study on the adoption of Enterprise 2.0 collaboration tools within a large South African ICT enterprise. Interestingly, although enterprise 2.0 is defined as the application of web 2.0 technologies within an enterprise environment to allow employees to collaborate, share ideas, communicate and generate content; there is no specific mention or commentary on web 2.0 content management systems where users are encouraged to contribute explicit knowledge artefacts in the study. It is therefore inferred that SST's are generally more considered to be the collection of ICT web based tools through which tacit knowledge is socialised and externalised remotely between individuals and groups in support of ***Nonaka and Takeuchi's*** (1995) SECI model. This view is supported by ***Hazlett et al.*** (2005) when they proclaimed that knowledge management has moved away from the traditional static-explicit 'knowledge-warehouse' computational paradigm. Web 2.0 applications are instead more concerned with the dynamic-tacit dimensions of the new people-centric organic paradigm embodied within communication-based networks.

In the grounded research case study conducted by ***Paroutis and Saleh*** (2009) the participants were asked questions on the barriers to successful use of web 2.0 tools, specifically willingness to contribute their own knowledge. The respondents cited information overload and inability to navigate to the information they needed as a main issue. The respondents were equally reluctant to contribute user generated content due to concerns on available time, whether anyone else in the company was interested in the artefacts and would use them, and whether anyone would be able to find them.

In the research survey conducted by ***Andriole*** (2010) the participants from the IT, Pharmaceutical, real estate and financial services industries were asked a series of questions on the business impact of web 2.0 technologies. When asked the question as to which business areas web 2.0 tools had the greatest impact the overwhelming response was collaboration and communication (81.6%), followed by knowledge management (53.9%), and then innovation (21.1%). This study focused on a broad array of SST's, but very limited attention was directed at web 2.0 'user-generated' content management system adoption for centralised explicit KM.

3.2 KM in Product Development & Systems Engineering

The next sections now present the notion of knowledge management as applied in the fields of product development and systems engineering.

3.2.1 KM in Product Development

In the automotive industry case study conducted by ***Zhang*** (2011) a KMS based on an Enterprise Architecture Framework (EAF) structure is proposed. The study proposes an 'easy-to-use' ICT folder system directed for the capture of explicit unstructured knowledge artefacts created during the course of NPD. The case study was conducted within an automotive manufacturer based solely in China and consequently there is limited consideration for the potential contribution from globally dispersed partners within the extended enterprise. Furthermore, the relatively simplistic NPD stage-gate process (***Cooper*** 2008) adopted lacks any of the necessary KMS considerations required for handling multiple concurrent systems engineering projects, and any broad participation from PD teams simultaneously delivering manufacturing projects across multiple regions.

The research conducted by ***da Silva and Rozenfeld*** (2007) conducted a case study within a Brazilian truck and bus manufacturer. The study focussed on 4 main operational dimensions that surround the PD process; strategy, organisation, activities, and resources. The authors suggest that in reality PD is actually a *non-structured process involving thousands of minor interdependent decisions conducted in the context of constant technological and market modifications that can affect the products future launch*. The study looked at 30 different PD process sub categories and how well each was found to align to the four dimensions of the SECI model. Once again the findings of this project were constrained to an automotive company operating in a single geographic location following the simplistic two-dimensional stage-gate process for NPD. No consideration was given to the value of making unstructured explicit NPD knowledge widely available to support continuous improvement once in operational service.

Conversely, the research conducted by ***Bradfield and Gao*** (2007) acknowledged the challenges imposed on KM systems when considering the broad array of participants with varying levels of PD experience engaged in global product development. The research highlighted knowledge sharing implications caused by multilingual requirements and how that may be met using meta-knowledge based synonyms with structured ontologies created using web-based *Protégé* ontology editor. The industrial case study, conducted within a large European heating systems manufacturer, focused on three sub process stages from the single conceptual design phase of the NPD lifecycle; *Project performance, generate project proposal, and product validation*. Although the narrow study was intentionally constrained it provides valuable insights as to how meta-knowledge may be practically employed to help organise knowledge and increase the chances of successful retrieval and re-use.

A separate publication by ***Bradfield and Gao*** (2008) extended the research to consider the wider application of meta-knowledge to facilitate knowledge sharing across all seven identified PD processes; *product strategy, product conception, functional design, detailed design, product and manufacturing process test and verification, industrialisation, and post launch product review*. The underlying proposition is that the provision of appropriate meta-knowledge classification ontologies should enable engineers to waste less time searching for knowledge artefacts directly linked to outcomes of each stage of the NPD process. The concept of meta-knowledge is of particular interest to this research, but the study was limited to a heating system manufacturer, and so the implications on extending the methodology to complex automotive systems and large scale multinational manufacturing need to be explored and tested.

3.2.2 KM for Systems Engineering Management

According to ***Baughey*** *'Systems Engineering (SE) forms the very centre of all product development activity, providing the framework from which the automotive community develops products and technology'* (***Baughey*** 2011a). The traditional views of the systems engineering 'V' model (***INCOSE*** 2011) are partitioned based on 4 sequential phases 'RFLP' that drive the systems engineering effort; initial Requirements, Functional analysis, definition of the Logical architecture, Physical product; which then goes through prototype test, integration and validation before full scale production as shown below in Figure 13.

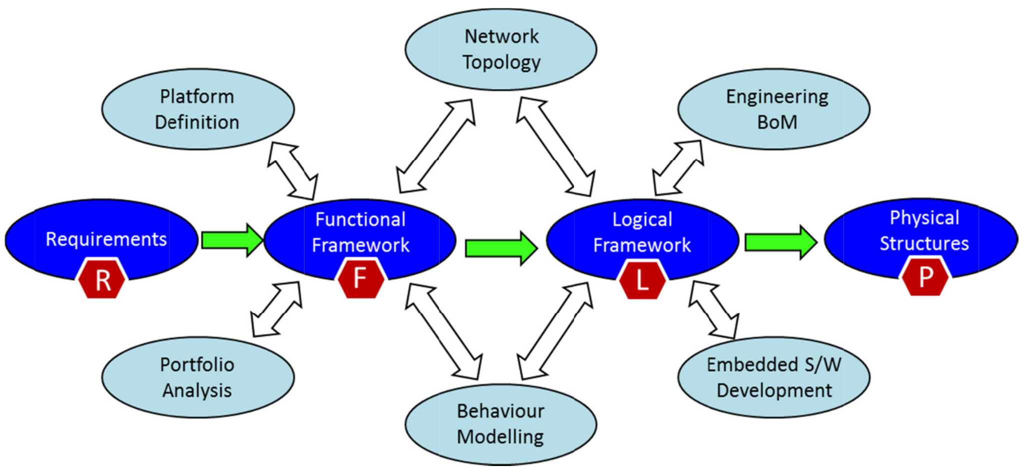


Figure 13. RFLP Systems Engineering Model (Baughey 2011a)

SE methodology embodies the collection of domains that embrace a plethora of tools and processes including; requirements management, architectural design, simulation modelling, prototyping, project management, acquisition and supply, quality management, design verification, production validation, etc.

Although the proposed framework does much to clarify the core systems engineering phases, the two dimensional characteristic of the proposed architecture, based on the systems engineering process only, provides no formal KM support mechanism for the unstructured knowledge input and resulting output generated in each subsequent phase of the systems engineering lifecycle.

In the published work of ***Gausemeier et al.*** in the field of mechatronics, the team asserted that *systems engineering is a powerful approach to manage product development* as there are intrinsically both technical and managerial components. The CONSENS ('CONceptual Design Specification Technique for ENgineering Complex Systems') model is proposed, which enables views on the 'big picture' of product development (***Gausemeier et al.*** 2013). The core elements are then assembled in the System of PD model in Figure 14 below;

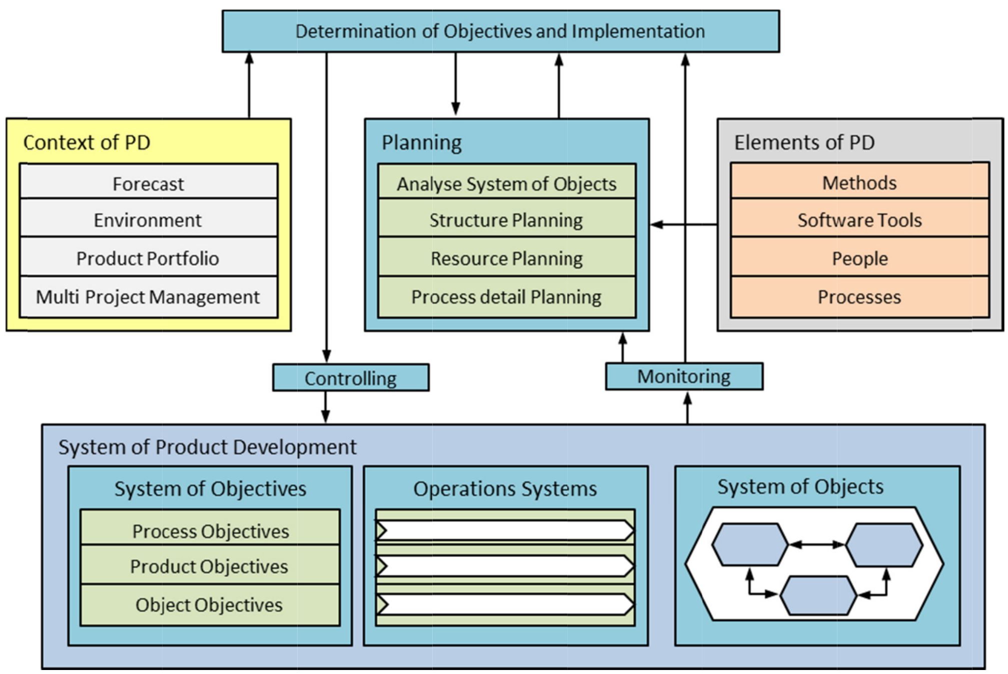


Figure 14. System of PD model (Gausemeier *et al.* 2013)

The 7 layer model presented in Figure 14 suggests the following elements are most critical; operational environment of the system, application scenarios, performance and attribute requirements, hierarchical sub divisions of system functionality and IPO analysis, active structure definition and interface relationships, 3D shape definition, and behaviour related to the mechatronic modeller built into the developed tool structure. The final conceptual model defines the inter-linkages between many of the vital key elements of PD and SE; but in isolation provides no direct ontological taxonomy from which to adopt the model as an integrated framework for an automotive PD based KMS.

ISO 9001 standard for Quality Management Systems (***ISO*** 2015), and the Technical Specification for its application for automotive production and relevant service part organisations TS 16949 (***ISO*** 2009), both make strong reference to the requirements for the control of documents such as engineering specifications, and the control and retention of records. Furthermore, within section 4.2.4 of TS 16949 (***ISO*** 2009) it specifically highlights the need to for the organisational Quality Management System (QMS) to define the documented controls needed for the identification, storage, protection, retrieval, retention and disposition of records. Additionally, section 7.3 of TS 16949 (***ISO*** 2009) then states that the automotive organisation is also required to identify and document all product design and manufacturing process inputs, as well as the evidence used to verify and validate that the design and development *outputs* meet the original *input* requirements.

Annex B of ISO 15288 standard for Systems Engineering – Systems Lifecycle Processes (***ISO/IEC*** 2008) strongly references the purpose and expected outcomes from the six SE lifecycle stages;

i. Concept
ii. Developmental
iii. Production
iv. Utilisation
v. Support
vi. Retirement

Although the outcomes are extensively listed they only give generalised insights into the themes for the likely types of knowledge that will be generated as part of the SE process. The ISO standards for QMS and SE both define the need to holistically conform to generic requirements, but neither makes any attempt to identify which types of detailed records or knowledge artefacts should be retained, or any proposal for a recommended KM system structure. In fairness, this is not to be unexpected from either ISO standard as both are general industry guides aimed at providing a framework for '*what*' should be done rather than specifically '*how*' it should be achieved.

3.2.3 KM to Support Automotive Systems Engineering Reliability

The field of automotive systems engineering reliability is shrouded in complex statistical mathematics. However, at the core of the subject lies the simple definition, *'Reliability is failure mode avoidance'* (***Clausing*** 2004, ***Davis*** 2004, ***Henshall and Campean*** 2009). This definition is then divided into two types of failure mode;

i. Hard failures – system ceases to perform its primary function (broken)
ii. Soft failures – system continues to function at a degraded performance level

Each type of failure mode may be attributed to either of two fundamental root causes;

i. Lack of useful life robustness (sensitivity to noise factors)
ii. Mistakes in manufacturing and assembly.

Therefore, a reliable product is mistake free and robust to noise factors throughout its useful life. In the real world application of FMA ***Campean et al.*** (2013) describes how complex *systems-of-systems*, such as automotive vehicles, must be decomposed into both the main functions and also the interface functions between adjacent systems within the logical architecture. The approach emphasises 4 core focal areas; function analysis, function failure analysis, robust countermeasure development, and robust design verification as illustrated in Figure 15 below.

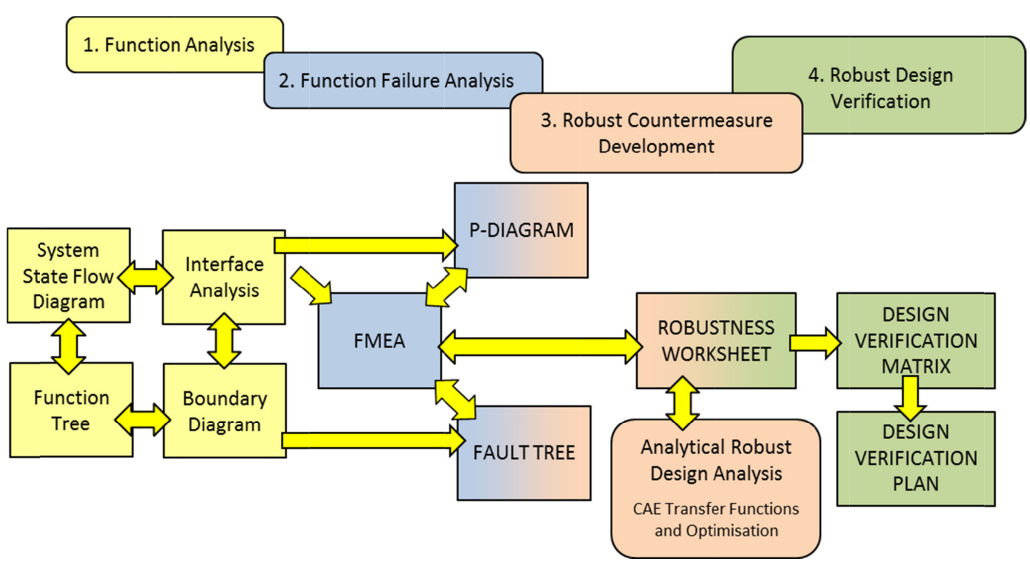


Figure 15. Failure Mode Avoidance Process Schematic (Campean *et al.* 2013)

Technical insights are provided on the practical application of the FMA process through a worked case study on an automotive exhaust system. The study demonstrates the complicated inter-linkages between the 10 critical SE knowledge documents (Figure 15). To guarantee a complete and successful outcome the approach must be applied to all levels of the vehicle system, sub system and components, and be integrated into the PD process from start to finish on every single vehicle program. This signifies how it is imperative to organise and manage the vast volume of crucial SE knowledge perpetually generated during continuous innovation.

In the technical paper presented by ***Fritzsche*** (2006) the theoretical application and best practice guidelines for constructing 'Parameter' diagrams is reported. Critical definitions for system input signals, noise factors, controls factors, ideal response and error states are presented which provide valuable insight regarding the comprehensive wide array of knowledge types employed in both failure mode avoidance and conversely in failure mode investigations.

In contrast, ***Heyes*** (1998) examined four physical case studies of actual real-world automotive failures. Photographic evidence is used to demonstrate the nature of the failed parts resulting from manufacturing and material defects. The background to the study is firstly augmented with an overview of the distribution of failures by component type and then secondly the distribution by root-cause demonstrating the essential need to categorise failure mode knowledge in context using an intuitive taxonomy and common lexicon. The research solely focuses on metallurgical hardware failures, but provides useful insight into the techniques employed and types of materials knowledge utilised when conducting such investigations.

Conversely, the research paper published by ***Saxena et al*** (2015) adopted the definitions for three FMA taxonomy structures cited in the prior research below;

i. Classification of *functions* (***Pahl*** *et al.* 2007)
ii. Classification of *failure modes* (**Blischke and Murthy** 2000, ***Ford*** 2004)
iii. Classification of *failure causes* (***Tumer et al.*** 2003, ***Uder et al.*** 2003)

The above classifications are expanded in greater detail in chapter 5.

3.3 KM for Collaboration in Extended Enterprises

The next sections now present the considerations of knowledge management from an organisational perspective within the fields of collaboration and extended enterprises;

3.3.1 KM for Collaborative Innovation

Du Plessis (2007) ventured there are 4 main drivers for KM in innovation;

- To create, build and maintain competitive advantage through the utilization of knowledge during collaboration practices,
- To reduce the complexity of the innovation process by managing the explosion of richness and reach of new knowledge,
- The integration of knowledge that is both internal and external to the organisation such that timely insights are made available at the right juncture to enable sense and decision making and;
- To manage the various activities in the KM lifecycle through the provision of an appropriate structure coupled with organisational context.

The value proposition advanced is that KM facilitates collaboration across functional boundaries within organisations, and also across organisational boundaries through the provision of collaboration platforms such as intranets and extranets. This ensures the explicit codification of knowledge used as the source input, and also knowledge generated as the resultant output from the innovation process.

Yahia et al. (2010) asserted that for collaborative innovation processes to be effective organisations must bring together the intellectual capital that resides in the minds of its members, is embodied in its procedures and processes, and is stored in its repositories. They define 'groupware' as the collection of software applications that support groups to communicate and collaborate throughout the innovation process, which must provide the following functionality;

- Communication between actors must be structured and formalized
- Shared workspaces must facilitate KM at the collective level
- Shared workspaces must be enhanced by utilizing meta-knowledge

A high level generic framework for collaborative KM is offered, but on balance is too superficial to provide any crucial insights that inform this project.

An et al. (2014) suggest that knowledge sharing promotes collaborative innovation through the creation of new social constructs such as; value networks, wisdom of crowds, and the formation of partnerships beyond organisational physical boundaries. They view KM as a mechanism that supports community capacity building which better connects group members, improves commitment of individuals to the group obligations, enhances the group ability to solve problems, and provides vital access to shared resources. However, once again, no framework or conceptual support tool is offered and so falls short of any tangible solution.

Rosell and Lakemond (2012) conducted an extensive literature review and focus group study on supplier contribution to collaborative innovation in NPD. They acknowledged that innovation is not solely a company internal matter but is increasingly generated in collaboration with external firms, and equally commented on the valuable access to external knowledge that suppliers provide. The integration of different inter-organisational knowledge then becomes the source of organisational capability and competitive advantage that adheres to the knowledge-based view of the firm. The *K-B view of the firm* proclaims that knowledge is the critical input and primary source of value to the innovation process (***Grant*** 1996), which in turn enables better decision making, faster problem solving, and more efficient transfer of best practices. The findings of the research by ***Rosell and Lakemond*** (2012) conclude that suppliers contribute most positively to the innovation process where they are the primary providers of know-how on new technologies. It is inferred that the majority critical proprietary knowledge on new such technologies may therefore reside solely within the supplier organisation, which creates a fundamental dilemma for OEM's when executing the four main components of the FMA process model (***Campean et al.*** 2013). To overcome this there must be a much greater openness and transparency, supported by the willingness of the supplier to share certain proprietary information on new technologies, if the approach is to be successful.

3.3.2 Organisational Culture and KM

The recent quantitative survey research finding of ***Gonzalez and Martins*** (2014) affirmed the existence of eight main contextual factors that support the four KM lifecycle phases in the Brazilian automotive sector;

i. Problem solving approaches and continuous improvement strategies that exploit embedded knowledge within the workforce (knowledge acquisition and utilisation).

ii. A learning culture that supports the creation of new knowledge, and teamwork that then encourages its subsequent dissemination (knowledge acquisition, storage, distribution and utilisation).

iii. An organisational culture and infrastructure that facilitates communication and interaction between individuals and across divisions within companies, and promotes the distribution of new knowledge (knowledge acquisition, distribution and utilisation).

iv. Shared identity and common language between individuals that creates trust and encourages primary knowledge transfer (knowledge acquisition, storage, distribution, and utilisation).

v. Knowledge absorption capability defined by a well-educated and diverse workforce that is able to acquire and then subsequently exploit new explicit knowledge during the course of collaborative innovation (knowledge acquisition and utilisation)

vi. Cognitive abilities that define the competence of individuals to act as retention agents for tacit knowledge, and subsequent aptitude to recall and exploit the knowledge acquired in practical situations (knowledge acquisition, storage, and utilisation).

vii. The innovation strategy of the company that intends to exploit the capabilities of the corporate knowledge base embedded within the workforce as a means through which to gain competitive commercial advantage (knowledge Utilisation).

viii. The information system as defined by the suite of tools that enables the retention of explicit knowledge and its subsequent dissemination (knowledge storage and distribution).

The underlying proposition is therefore that one of the main tasks of KM is to create an organisational context that encourages the creation and dissemination of new knowledge as a continuous process.

Alavi et al. (2006) also adopt a similar knowledge-based view of the firm that understands the intellectual resources possessed by a firm are the key organisational assets that enable sustained competitive advantage. The ability to effectively manage knowledge resources enhances customer services, enables better decision making, faster problem resolution, and more efficient transfer of best practices. The exploratory case study research, conducted at large global US based high-tech firm, was directed at seeking detailed insights into the specific relationship between organisational values and the implications on KM practices and tools. The study concluded that differences in cultural values within firms can lead to divergent outcomes in individual and organisational use of KM systems. As such, the team recommended several countermeasures;

- The development of KM systems that incorporate technical features and broad functionality that appeals to all the cultures they will be embedded within.
- Build a social environment within the workplace that values effective KM behaviours and fosters knowledge-related collaboration.
- Develop KM tools that harness and accumulate intellectual capital and encourage organic growth of KM communities that are driven by the social connection and interaction between diverse cultures and geographically dispersed teams.

The ***European Guide to good Practice in Knowledge Management*** working group findings collated many of the mechanisms and approaches that create the right cultural environment for KM (***CEN*** 2004b). The workshop agreement focused on human and cultural aspects such as trust and motivation, change management methodologies and business processes as key enablers towards multidisciplinary knowledge sharing, communication and collaboration. Thirteen barriers to KM are ventured, among which the notion of 'organisational amnesia' is described as the failure by organisations to retain knowledge and lessons learned as employees exit companies and no retrievable record remains. Corporate apathy towards KM, particularly driven by commercial pressures to focus on priorities to deliver against cost and time schedules, must also be balanced with formal management expectations and sustained leadership that values and recognises the credibility of individuals to develop and share their own knowledge within self-organizing groups and communities of practice.

3.3.3 KM for globally dispersed projects and Extended Enterprises

Filieri and Alguezaui (2012) define the Extended Enterprise (EE) as the set of collaborating companies that includes suppliers, vendors, buyers and customers; both upstream and downstream from raw material to end-use consumption, that bring value to the market place. The EE organisational model is therefore considered flexible and adaptive as it fosters knowledge-sharing activities between different partners to improve innovation performance. The firm central to the EE manages all activities related to acquiring, sharing, and integrating knowledge that accelerates the decision making process and creates value for all members of the relational network.

Extrapolating the concept of the EE, ***Adenfelt and Lagerstrom*** (2005) studied the importance of leveraging knowledge in Multinational Corporations (MNC's) as the central focus of the case study research on transnational projects. The enablers for knowledge creation and sharing are broadly categorised into two perspectives;

i) The social dimension including organisational culture, structure and people, and
ii) The technical dimension centred on communication technologies.

The study concluded that centralisation and formalisation of knowledge is of paramount importance to ensure that all participants are afforded the same level of access to the important flow of project knowledge that informs decision making. However, the team also concluded that although the corporate intranet made it possible to access explicit knowledge, it could not replace the tacit knowledge socialisation and transfer imparted during face to face meetings. In this respect, ICT only compliments the social knowledge transfer process rather than substituting it. It is however acknowledged that since that period the rise of web based conferencing, instant messaging and numerous other social media tools have overtaken the need for regular direct face to face contact, and have equally reduced business travel costs.

3.4 Literature Review – Synthesis

The literature review sought to closely examine the prior research studies carried out within the fields of collaborative product development and systems engineering where knowledge management was the central unit of analysis. There now follows a brief summary of the findings;

The need for improved KM practices and solutions appear to approximately follow the same set of motivational factors throughout the literature. These included the loss of vital knowledge caused by churn and attrition of knowledge workers driven by organisational restructuring, downsizing and captive offshoring. The loss of experienced knowledge workers through retirement is a further key factor.

The *knowledge-based view of the firm* holds that KM enables better decision making, faster problem solving, and more efficient transfer of best practices. The potential key benefit of effective KM also includes improved organisational learning and effective capture of lessons learned. However, although the literature states that it is critical to 'map' the knowledge domain in order to establish a standard common understanding where knowledge resides; it is also argued that it is pragmatic to only attempt the capture of specialist categories rather than all industry specific knowledge. In this respect the literature states that meta-knowledge is a key enabler to improve the chances of success when searching within large knowledge-bases.

However, many of the proposed approaches are disparate and directed at discrete sub issues within KM rather than any holistic approach towards supporting the systems engineering effort throughout the complete product lifecycle. Those that did specifically examine automotive product development were solely constrained to the early phases of product development; design requirements, conceptual design, and rapid prototype development. In this respect no attention has been given towards establishing an integrated framework to represent the continuum between the knowledge utilised in the original PD program and new knowledge acquired through investigating and resolving product functional reliability failures in operational service.

Furthermore, existing frameworks that attempt to align KM with global collaboration were found to be too generalised and conceptual in nature. Consequently many of the abstract frameworks lacked any tangible alignment with the real world SE knowledge transactions between globally dispersed teams across large scale extended enterprises. In this respect, no formal methodologies for defining taxonomies or classification systems have been advanced that accommodate all critical dimensions and facets of global product development operations, including; stakeholder requirements, product family portfolio and sub system hierarchies, systems engineering technical processes, product development and project management processes.

Similarly, although there is a reasonable body of literature dealing with the subjects of systems engineering and failure mode avoidance principles and tools, no prior research appears to have attempted to establish any form of meta-knowledge classification scheme to facilitate the effective capture of new knowledge learned during the course of investigating product functional reliability failures. This knowledge is considered critical if a firm is to learn from the costly mistakes of the past and put necessary actions and safeguards in place to prevent future reoccurrence.

Many of the publications bestow the virtues of web 2.0 ICT tool solutions as an efficient means to improve knowledge sharing, collaboration and communication. There is a clear distinction in philosophies between those advocating social software tools aimed at enhancing tacit knowledge transfer capabilities by leveraging the *'wisdom of crowds'*, and those aimed at explicit knowledge capture and sharing through the use of structured knowledge-bases. Since the latter is the prime focus of this research it is important to reiterate that several publications also cautioned that the key barriers precluding the success of such tools include information overload, inability to navigate intuitively, lack of available time to populate, and lack of adoption by others. Corporate apathy towards KM is also a key contributor to the failure of ICT solutions which can be mitigated by sustained leadership that proactively recognises the credibility of individuals to share knowledge in self-organising groups.

3.5 Identified Research Gaps

The synthesis of the literature review informed the development of the following research gaps.

GAP 1: ***ISO/IEC*** (2008) describes the generalised outcomes from each SE lifecycle phase but the standard does not identify or prioritise the particular types of valuable automotive SE knowledge that should be captured for future sharing and re-use. Furthermore, the current literature has also not advanced any suitable SE KM taxonomies that account for the complexity derived from vehicle platform variant portfolio, the array of sub-system technologies, or the phase within the vehicle SE lifecycle. This aspect will be addressed by research objective 1 (table 2).

GAP 2: No specific reference could be found within the literature that defines the knowledge transactions between the various actors throughout the automotive extended enterprise in each of the different phases of the SE lifecycle. This aspect will be addressed by research objective 2 (table 2).

GAP 3: No identification of knowledge utilised during the course of investigating product reliability failures during vehicle operational service could be found within the literature. Equally, no suitable methodology for establishing an appropriate meta-knowledge classification scheme could be found. This aspect will be addressed by research objective 3 (table 2).

GAP 4: Existing KM frameworks are too generalised and lack any tangible alignment to the real world knowledge interactions between geographically dispersed teams and the systems engineering knowledge transactions across the extended enterprise. Equally, no meta-knowledge classification systems could be found that connect new knowledge regarding vehicle reliability performance issues during operational service back to the integrity of the Systems Engineering core knowledge used in the original vehicle PD program. These aspects will be addressed by research objective 4 (table 2).

GAP 5: ***ISO*** (2009) makes clear reference to the general requirements for control of documents and records retention. However, the standard provides no framework or methodology for developing a KM support tool for the capture, sharing and re-use of unstructured SE knowledge generated during the course of continuous innovation on multigenerational platform programs. These aspects will be addressed through the research aligned to objective 4 (table 2).

GAP 6: Although much of the literature on KM frameworks attempts to address the complications of connecting globally dispersed teams none could be found that developed a working ICT support tool to evaluate the KM framework proposition. These aspects will be addressed through the research aligned to objective 5 (table 2)

It is envisaged that exploring the above identified research gaps will address the research aim and contribute new knowledge in the KM domain.

The juxtaposition of this research project between the domains of Systems Engineering and Quality Management Systems is shown in Figure 16 below.

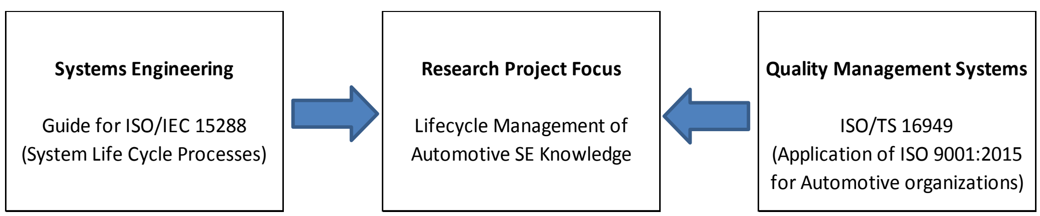


Figure 16. Juxtaposition of this Research Project

3.6 Initial DRM Models

This section presents the *initial DRM reference and impact models* developed from the findings of the provisional state-of-the-art literature review (refer to Figure 9). The initial DRM models were constructed using the graphical notation advanced by ***Blessing and Chakrabarti*** (2009) as presented in section 2.3.

3.6.1 Initial Reference Model

The basic initial DRM Reference model, shown below in Figure 17, depicts the relationship between the organisational ability to deliver the required SE integrity with each new product offering launched into the market place, irrespective of the region where the vehicle is built or sold *(See Figure 10 for DRM Notation)*.

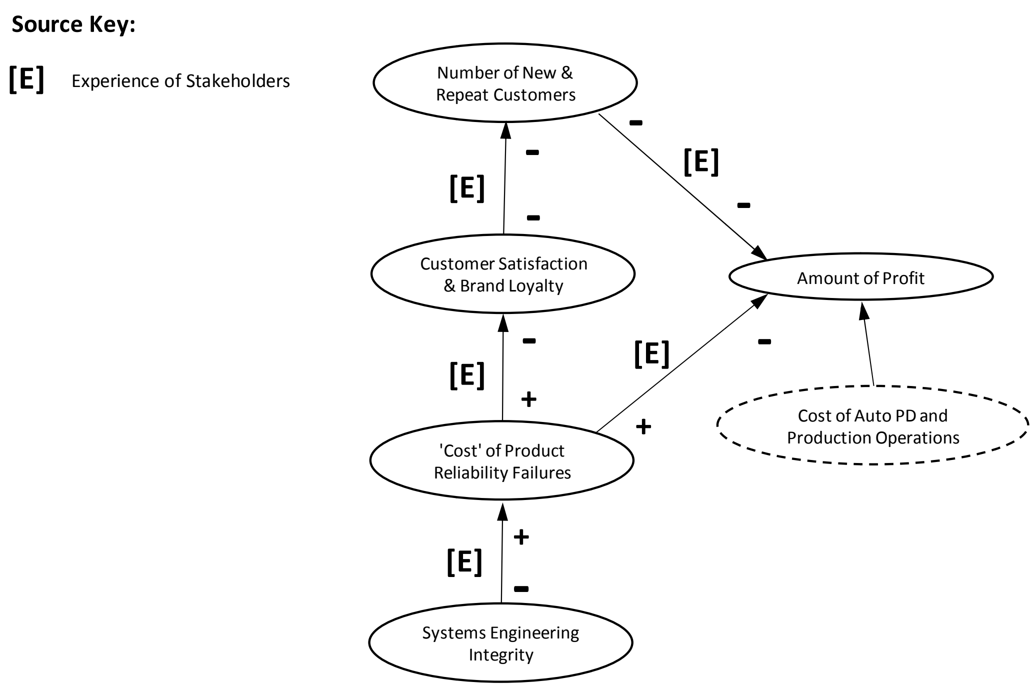


Figure 17. DRM – Initial *Reference* Model

The original assumption, based on the literature review and industrial experience is that a sub optimal organisational capability in delivering the required SE integrity is linked to the increased potential for product reliability failures, which in turn is linked to an increased 'Cost' to the business through reduced profits. In this context 'Cost' is attributed to both the direct tangible costs incurred through vehicle repairs and associated warranty obligations, as well as the 'softer' intangible costs associated with customer dissatisfaction and loss of brand loyalty.

3.6.2 Initial Impact Model

In order to better support the organisation in reducing the propensity for product reliability failures the initial DRM Impact model, shown in Figure 18, depicts the envisaged benefits that may be achieved by defining the requirements for a KM support tool which could help improve system engineering integrity on all subsequent multi-generational vehicle platform programs *(See Figure 10 for DRM Notation).*

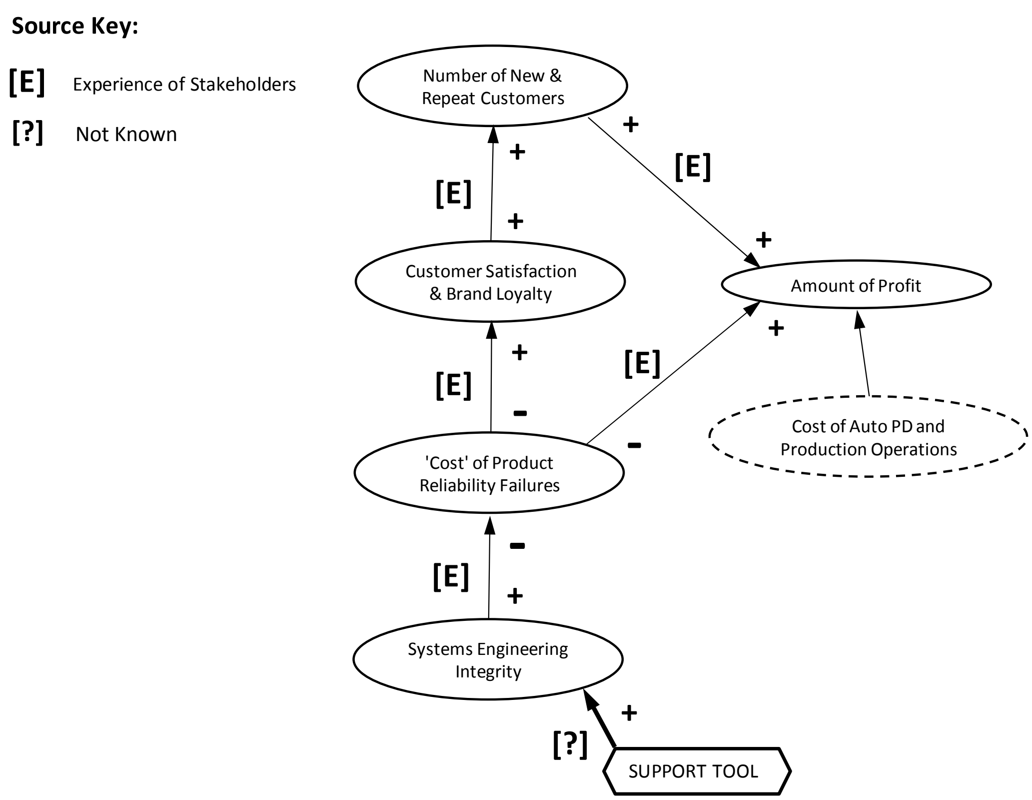


Figure 18. DRM – Initial *Impact* Model

The research presented within the remaining chapters of this thesis therefore aims to ascertain if such a support tool could achieve the proposed benefits as described in the above initial DRM *Impact* model. The next chapter presents the approach and findings of the industrial investigation which was conducted in order to establish the current KM practices and challenges encountered within a real-world industrial context.

4 INDUSTRIAL INVESTIGATION

4.1 Introduction

The industrial investigation was conducted at Ford Motor Company, a large multinational automotive OEM with a vast and diverse extended enterprise that comprises of highly intensive product development and large-scale manufacturing. The purpose of the industrial investigation was to research the critical aspects of the company that support the primary two objectives;

i. Conduct an exploratory industrial investigation with Automotive PD practitioners focusing on the real-world application of systems engineering knowledge.

ii. Propose an automotive enterprise architecture model to represent the knowledge transactions across the extended enterprise throughout the SE lifecycle.

The industrial investigation was designed to progress through five distinct stages (adapted from the prior research by ***Bradfield*** 2007), each aimed at improving and widening the generalization of issues found as shown in in Figure 19.

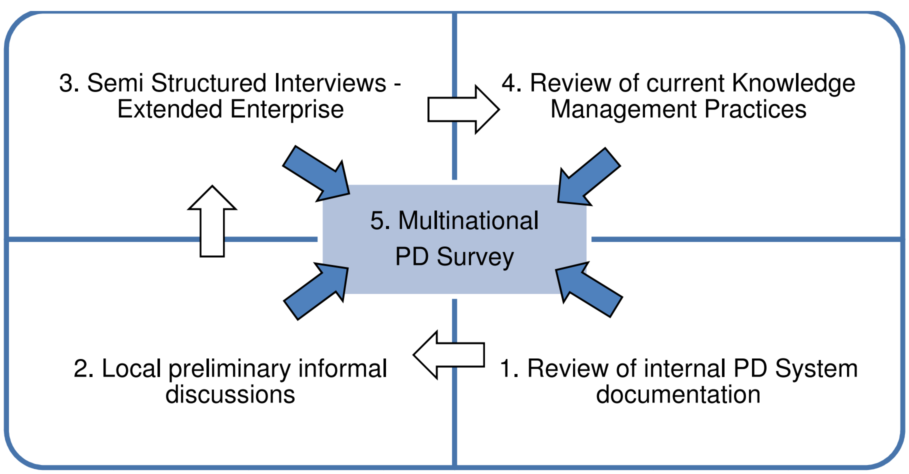


Figure 19. Industrial Investigation - Five Stage Approach

The first stage was to secure all company documentation pertinent to the key elements of ***product, people, processes and tools***. This stage was undertaken in order to inform the research with a greater richness and understanding of the interlocking units that form the global PD system within the company.

The second stage involved informal discussions with a small number of locally based engineers in the UK PD centre. These discussions were aimed at understanding the general complexities and issues faced with knowledge creation, storage and retrieval.

Once the general areas of concern had been captured in the preliminary informal discussion the third stage was to refine the approach and more centrally focus on the issues raised through conducting a number of semi structured interviews with a wider audience across the extended enterprise, including engineers based in other countries and also engineers based in supplier companies.

The fourth stage was to review the current knowledge management practices already employed within the company, and thereby generate a classification of the ontologies, hierarchies and taxonomies employed.

Finally, the fifth stage was to construct a web-based multinational PD survey, which was deployed to a vast number of PD engineers across all regions, and centrally focused on the key issues and themes raised from the first four stages.

4.2 Overview of Ford Motor Company

Ford Motor Company is a global automotive industry leader headquartered in Dearborn, Michigan USA. In 2015 the company manufactured and distributed 6.6 million vehicles across six continents. Worldwide Ford has approximately 200,000 employees, 65 vehicle assembly plants, and is organized by five regional business units: North America, South America, Europe, Asia Pacific, and Middle East & Africa.

The Ford Sustainability Report (***Ford*** 2015) is published annually and highlights the key corporate priorities to address the long term sustainability of the company. In the context of this research project Ford places the following among the top priorities; Product Innovation, Mobility Innovation, Brand Perception, Supply Chain Management and Capacity Building, and Product Quality (**Appendix B**).

Ford's Global Supply Chain

Ford's complex supply chain manages 100,000+ purchased parts from 1,400+ external part suppliers which drives an annual expenditure exceeding $110 billion/year. Ford's global supply chain footprint extends across 60 countries and 4,400 supplier site locations. PD and collaborative innovation are both central to the evolution of Ford's vehicle product portfolio, which in turn sustains the global manufacturing operations, business revenue, and profit from vehicle sales.

Ford of Europe

Ford of Europe produced 1.5 million vehicles in 2015, and is responsible for selling and servicing vehicles in +50 individual markets through its Ford Customer Service Division. In Europe, Ford employs +53,000 people across 13 wholly owned manufacturing facilities (increases to 67,000 people across 23 manufacturing facilities when Joint Venture partnerships are taken into consideration). The Ford PD Dunton Engineering Centre (DEC) in Essex was selected as the primary location for the initial industrial investigation.

The DEC houses +4,000 engineers and the extensive R&D facilities include high speed and special surface tracks, environmental test cells to simulate hot and cold ambient conditions, emission laboratories, rolling roads, crash test simulators and engine test cells. There are two major Ford manufacturing sites in the UK; Dagenham engine plant is central to diesel engine manufacture and assembly, whilst the Bridgend engine plant in Wales is the centre for petrol engine production.

4.3 Identified Sources for Empirical Data Collection

In the selected case study research strategy it was important to first identify potential data sources that are most likely to yield the evidence required to answer the research questions and achieve the initial primary objectives. There are six primary sources of information and data that are generally accepted in case study research (***Yin*** 2013).

The relative merits of each are outlined in Table 3 below and the specifically identified records used within this industrial investigation are highlighted alongside;

Types of Evidence	Strength	Weakness	***Identified Sources***
Documentation	Can be repeatedly reviewed. Multiple sources can enable data triangulation.	Existence of records may not be known unless declared. Biased reporting if not all records retrieved.	*Organisation charts. Bill of Material lists. Product drawings. Product Development process documentation.*
Interviews	Targeted focus directly on case study topic. Increased richness and greater insights from open ended and focused interviews.	Poorly constructed questions. Response bias. Vague recall and reflexivity. Poor response rate to surveys.	*Informal discussions (open-ended). Semi-structured interviews. Structured Global PD Survey questionnaire.*
Archival Records	Precise and quantitative. Broad coverage of many events over long span of time.	Accessibility may be blocked due to privacy or confidential nature of corporate records.	*Electronic folder system archives for files and emails embedded within local PC hard drives and shared access drives. Existing web-based Content Management Systems.*
Direct Observation	Real-time event observation in context	Reflexivity due to event being observed	Not applicable to this research project
Participant Observation	Opportunity to evaluate interpersonal behaviours and participant motivations	Bias due to investigator manipulation of events	Not applicable to this research project
Physical Artefacts	Rich insight into technical operations and culture	Selectivity unless broad coverage available	Not applicable to this research project

Table 3. Identified Sources of Evidence – Adapted from (Yin 2013)

The use of multiple sources of evidence in case studies is an accepted way for the researcher to develop converging lines of inquiry towards a process of triangulation, providing multiple measures of the same phenomena thus increasing the construct validity (***Yin*** 2013).

4.4 Corporate Documentation Review (Stage 1)

In order to establish the foundation for the research it was first necessary to gather insights regarding the three cornerstones of the PD enterprise architecture, namely;

Product – Ontological hierarchies and taxonomies that define the functional grouping of part design families.

People – Organisational structures and partitioning of responsibilities across the extended enterprise operations, internal PD teams, and the supplier network.

Processes – That govern the key stages of new product development, and continuous improvement during ongoing product development after production commences.

The strategies, policies and definitions embedded across multiple corporate documents were secured through discussions with the relevant key contacts in the company. The above three domains were used to frame the current infrastructures within the case study company and describe how the interacting business units are organized to deliver the systems engineering effort.

4.4.1 Product Structure

The Product system is a multi-layered complex ontology. It is defined at the highest level by the different vehicle platforms according to passenger car and commercial vehicles, and additionally the segment class based on the overall size (Table 4).

Class	Size / Segment	Vehicle Models
B	Small passenger car	Ka, Fiesta, B-Max
C	Medium passenger car	Focus, C-Max, Kuga
CD	Large passenger car	Mondeo, SMax and Galaxy
CV	Commercial Vehicles	Ranger, Transit

Table 4. Vehicle Classes, Segments and Model Types

At the next sub-level the product is defined by the architectural position within the structure of the vehicle, with the key distinctions of under or upper body groupings as shown in Figure 20 below.

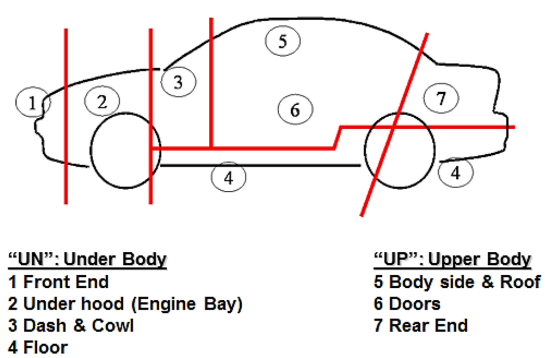


Figure 20. Vehicle Body Structure - Architectural Definition

At the next sub-level the vehicle architecture is partitioned according to a six level hierarchy within the corporate Part Address Database (PADB) as shown in Figure 21.

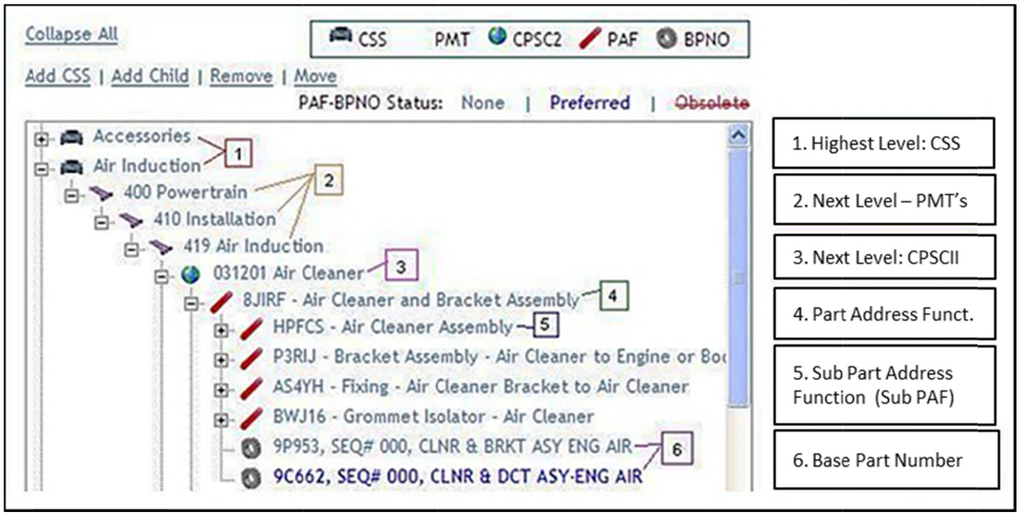


Figure 21. Part Address Database

Level 1: Common System Structure (CSS) is the logical grouping according to the different functional commodity parts that form natural ontological families.

Level 2: Program Module Team (PMT) defines the major five functional commodity engineering groups each technology sub system falls under are; PMT1 - Body Exterior, PMT2 - Body Interior, PMT3 – Chassis, PMT4 – Powertrain and PMT5 – Electrical (Figure 22).

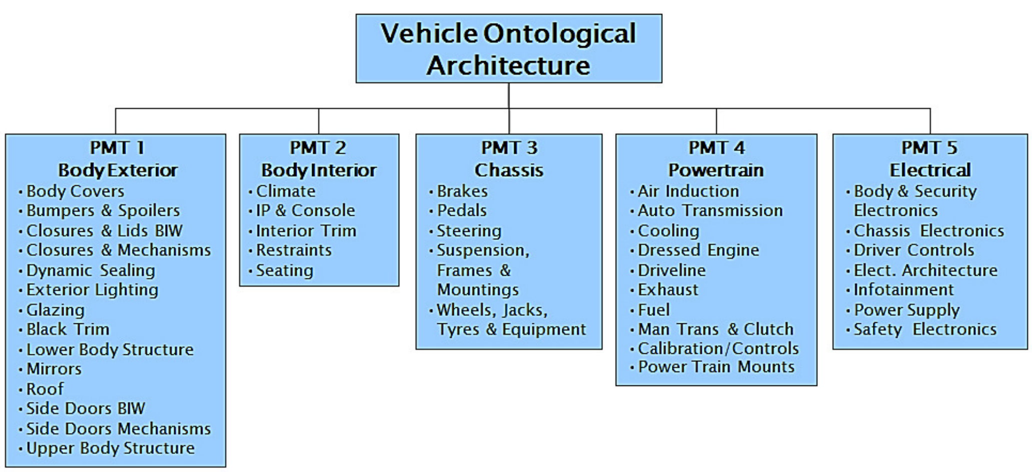


Figure 22. Vehicle Ontological Architecture – Module Teams

Level 3: At the next sub level the company strictly adheres to the Corporate Product Systems Classification (CPSCII) which uses a six digit numbering system. The first two digits classify all the vehicle parts into nineteen major modules, the second pair of digits refer to the system within the module group, and the third pair of digits call out the sub system.

Level 4: At the fourth level the Part Address Function (PAF) further defines the CPSCII coded system with a five digit alpha-numeric address code and associated plain English word description of the part assembly names.

Level 5: The fifth level is reserved for sub Part Address Functions where several component parts are bought together to form a sub assembly.

Level 6: The lowest level of granularity on product classification is the Base Part Number as assigned within the full engineering part number.

4.4.2 PD Organisational Structure

In order to ground the research in the structure of the interlinked teams engaged in the global PD operations a multitude of corporate documentation was secured in the form of organisation charts, presentations, and intranet multimedia. There now follows a brief overview of the main organisational divisions and departments;

Research and Advanced Engineering identifies and develops future technologies and features to enable technical, business and/or strategic objectives 5 to 10 years in advance of the legislative or regulatory requirement. The team has ownership of technology development from initial concept through to implementation ready for new vehicle or powertrain programs.

Product Planning and Strategy are responsible for global cycle plans, vehicle and powertrain product plans, business planning, competitive intelligence and forecasting, technology and feature planning, safety, fuel economy and emissions planning. The team is responsible for developing the future product and technology strategies and the supporting execution plans to maintain a pipeline of competitive and profitable products.

Vehicle Design is responsible for the vehicle interior and exterior styling, geometric design, material & color selection, craftsmanship and ergonomic details. The team styles vehicles to make sure they are attractive and appealing to customers. They utilize digital renditions, clay models, small 'bucks', & full vehicle concepts to help communicate the styling requirements of the vehicle.

Vehicle Engineering Systems have responsibility for the body exterior, body interior, chassis, electrical and electronics, and digital innovation and CAE. The team has engineering responsibility for all (non-powertrain) systems and suppliers to meet all vehicle performance, cost, quality, & weight objectives

Powertrain Engineering Systems are responsible for the development of Engines, Transmission & Driveline, "As Installed" systems such as air intake system, exhaust system, powertrain mounts, engine cooling, and the engine Controls & Calibration. This team has engineering responsibility of all the powertrain systems and suppliers to meet all vehicle performance, cost, quality, & weight objectives

Vehicle Product Programs includes engineering teams for each carline platform, Vehicle Engineering (VE), Vehicle Evaluation and Validation (VEV). These teams focus the efforts of all the PD commodity teams' technical capabilities to create world-class vehicles. They set the key attribute objectives including performance, fuel economy, payload, quietness, and weight.

Alongside the above fundamental PD engineering divisions resides an equally complex number of supporting teams which either feed information into the PD programs or help to manage key aspects of the business such as; sales and marketing, finance, purchasing, material planning and logistics, customer service division, new model program launch, and manufacturing.

The PD Organisation that delivers new vehicle and powertrain programs is essentially a global 'Matrix' organisation. This structure aligns responsibility for program delivery under Global Chief Program Engineers (CPE's), and the Chief Functional Engineers (CFE's) that each have the responsibility for commodity functional engineering design and development.

4.4.3 PD Processes

The product development project processes employed by the company reside within the Global Product Development System (GPDS), which is strictly imposed companywide for all NPD. The overall architecture of GPDS follows the Integrated Master Plan (IMP) stage-gate approach (Cooper 2008).

The GPDS process aligns key program milestones and gateways with the Work Breakdown Structure (WBS) of the numerous departments that provide the inputs and outputs as the program passes through the sequence of chronological program events. There are a total of fourteen standard program milestones, and eight engineering gateways, which are divided between the upper and under body technology groups.

The Engineering Quality Operating System (EQOS) is embedded within GPDS. The EQOS is a collection of standardised tools and practices that are systematically applied throughout the course of every new vehicle program. The EQOS is defined by seven main procedures below, each of which has several sub processes to ensure each new vehicle program is able to track and manage the engineering tasks for each and every vehicle sub-system part number.

Consumer focus: Determination of new vehicle technical content, and competitive positioning of product functions and attributes, to meet/exceed customer satisfaction.

Target setting: Development of customer driven satisfaction metrics for attributes and functions, including quality and performance metrics.

Technical requirements: Development of transfer functions to demonstrate the link between customer defined attribute requirement and how it is satisfied technically to meet the customer requirement.

Robustness Engineering: Application of failure mode avoidance tools to ensure the new vehicle delivers the intended attributes and functions for the complete intended useful life without interruption of influence due to internal or external noise factors.

Mistake Prevention: Establish manufacturing quality control plans for externally supplied sub-systems, and the final assembly processes in the vehicle plants.

Design Validation: Develop and execute the Design Validation plan (DVP)

Production Verification: Develop and execute the Production Verification plan (PVP)

The main complex powertrain technologies (Engines and Transmissions) are developed separately, typically at least six months in advance of the vehicle product development timeline, to ensure the engine and transmissions assemblies are sufficiently mature to be integrated into the first vehicle builds on time.

Once the initial digital prototype assembly (DPA) exercise has confirmed that all interfacing parts are compatible within the 3D package environment there are two physical prototype vehicle build and test phases which form part of the initial engineering design validation sign-off. Once these have successfully completed test, and passed through the final engineering gateway, the program then transitions into the initial phases of the manufacturing plant based vehicle builds.

The production verification builds are manufactured in the intended vehicle operations assembly plant and then tested according to the PVP. Where necessary the teams further refine the engineering and quality robustness before final authorisation is given for supplier manufacturing and vehicle assembly plants to proceed and ramp-up to full scale volume product launch.

4.5 Local Preliminary Informal Discussions (Stage 2)

Having secured and reviewed the company documentation in the first stage of the industrial investigation, the second stage then centred on a number of informal face-to-face discussions (see Figure 19).

The approach employed was to initially hold informal discussions with a number of Ford engineers from different teams, working on different part type designs, and with a varied cross section of background and number of years' experience working in the industry.

The engineers involved included a mix of Design and Release (D and R) engineers that work on New Product Development (NPD) for future model programs and 'Ongoing Product Development' (OPD) engineers that maintain current model product quality and integrity. The specific pool of engineers approached worked within the Transmission, Clutch, and Driveline teams in the Powertrain division at the UK based PD facility in Essex.

The following four fundamental KM themes were adopted to prompt the discussions (Pitt and MacVaugh 2008, Durst and Edvardsson 2012, Gonzalez and Martins 2014);

- **Creation** - *capture, acquisition, generation or identification*.
- **Storage** - *archiving or retention*.
- **Sharing** - *diffusion, dissemination, mobilization, distribution or transfer*.
- **Reuse** - *adoption, retrieval or utilization*.

Each of these four areas were also discussed in the context of both structured and unstructured knowledge types since the former is typically stored and accessible through formal PLM systems, whereas the latter is more disparate and uncoordinated. The main findings of the preliminary informal discussions are now summarised;

Organisational 'churn' was cited as a fundamental concern towards the inability to locate critical knowledge. This generally results from several factors whereby the key contact who had worked on particular aspects of product development was no longer directly accessible due to reasons such as; they had resigned from the company, had been promoted, or had moved into another department.

A further dimension was the resulting loss of knowledge caused by organisational restructuring that caused complete teams or departments to be disbanded and the PD work to be migrated to another geographical location. In this instance it was mentioned that the quality of handover documents and files varied greatly and one respondent noted “just because you’re given an entire lifetimes worth of background and history on a memory stick by your predecessor, it doesn’t mean it’s organized in such a way that you can make sense of which files contain the particular information you’re looking for”.

When questioned why this was the case it became evident that the lack of any formal notation for file naming convention was the main cause, with the majority of documents saved with very closely matching filenames such as ‘Clutch analysis’ or ‘Bearing calculation’ etc. Consequently, many such handover files which fall into the category of unstructured knowledge documents were considered difficult to work with and were quickly forgotten.

Another common response was that the sheer volume of information exchanged via email causes a form of ‘paralysis’ as engineers simply end up spending a good portion of each working day dedicated to reading and comprehending information sent to them; and then deciding whether attached large files should only be stored with the email within their .pst folder system, or also stored separately out of context without the email as a separate file on their local PC hard drive.

To complicate matters further, the originator of the email would quite often send the file to multiple recipients who all then save local versions of the file, and may in turn reissue the email to many more colleagues around the global organisation; causing a massive proliferation of the same media stored in multiple locations.

It also became apparent that there are three discrete engineering teams working on different stages of the Product Life Cycle (PLC) at any one time, and the knowledge documents generated by each group is often also required by the other groups.

The ***CORE engineers*** have total global responsibility for commodity design and engineering sign-off on all vehicles programs, thus assuring all designs are ‘fit-for-purpose'. They are also responsible for the quality foundation documents that comprise the failure mode avoidance plan for each program. The ***CORE engineers*** also work closely with the supplier engineering teams in the early conceptual stages to establish design alternatives that will satisfy the quality, cost, weight and functional requirements.

The ***NPD application engineers*** then 'adopt' the bill of material for the group of parts to then take the selected design through the program systems engineering disciplines to ensure the parts are truly robust during assembly testing on supplier rigs and full vehicle testing on the proving ground. However, the core and application engineers must work closely together with the supplier engineers if any design failures or issues are identified to ensure they are resolved before the final product launch.

Finally, once the product has been launched the current model ***OPD engineers*** are responsible to investigate any reported issues on customer vehicles in the field that cause attribute quality concerns or warranty failures. The root cause investigation into any such failures is typically driven using the Six Sigma DMAIC-R approach (Define, Measure, Analyse, Improve, Control and Replicate) problem solving format. To complete all stages of the DMAIC-R report the investigating engineers need access to the original design calculations, supplier quality control documents and engineering sign-off summaries. The NPD knowledge documents are needed to help understand if the cause of the failure is due to any deviation in supplier manufacturing or vehicle assembly build quality, or conversely design related and somehow escaped being discovered during the original test and development. The worse-case scenario presented in this respect was any potential customer vehicle recall campaigns which can cost the company tens of millions of dollars. In this instance it is absolutely vital that all pertinent documents relating to the original design selection, testing and development, and quality controls are all made available to support the investigation to demonstrate robust due diligence was correctly exercised through the original PD process; and vindicate the company of any identifiable incompetence.

The issues reported became confounded when extrapolated across the extended enterprise. Several UK based respondents noted that they commonly encountered issues with not being able to get hold of information because the core engineers that had originally conceived the designs were located elsewhere such as in the North

American PD facilities. Common problems between geographically dispersed teams were caused because non collocated engineers either did not respond to urgent email requests or could not be contacted by telephone call.

In the context of knowledge retrieval and sharing a common response was that many engineers often found themselves frequently searching for documents which they had either created, or received from other third parties such as suppliers, but could no longer locate within their own personal archives. Many felt that this was symptomatic of always needing to contemplate the most appropriate folder location in which to store relevant documents in the first instance. The complexity faced was due to the lack of any strict discipline for the appropriation of files types to any pre-specified ontological structure associated to the job function of the originator who created the documents.

Equally, those that had attempted to establish their own personal formal archiving ontologies found that the crossover between core, application and OPD files types, specific to the complex number of part designs related to the same group of engineered products, meant that folders commonly evolved into an amalgamation of document types that accumulated over many years; which made relocating information either difficult or impossible.

The general theme of lack of 'trust' was also clearly evident and resounded with many UK based engineers concerned that sharing 'core' design knowledge with other teams in low cost countries could undermine their long term viability, citing historical incidences of organisational restructuring where work had been moved from the UK to low cost PD centres in Turkey, Brazil and China as a part of several captive offshoring initiatives to reduce the cost of PD resources.

Summary of Stage 2 Findings

The key findings of the initial discussions regarding the knowledge management complications centred fundamentally on the lack of knowledge access and exchange between the three main engineering domains in the PD Systems Engineering teams, namely the; Core Engineering teams responsible for product and process best practices, Program Application Engineering teams working on New PD, and the Ongoing PD engineering teams that resolve problems once full scale manufacturing production has commenced post launch.

The folder structures on the local PC's of engineers was an eclectic and fragmented hybrid arrangement with intermixed Core engineering knowledge documents. The primary reason for this was cited as being due to the engineering teams being geographically dispersed with each possessing localised 'Information silos', and instead of knowledge being readily accessible it was typically 'kept' by the respective owner, and only shared on request. The additional key findings were as follows;

- The global product development system is highly complex with many individual processes that perpetually drive the creation of new knowledge documents as supporting evidence to demonstrate that all the necessary systems engineering processes have been correctly followed.

- The majority of documents are generated and stored in an unstructured fashion, with no formal classification or appropriate structure to support effective storage in way that facilitates sharing or retrieval for future reference or Organisational Learning (OL). The main exception to this is the formal configuration management of 2D/3D CAD aligned to the formal part numbering format within the Teamcenter and Worldwide Engineering Release System (WERS).

- Exchange of knowledge documents across the extended enterprise, between different teams and departments, and also suppliers, results in a huge volume of unstructured documents being informally stored in personal archives such as email and PC hard drive folders. This is further confounded by the complexity of different product design types and different engineering roles within the company.

4.6 Semi-structured Interviews (Stage 3)

The third stage of the industrial investigation was to build further on the initial findings of the preliminary local informal discussions (Figure 19). This was achieved by conducting a small number of semi-structured interviews (***Creswell*** 1998) with Ford PD engineers and managers, and also with supplier engineers and managers. The regionally based participants were selected from within the global Transmission and Driveline Engineering (TDE) division, so that synergies could be drawn with the initial feedback from the UK based TDE engineers, therefore reducing any potential risk of misunderstanding responses so early in the investigation.

Potential candidates were initially identified from the global organisation chart secured in stage 1, and each was provisionally approached via a standardised 'covering letter' email that outlined the background of the research, potential areas for discussion, and enquired on their willingness to participate. A slightly adapted version of the email was also sent to supplier PD engineers working in different locations to also engage a wider population of the extended enterprise.

The respective semi-structured interview outline discussion points used to prompt the discussions can be found in **Appendix C and Appendix D**. The generalised summary of responses can be found in the following sections.

4.6.1 Storing Informal PD Technical and Program Documents

Informal technical and program documents are transient and project specific, and constitute ancillary information that forms part of the design selection, development and general decision making processes. Although required for future reference these types of documents do not generally form part of formal evidence submitted to demonstrate completion of the systems engineering processes.

Examples of informal documents and file extension types include; *email communications (.pst), in/formal financial analyses and data in spreadsheets (.xls), investigations and reports (.doc), project work schedules and timing plans (.mpp), and project presentations (.ppt).*

The responses gathered suggested that most of these document types are mostly stored in local PC hard drives, shared network drives, SharePoint® sites, portable hard drives such as memory sticks and Microsoft Outlook .pst folders. Many of the respondents suggested that these documents were mostly unstructured and disorganised in terms of ambiguous file naming convention, informal approaches towards assigning future value for reuse, long term storage and eventual disposal. Many of these documents are created and shared on an ad-hoc basis and collectively form the major volume of information exchanged via email.

4.6.2 Approaches towards Organising PD Knowledge

This line of questioning was aimed at understanding what approaches were currently employed by engineers to structure electronic archival systems where they stored knowledge documents they either created or received. In total a mix of nine different approaches were volunteered as detailed within Table 5 below.

	Approaches towards Organizing Knowledge	**Example**
1	Component Part Description	Transmission > Shaft, gears
2	Program Codes	B2xx, C5yy, CD3zz
3	Type of Issue	Failed bearing, Cracked case
4	Type of document	5D report, Bill of Material
5	Formal Product Ontology structure	CPSCII, BoM Hierarchy
6	Vehicle model and Customer Concern codes	Fiesta >Transmission noise
7	Functional team	Powertrain > Auto Trans
8	Originators name	Name / Surname
9	No structure	Completely Ad-Hoc

Table 5. Approaches towards Organizing PD Knowledge

The intent of soliciting responses to this aspect was to understand the scope and types of different approaches the engineering teams employ when no formal structure is recommended or imposed.

It was clear that the more experienced engineers who had worked on several different groups of parts or designs, or multiple programs on different vehicle platforms took a much wider stance towards structuring their personal and shared knowledge repositories in terms of improving the overall structure to allow for better allocation and retrieval of documents. The acknowledgement that the complexity of the approach needed to be carefully thought through diminished with the less experienced engineers, with the general impression that all new engineers start out with zero guidance, and so start with no structure, but eventually build semi structured approaches around the body of information received as it grows over time. In the absence of any formal starting point many engineers working with similar knowledge document types had developed completely different structures.

4.6.3 Storing Formal PD Technical and Program Documents

Formal knowledge documents are those considered specific to the function of the sub system commodity. The core fundamental knowledge within each document has been built up over many years, and is typically maintained by technical specialists to ensure it is continually updated with latest thinking in best practice. This group does not include formal data transfer files that would be exchanged using official PLM systems for 2D drawings, 3D CAx models. A provisional non-exhaustive list of examples of the types of documents handled that were classified as formal is provided below;

- Request For Quotation (RFQ) document templates including standardized functional target lists.
- Engineering Statement of Work (ESoW) for defining the split in program responsibilities between the OEM and the supplier.
- Formal financial analyses, including supplier quotation responses.
- System Design Specifications (SDS) and Design Rules (DR).
- Quality foundation documents such as DFMEA, PFMEA, P-diagram, Function Tree diagrams, Boundary Diagrams, and Interface Matrices.
- Design verification and product validation testing methods: vehicle testing, supplier rig testing engineering specification (ES test).
- Problem solving reports such as Six Sigma, Global 8D and Ishikawa diagrams.

The responses gathered suggested that these types of documents are generally created using standard formats, templates and processes. Equally, all documents were volunteered as needing to be formally stored for future reference, but once again there was no single approach towards structured sharing and retention. In fact it became evident that the formal documents are typically created and stored locally on PC hard drives and found together with informal knowledge types. Formal documents were then also uploaded to the formal ICT knowledge repository, so exact copies of the files generally existed in at least two independent locations.

A large number of different official ICT systems that are used for storing formal knowledge documents were volunteered by those interviewed. The content types and hierarchical structure of these systems is discussed in more detail in section 4.7.

4.6.4 Methods of Sharing PD Knowledge Documents

The number of different methods employed for sharing both formal and informal PD knowledge documents was concisely limited to four distinct common approaches;

Emailing files as attachments, including context to the document within the body of the email text. This was preferred method due to speed and ease, but is generally restricted to smaller file sizes due to the 10Mb file size limitation imposed within the Outlook email system by the IT Department. Recipients of files shared this way complained that their email inboxes were frequently paralysed through the cumulative build-up of bulk emailing to distribution lists throughout the course of the day, with many citing needing to spend hours per day deleting emails and files for which they had no interest and should never have received, but that prevented them getting to information that was important and responding in a timely fashion.

Emailing the URL for the stored location of a file in a MS SharePoint® site folder as a hyperlink embedded within the body of the text, and again combined with context for the document in the text of the email. This method was preferred when receiving files as it poses limited impact on exceeding inbox storage capacity limits since the file is not actually attached to the email. The main benefit of this approach is security and version control of the document since although the email with the hyperlink can be forwarded outside the original intended audience, they are not automatically granted access to the file without first requesting permission from the SharePoint® admin or file originator.

Access to files in common location MS SharePoint® 'team and department sites', which are essentially common repository sites that have been created with a dedicated formal structure, normally devised by the site admin, based on the types of knowledge documents the team typically handles. The hierarchical structures of these sites are specific to the teams that construct them, and site content contribution permissions are restricted to local team members only, with access rights to read stored documents granted to those outside the team if an email request is sent to the site admin from within the MS SharePoint® site itself. MS SharePoint® has been deployed globally as the corporate sponsored ICT collaboration tool since c.2008, and it was estimated that wide spread adoption has since resulted in thousands of individual team sites that contain a varying mix of structured and unstructured knowledge, and a plethora of hierarchies based on local preference for ontological structure, which is rarely completely intuitive to anyone outside the team that attempts to navigate the site.

Accessing files from ***common shared network drive location*** was also volunteered as common approach. Complications with this approach centred on accessibility to wider audiences across the extended enterprise as it is not a simple process to map network access outside the geographic region where the server resides. Most that used this method typically only used it for large file sizes and only uploaded the file on a temporary basis so that other recipients could download the file locally to their own personal hard drive repository. Consequently, there is very poor structure to these shared network drives and sharing is generally limited to local colleagues only.

4.6.5 Adequacy of Current Knowledge Management

The next area of interest explored was to understand whether those interviewed believed the current approaches, methods and systems available provided sufficiently adequate knowledge management within the company. This included open-ended questions regarding what the greatest impacts on the business might be and how any concerns regarding inadequacies might be addressed.

The general consensus among the responses was that knowledge management of informal and formal unstructured knowledge documents, outside of formal corporate PLM systems, was generally random and ad-hoc. The personal storage of emails and files had become unmanageable and the crisis of increased storage capacity burden on resources was deepening each year. The true extent of the problem is most prevalent when engineers are tasked with locating historical documents that may have been created or received several years ago but can longer be located within the archive systems. Furthermore, many engineers from within Ford and also among the suppliers provided examples of loss of critical knowledge documents as a result of changing interfaces within the organisation caused by staff moving to new positions, leaving the company to pursue alternate employment elsewhere, or retirement.

The phrase ***'Corporate Memory loss'*** resonated among many as an appropriate way to describe the phenomena, with examples of late design changes caused by the lack of traceability to the original requirements, inability to locate design validation test reports to support failure analysis investigations, and even designs not complying with latest standards and specifications.

When questioned how the situation could be improved, the general consensus was that a ***standardised PD document folder structure*** was needed that harmonised the current approaches in local PC hard drives and SharePoint® sites. This would overcome many of the issues caused by workforce 'churn and attrition' such that a greater portion of unstructured PD knowledge could then be stored within recognisable hierarchies, that could be more easily navigated, and then knowledge could be retrieved independently from the engineers that originally created the documents.

When questioned further about the experience of ***ICT tools and dedicated Content Management Systems (CMS's)*** an additional layer of complication became evident. Many of the CMS's conceived as program management reporting tools were often also misconceived as formal knowledge repositories. In terms of organisational learning, many of the less experienced engineers were not even aware of many of the fundamental CMS's and did not know what type of information they contained or how to locate the website within the corporate intranet system. In this respect many felt that a knowledge hub that centralised all of the PD CMS's would provide a marked improvement over the current fragmented and heterogeneous arrangement.

4.7 Review of Current KM Practices (Stage 4)

The purpose of Stage 4 of the industrial investigation (Figure 19) was to review the current KM practices for storing, sharing and retrieving explicit knowledge documents within the company. The findings of the semi-structured interviews revealed two key areas that defined the current KM practices that needed to be reviewed in more detail, namely;

i. The document archival records of engineers' PC hard drives.
ii. The array of existing corporate PD Content Management Systems (CMS's).

Follow up discussions were subsequently organised with a small number of the semi-structured interview participants to better understand the complexity and inter-linkages between the different approaches and systems used within the PD environment. There now follows a brief overview of the approach and provisional findings.

4.7.1 Review of PD Engineers Personal Archival Records

This section outlines the further investigations into the personal electronic archive systems for eleven of the semi structured interview participants that agreed to share and review their personal and shared document library folder structures (i.e. PC hard drive C:// and W:// directories).

This part of the industrial investigation aimed to provide insights on the following main aspects;

i. Establish the ontological groupings employed by individuals when building knowledge repositories, and how they are influenced by different engineering team functions and roles in different global regions across the extended enterprise.

ii. Identify the preferences for hierarchical structures employed for document repository folder systems, used for identifying the logical storage location and subsequent retrieval of critical PD documents.

iii. Understand the taxonomies that define the spectrum and types of PD engineering knowledge documents that are typically created and stored during the course of automotive systems engineering; according to the specific phase within the product lifecycle.

Interviews were conducted locally with engineers that were based in the UK, and WebEx conferences were arranged with the participants based in China, Australia, North and South America. In each interview the engineers were asked to explain the logical structures and approaches they employed, and screenshots of the folder structures were captured and marked-up to indicate the hierarchy from the root folders through the network of sub folders to the eventual taxonomy of knowledge documents.

The detailed analysis of the collected archival records revealed a vast number of different approaches towards structured folder hierarchy. For brevity the specific detailed output captured from the series of interviews is found in **Appendix E**.

The audit of the archival records revealed that no single standardised common formal approach exists for engineers to follow, and as such the taxonomies and hierarchical structures employed by engineers varied considerably according to the vehicle programs and functional commodity part designs they were responsible to deliver.

Furthermore, the engineering role of each engineer has a huge influence on the type of knowledge documents handled, which also greatly influences the preferred type of hierarchical taxonomy. This resulted in a complicated overlap between various knowledge types and document classifications generated by different parties within the extended enterprise at different phases within the product lifecycle.

Across the body of evidence three dominant dimensions that appeared most frequently within the document library taxonomy structures were according to the ***Vehicle Product Assembly*** structure, the ***Functional Commodity Design*** structure, and the ***PD Systems Engineering Lifecycle Phase*** Structure. There now follows a brief overview of each hierarchical structure.

VEHICLE PRODUCT ASSEMBLY viewpoint - Organises knowledge according to the specific vehicle line, PD program, vehicle variants, and vehicle assembly plant locations that comprise a pseudo 'bottom-up' hierarchical structure.

This viewpoint is inherently embedded in the part manufacturing and vehicle assembly environment due to the *integration* of components and sub assembly functions. The ***vehicle product assembly*** viewpoint is shown in the eight level hierarchical taxonomy in Figure 23.

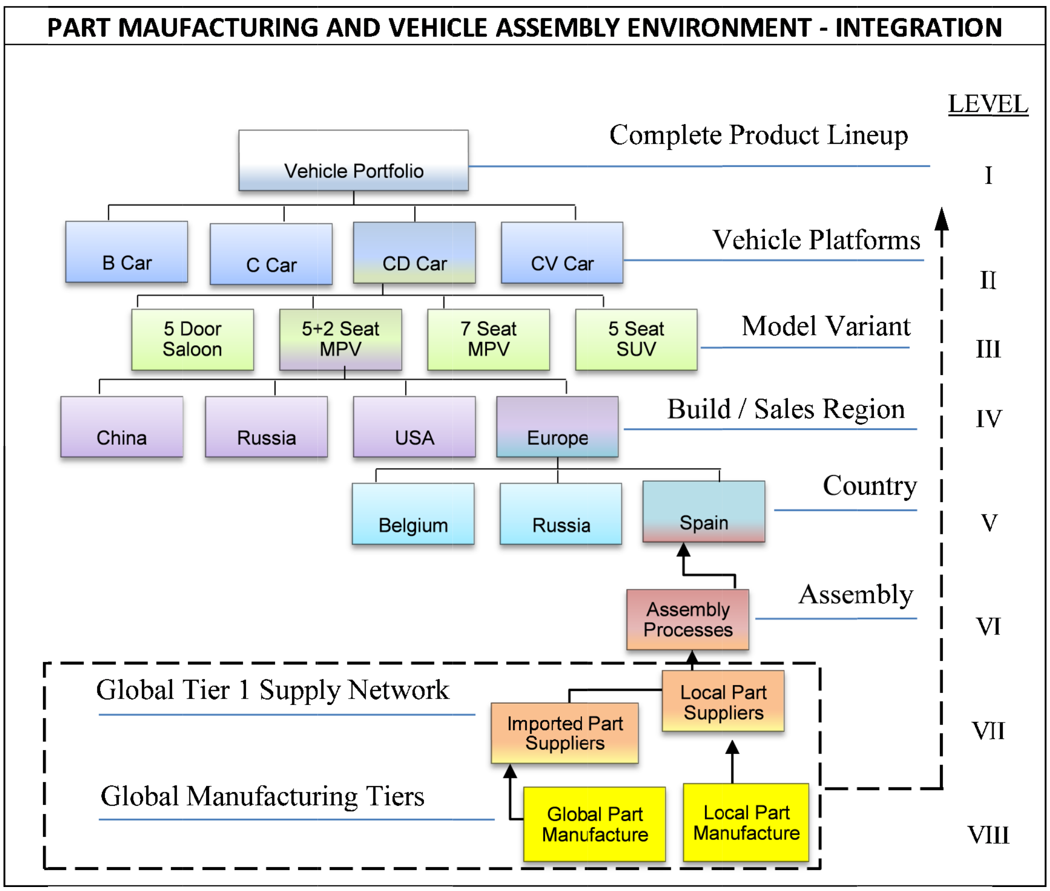


Figure 23. Vehicle Product Assembly Viewpoint Taxonomy

FUNCTIONAL COMMODITY DESIGN viewpoint – Organises knowledge according to the associated functional systems, sub systems, assemblies and components in a pseudo 'top-down' hierarchical structure. This reflects how the different sub-system functions are partitioned between the various SE organisational teams.

The ***Functional Commodity Design*** viewpoint is shown in the seven level hierarchical taxonomy in Figure 24.

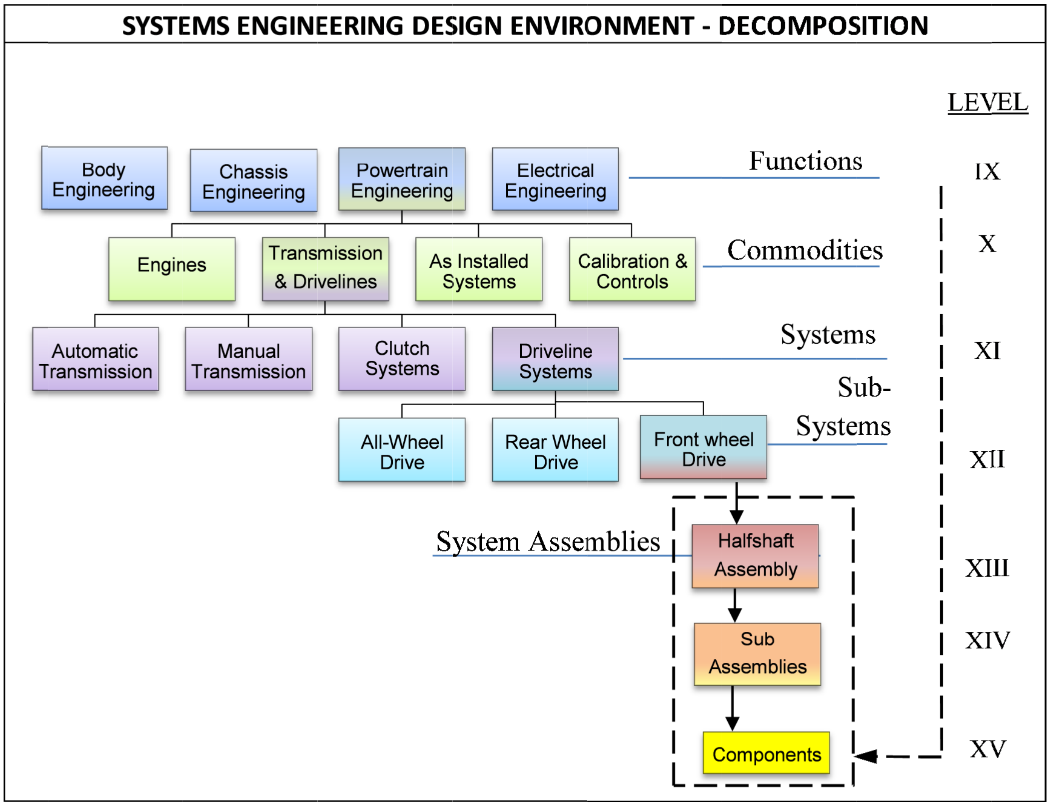


Figure 24. Functional Commodity Design Viewpoint Taxonomy

Most document libraries reviewed (**Appendix E**) started at level XII or XIII as the directory root folder. This was predominantly because the PD activities that engineers engage in is generally constrained to the specific sub systems that they are allocated to work on. Engineers with a broader experience had generally accumulated knowledge across several different technology groups.

Generally, the teams of ***CORE*** engineers followed the *Functional Commodity Design* taxonomy, and the ***NPD*** application engineers followed the *Vehicle Product Assembly* taxonomy.

However, ***OPD*** engineers were observed to employ a strange mix of approaches which could adopt a folder name from any level, as shown in the combined view in Figure 25.

The ***VEHICLE PRODUCT ASSEMBLY*** and ***FUNCTIONAL COMMODITY DESIGN*** viewpoints are combined to reflect the ***OPD*** taxonomy in Figure 25.

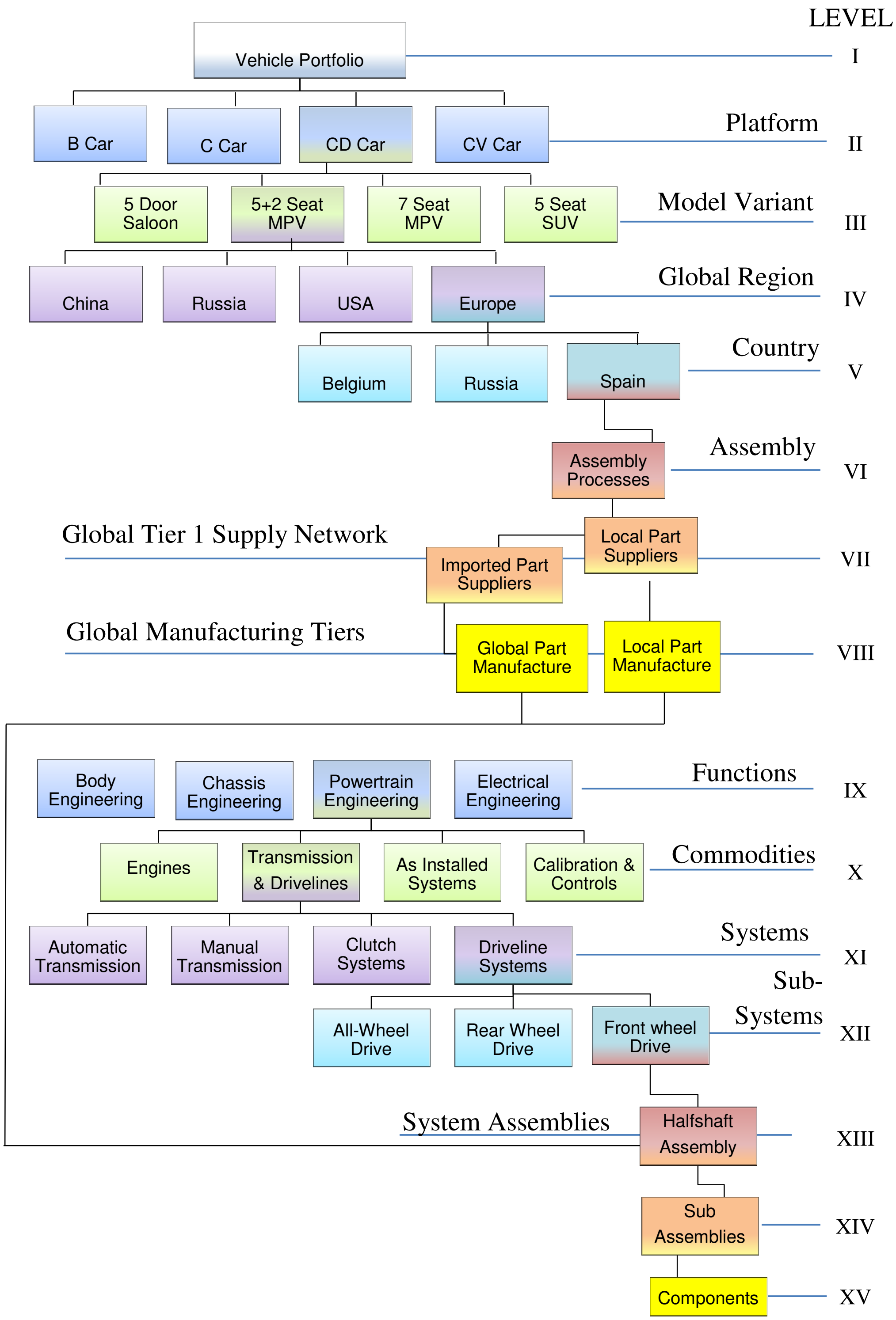


Figure 25. Combined Product Assembly and Functional Design Taxonomy

The third dimension established from the knowledge document library reviews was the classification of the actual knowledge documents according to the stage within the SE lifecycle phase.

PD SYSTEMS ENGINEERING viewpoint – Organises knowledge based on either the PD program *event* (milestone or gateway) or Systems Engineering *process* phase name, and therefore aligns to chronological point within the vehicle product lifecycle as represented earlier in Figure 6.

The three separate viewpoints of ***Systems Engineering lifecycle phase*** (Figure 6), ***Vehicle product assembly*** (Figure 23), and ***Functional commodity design*** (Figure 24) are combined in the proposed abstract model for ***SE Knowledge classification*** below.

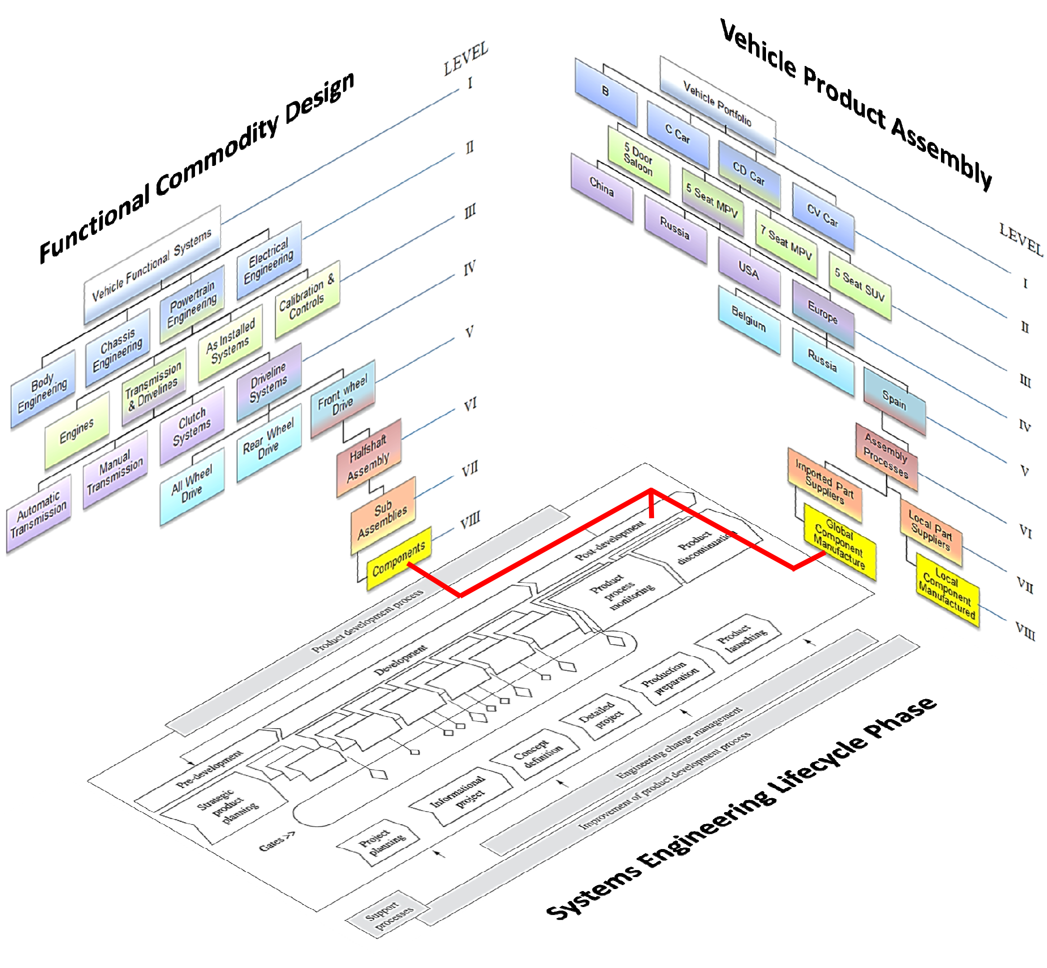


Figure 26. Abstract model of SE Knowledge Classification Viewpoints

4.7.2 Review of Existing Corporate Content Management Systems

The initial preliminary discussions and semi structured interviews revealed three distinct groups of CMS's. The first group comprise a series of knowledge repositories used to store formal documents relating to engineering 'core' design disciplines. The second group comprises a series of ICT tools used to capture and share product specific knowledge routinely created as part of NPD for delivering new vehicle programs. The third distinct group of ICT applications manage various aspects of the product life cycle after full scale volume production has commenced, as part of Ongoing Product Development (OPD), through to the end of production manufacturing. A number of systems cross over between all three domains.

CMS's used for 'Core' design knowledge

Other than knowledge stored in local PC hard drives and SharePoint® sites a further eight corporate CMS's, developed in-house for capturing various forms of 'core' design knowledge, were identified during the semi structured interviews. Screenshots of a number of these web-based CMS's can be found in the **Appendix F**, and a brief description of each is provided in Table 6 below.

	'Core' Design KM System	Type of Knowledge	Ontology
1	Electronic Data Management System (EDMS)	Multitude of various PD documents	Product Description / CPSC
2	Ford Standards Management System (FSMS)	Test Procedures and Design Standards	Product Structure Description
3	Analytical Powertrain Data Manager (APDM)	Multitude of various PD documents	Product Structure Description
4	Enterprise Engineering Knowledge System (E2KS)	Multitude of various PD documents	Product Structure, CPSC
5	Lean Failure Mode Avoidance (LFMA)	Quality foundation documents	CPSC, Vehicle Program Code
7	Powertrain electronic Bill of Design (PeBOD)	Design Rules	CPSC - Product Sub System
8	Powertrain Global Core Engineering Foundation Documents (PTGCEF)	Multitude of various PD documents	Product Commodity System Description

Table 6. Summary of 'Core' Design CMS systems

ICT system tools used as Program delivery and Maintenance CMS's

A total list of twenty five main Content Management systems commonly used during the delivery new vehicle programs, and subsequent management through the product life cycle, were identified. The utilisation of each system is aligned to the three main PD engineering roles below, and as shown below in Table 7;

	KMS	Type of Information and Knowledge	CORE	NPD	OPD
1	6 Sigma	Six Sigma Training Material and Reports	x	x	x
2	AIM	Automated Issue Matrix reporting system	x	x	x
3	AVBOM	Automated Vehicle Bill of Material – Part Lists	x	x	
4	AWS	Automated Warranty System	x		x
5	BSAQ	Quality Issues Metric Reporting and Tracking	x		x
6	CETPs	Corporate Engineering Test Procedures	x	x	x
7	DURIS	Durability Information System (Testing)	x	x	
8	eFDVS	Electronic Ford Design Verification System	x	x	
9	ELMS	Workshop Requests – Vehicle Updates	x	x	x
10	ETiS	Electronic Technical information for Service	x		x
11	Explorer	C:// personal and W:// network drives	x	x	x
12	FACTS	Competitor Benchmarking Information	x	x	
13	FordDoc	2D Drawings for all Part Designs	x	x	x
14	FSMS	Test Procedures and Design Standards	x	x	x
15	Global 8D	8D Problem Solving Reporting Tool	x	x	x
16	GPDS	Global Product Development System processes	x	x	
17	Integrator	Program Deliverables Health Chart Reporting	x	x	
18	LFMA	Quality Foundation Documents	x	x	x
19	Outlook	Email system – Personal .pst Folders	x	x	x
20	PeBOD	Design Rules	x	x	x
21	RPS	Prototype part ordering and tracking system	x	x	x
22	SharePoint®	User generated CMS and shared workspaces	x	x	x
23	Teamcenter®	3D Models – Virtual Digital Build Environment	x	x	x
24	WERS	Global Release System – Part number database	x	x	x
25	WCR's	Worldwide Customer Requirements	x	x	x

Table 7. Top 25 Corporate Content Management Systems - Overview

The above study revealed that a large number of discrete knowledge types are already centralised within isolated CMS's to allow the large volume of individual inputs to be managed across complete PD programs. However, the content within each of these CMS's is only a mere record with limited value when viewed in isolation and out of context with the original PD program.

4.8 Multinational PD Survey (Stage 5)

The fifth and final stage of the industrial investigation (Figure 19) was to conduct a multinational PD survey, based on a culmination of questions derived from the findings in the previous four stages. The survey was deemed necessary in order to cross check the validity of the findings from the semi structured interviews and confirm if the same problems and approaches could be generalized as applicable across all regions. The outcome of the survey should then provide sufficient confidence to ensure wide scale adoption for the proposed prototype tool.

An online web-based 'Global Product Development' survey was constructed within MS SharePoint®, which consciously incorporated the Ford logo and adopted the same colour schemes to give the Graphic User Interface (GUI) the overall impression of an official corporate 'look and feel' to help maximise participation. Furthermore, dedicated pages for each business unit region were embedded into the front page to provide a sense of inclusion for all participants as well as a response statistics page to provide complete transparency of responses for all participants. This had a secondary benefit of creating a sense of competition between regional managers, which encouraged them to 'boost' participation from their departments. Details and screenshots of the survey webpages are provided in **Appendix G**.

The series of questions were then developed with MS SharePoint® using the inbuilt questionnaire tool. The large scale survey was constructed with an intended target population of +1000 engineers, working in multiple countries and teams, and working on a vast number of different part types. With this in mind, the initial five questions were necessary to collect demographic information about each participant's Business Unit, location (Region and Country), relevant experience working in PD, and Program Module Team (PMT) which defines the product type each individual works on.

Questions 6 to 12 then explored the same lines of inquiry developed in the semi structured interviews. The multiple choice questions were organised so that responses were based on a predefined selection of potential answers derived from the responses previously given by individuals. The survey was initially piloted on a small number of local UK based PD engineers, which highlighted the need to remove ambiguity in particular questions, and adjust the branching logic in certain sub questions, to ensure they looped back into the main series of questions correctly based on selected alternate responses provided. Finally, the survey participant list was created by requesting email distribution lists from the chief engineers and managers of all the engineering teams in all regions. Tailored emails were sent requesting the lists which were then mapped into the survey webpage participant list manually. Separate tailored emails were then also sent to each distribution list with background information on the purpose of the survey and how the information would be used. The URL Address for the survey webpage was embedded into the email to provide a direct link that the participants could 'click' to take them directly to the survey.

4.8.1 Multinational Survey - Demographics of Survey Participants

The survey was sent to a total of 1,065 nominated participants. The initial response was slow but after several follow up prompts via email over the course of the proceeding months a final total of 362 responses were received (Table 8), yielding a 34% response rate. The figures and tables below summarise the responses to survey questions 1 to 5. These provide insight to the demographic of survey participants according to their geographic region, sub region, number of years' experience, and the engineering systems and sub functions the respondents work on. The following sections provide a summary of the responses received.

Q1. Which PD Business Unit do you currently work in?

North America	56
South America	55
Europe	104
Asia Pacific and Africa	147
Total	362

Table 8. PD Survey Participation by Region

The majority of respondents resided in the Asia Pacific and Africa (APA) business unit (41%). The second largest group of respondents came from Europe (29%), followed by North and South America with 15% each (Figure 27).

The high number of responses received from the APA regions was considered particularly important to this research as it ensured that useful insights were gathered from an aggregated mix of eastern cultures across Asia that could then be balanced with the views of the participants from central and western cultures in Europe and the Americas.

Ford Motor Company has a strong heritage tied back to North America, and Europe and South America both have long standing ties to the company headquarters in Detroit. The broad cross section of global participants should therefore provide a balanced view that includes the strong emerging growth markets in Asia as shown in Figure 27 below.

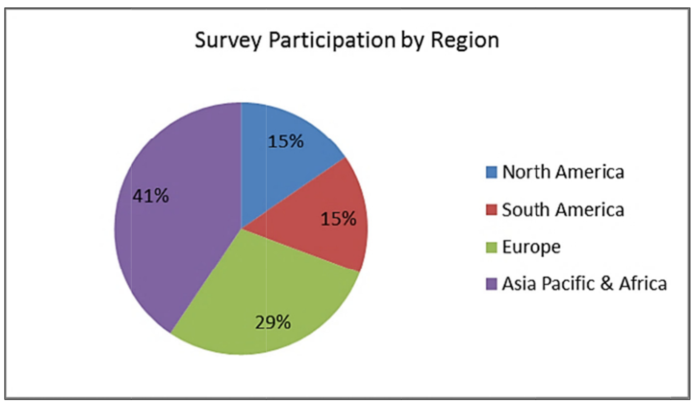


Figure 27. PD Survey Participation by Region

The second demographic profiling question was a branching logic to sub categorise the number of respondents from within the Asia Pacific and Africa business unit. This diverse collection of sub continents and countries had been historically grouped together as a single business unit since a period when local manufacturing volume was extremely low, and the majority of sales came from vehicles exported from other regions such as Europe.

In more recent times though these markets have expanded greatly and participation by the PD engineering teams on global platform engineering has grown to the extent that dictated the necessity to include these smaller teams to ensure a balanced view was reached.

This in turn also provided a mechanism through which to ascertain how well networked the 'satellite' teams are connected to the more well-established regions in terms of access to the same ICT systems and communication channels.

An overwhelming number of responses came from the PD engineers in India that represents 64% of the total response population for the Asia Pacific and Africa regional business units (Figure 28). This is more than explained by the reaction to an early concerted effort to engage the teams in the furthest most out reaches of the company.

Q2. If you work in Asia Pacific and Africa; which sub region do you work in?

India	94
China	29
Australia	11
Thailand	6
South Africa	7
Total	147

Table 9. PD Survey Participation by Asia Pacific Sub Region

Several email communications were initially sent to the senior powertrain manager in India to explain the purpose of the survey and the expressed need for their participation. This resulted in a follow up face to face meeting with the Ford of India PT manager when he visited the UK on business trip and he subsequently instructed his team in India to participate. A similar approach was taken with the PT Manager in China which equally generated a mild surge in responses.

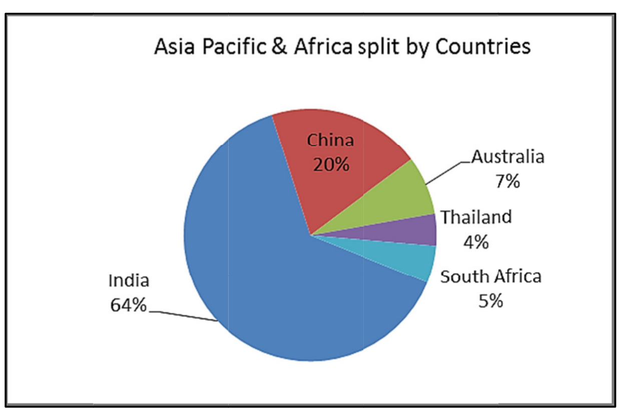


Figure 28. PD Survey Participation by Asia Pacific Sub Region

The third demographic profiling question sought to ensure there was a broad cross section of experience regarding the number of years' experience each respondent had working within the PD environment (Table 10).

Q3. Approx. number of years' experience working in Product Development?	
0 - 2	85
3 - 5	81
6 - 10	77
+10	38
+15	81
Total	362

Table 10. PD - Survey Participation by Experience

The profile of responses received again revealed there was an acceptable even representation of experience across the complete population.

The engagement of the early career engineers with <5 years experienced ensured that the recent generation of graduate recruits, which are assumed to have a higher degree of digital ICT literacy (digital 'natives') were able to express their views alongside the more 'seasoned' engineers with >10 years' experience that have witnessed the ICT revolution in practice. The inclusion of respondents from polar opposite ends of the experience spectrum once again hopefully ensured a complete and balanced view of all PD engineers across the company (Figure 29).

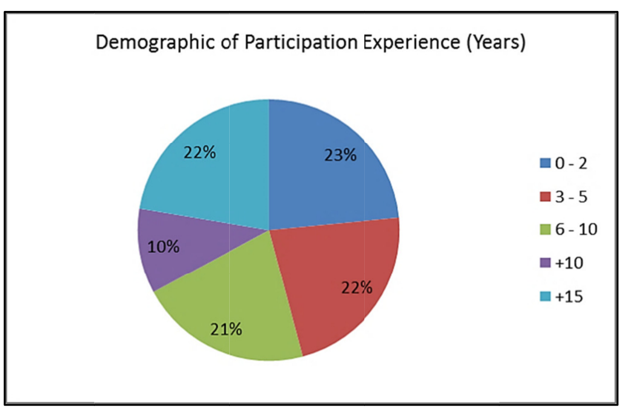


Figure 29. PD Survey Participation by Experience

The fourth demographic profile question sought to capture which functional engineering team each respondent worked within (Table 11). This question was necessary as although the survey was primarily targeted to the Powertrain engineering teams the original communication that was issued with the survey instructions also encouraged participants to share the survey URL address with their local colleagues. This open approach meant it would be uncertain which functional teams all respondents belonged to without capturing the response to question 4.

Q4. Which PD Functional team do you work in?	
PMT1 - Body Exterior	14
PMT2 - Body Interior	8
PMT3 - Chassis	13
PMT4 - Powertrain	296
PMT5 - Electrical	11
Vehicle Eng	4
Program Integration	7
PVT / Launch team	9
Total	362

Table 11. Demographic of PD Survey Response by Commodity team type

In total 296 responses were received from PD engineers within the Powertrain divisions, representing 82% of the population. However, a further 66 responses were also received from respondents across the broad array of other non PT functions, including Body Engineering (6%), Chassis (4%), Electrical (3%), and then Vehicle Integration and Program Integration and PVT / Vehicle launch (5%) as in Figure 30.

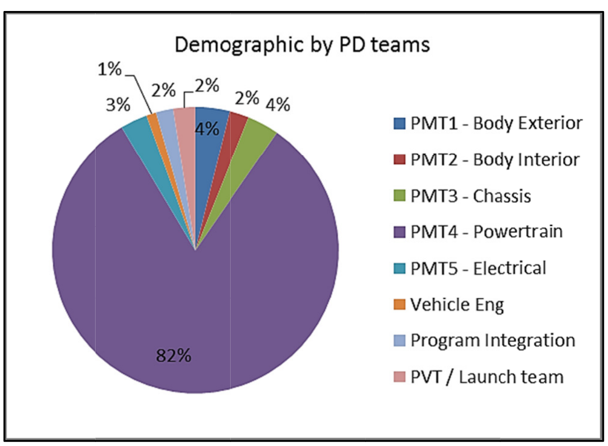


Figure 30. Demographic of PD Survey Response by Functional team type

The fifth and final demographic profile question was once again a branching logic sub question to ascertain which of the Powertrain *sub* functional teams each participant worked within (Table 12).

Q5. If you work in PMT 4 - Powertrain; which Sub Systems do you work on?	
Engine	59
Powertrain Installed	80
Transmission and Driveline	135
Calibration and Controls	22
Total	296

Table 12. PD Survey Respondents by Powertrain Sub Functions

The majority of the Powertrain responses came from the Transmission and Driveline functional teams at 46%. The Powertrain 'As-Installed' functional group, which engineer systems such as exhausts, engine mounts, air induction and powertrain cooling was the second most represented at 27% (Figure 31).

The engine team was well represented with 20%, but the powertrain controls and calibration team was under represented at only 7%. On balance this was not deemed to be a major problem as the scope of the research had already highlighted that the main focus was constrained to under-hood mechanical assemblies.

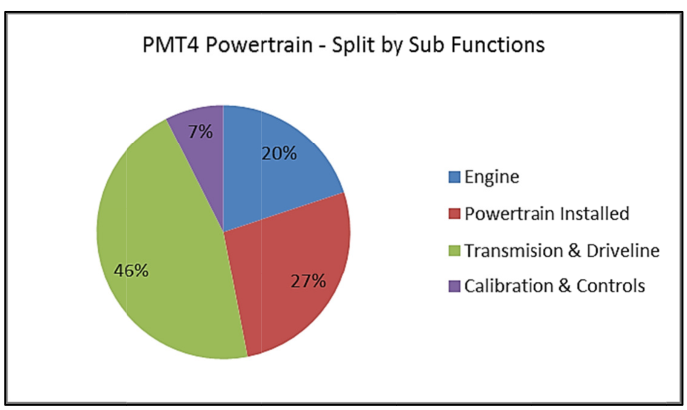


Figure 31. PD Survey Respondents by Powertrain (PMT4) Sub Functions

The intention of the multinational PD survey was to encourage a strong response rate from participants in all of the globally dispersed teams. The survey response rate required to make the exercise statistically viable assumed a 95% confidence level and a 5% margin of error, which were both adopted as predefined survey industry standards (Fluid-Surveys 2015). The required number of responses is based on the following two calculations;

Sample Size = (Distr. of 50%) / ((Margin of Error% / Confidence Level Score) ^2)
True Sample = (Sample Size * Population) / (Sample Size + Population – 1)

The actual number of PD engineers within the company was estimated at 25,000 employees worldwide. According to the above calculations a total number of 379 responses is the suggested population sample size for the responses to be statistically significant. The survey was deployed to 1,065 employees and 362 responses were received; representing a 34% response rate, which was deemed acceptable.

The high proportion of responses received from the Asia Pacific region, particularly India and China, was especially encouraging. Inclusion of all the regions was a key feature built into the survey from the outset, firstly to gain a true broad perspective of the type and significance of KM issues faced, and secondly whether there is synergy in the spectrum of issues between different global locations.

4.8.2 Multinational Survey – Main PD KM questions

Once the initial demographic data had been collected the participants were presented with the main PD KM survey questions. The first survey question regarding KM practices was posed regarding ***where*** PD engineers store informal technical and program files?

The question centred on the storage of unstructured explicit knowledge (Figure 32).

Storing Informal Technical and Program Files (Percentage of 362 Responses)

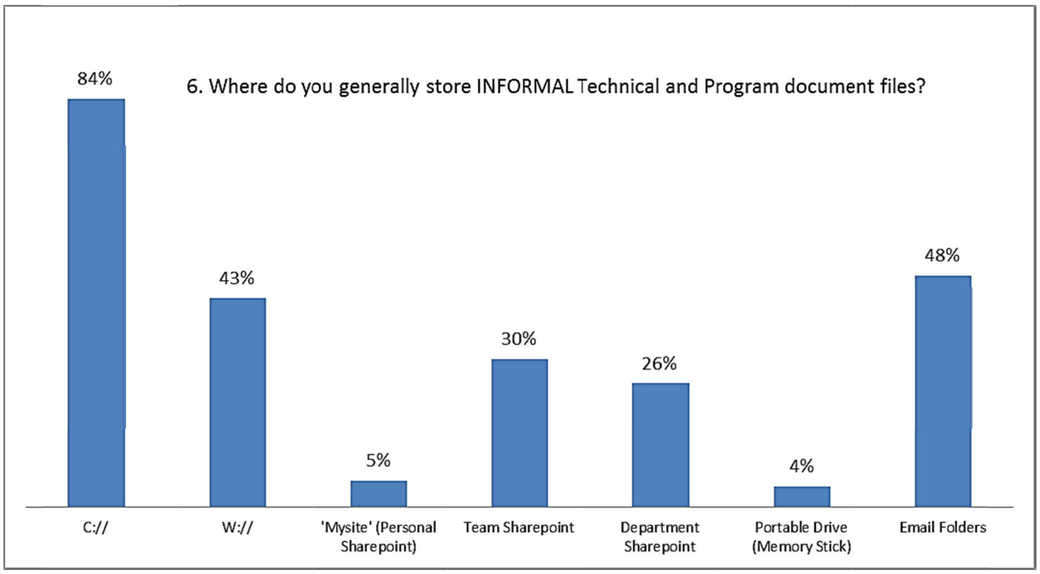


Figure 32. Storage of Informal Technical and Program Files – Survey Response

The survey permitted the respondents to select as many of the predefined answers as applicable, so no constraint was placed on only selecting a single option. The overwhelming majority of respondents selected their *local PC hard drive (C://)* as the primary storage repository at 84%. This was followed by *email folder storage (.pst files)* at 48%, and then *shared network drive folders (W://)* at 43%. The use of *MS SharePoint® sites* was found to be more popular for *team sites* and *department sites* as 30% and 26% respectively when compared to the use of *personal SharePoint® 'mysites'* which were only cited by <5% of respondents. Finally the use of portable drives such as mobile hard drives and *memory 'sticks'* received only 4% of responses. Although not approved due to security risks, several engineers mentioned they used portable drives to back up their C:// once or twice per year as a contingency due to concerns of laptop hard drive failures etc.

The second main survey question posed regarding KM practices was directed towards understanding the types of logical structures PD engineers employ to organize their knowledge files (Figure 33). This question centred on the storage of unstructured explicit knowledge, and ***how*** it is stored in respect to the preferences for different folder system taxonomies and classification approaches.

Logical Structures for Organising Knowledge (Percentage of 362 Responses)

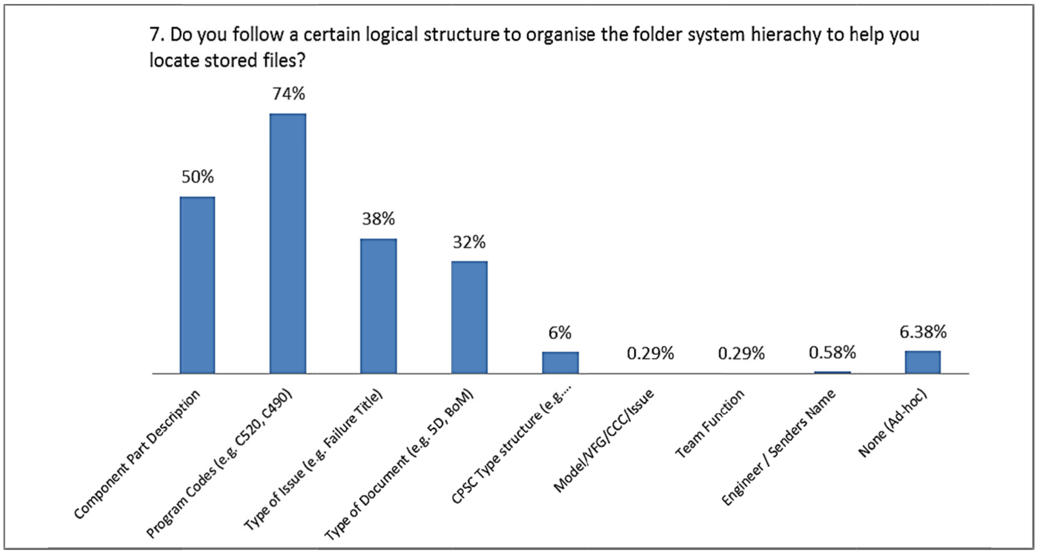


Figure 33. Logical Structures for Organising Knowledge – Survey Response

The survey permitted the respondents to select as many of the predefined answers as applicable, so no constraint was placed on only selecting a single answer. This allowed respondents to express preferences for the various types of hierarchical taxonomies. The majority of 74% of responses suggested a strong preference for associating knowledge created during the course of PD with the respective *vehicle program code*. The second most popular approach was to align folder systems based on the *product part description* at 50%. The *type of issue* was also popular at 38%, as was the *document type* at 32%. The most unexpected response was the very low application of *CPSC Type Structure* hierarchies, which received a similar number of responses at 6% as those with a completely random and ad-hoc approach i.e. no formal systematic approach. Only <1% of responses were received for *Model/VFG/CCC* taxonomies and *Team Function* and *Engineer/Senders name* which were both originally cited as folder systems employed for structuring .pst folders for emails within MS Outlook.

The third main survey question posed regarding KM practices was directed towards understanding the utilisation of numerous formal corporate intranet based content management systems specifically constructed for the sole purpose of storing formal knowledge documents (Figure 34).

This question centred on eight separate formal CMS's identified during the earlier semi structured interviews, as reviewed in **Appendix F**. The aim of this question was to ascertain ***where*** PD engineers generally store structured explicit knowledge and the level of utilisation for the various CMS's already in existence.

Storage of Formal Technical and Program files (Percentage of 362 Responses)

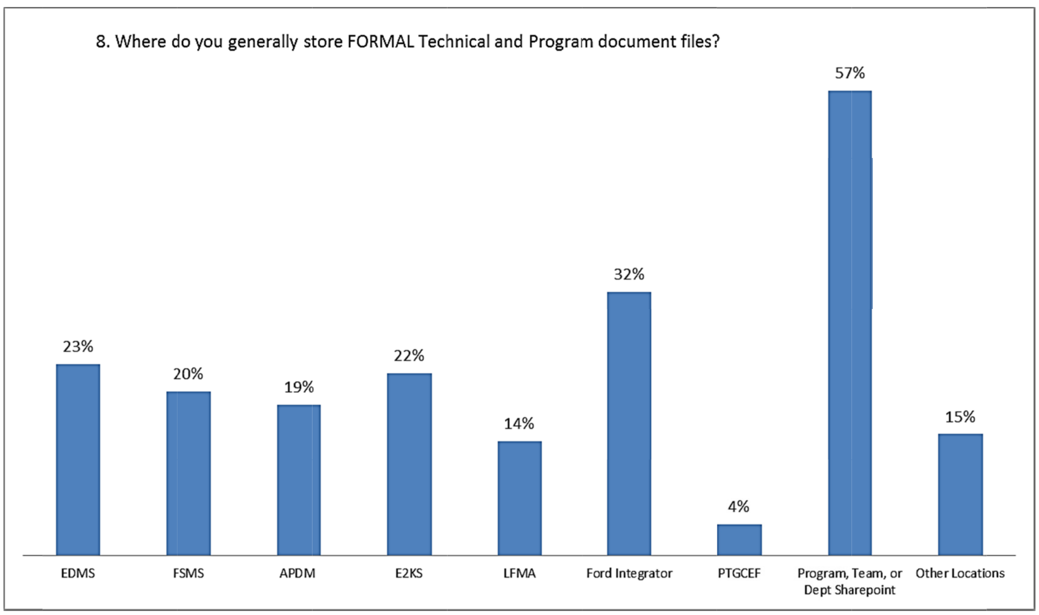


Figure 34. Storage of Formal Technical and Program Files – Survey Response

The responses for the initial four CMS's namely; *EDMS, FSMS, APDM* and *E2KS* yielded a reasonable 19% - 23% utilisation rate.

LFMA appeared to be far less utilised, which may be primarily explained by the specialist nature of the site which is dedicated to quality foundation documents, such as FMEA's, Interface diagrams, boundary diagrams etc. only.

The *Ford Integrator* system is primarily used by NPD application engineers to monitor program deliverables are met and received a 32% utilisation. It was recognised during the course of collating the results that the *PTGCEF* system had never been formally ‘launched’, and so the low response rate of 4% is explained by the fact that the system had never been rolled out to the wider teams.

The majority of responses however all tended towards the use of MS SharePoint® team and department sites as the most popular location for storing formal explicit knowledge documents, with 57% of respondents citing the use of these independent local knowledge repositories as the most common storage location.

Crucially, 15% of responses indicated that they never used any of the locations offered; suggesting a great deal of formal explicit knowledge may reside only on local PC hard drives, or within other smaller local web based repositories.

The fourth main survey question posed regarding KM practices was directed towards understanding ***how*** PD engineers share (send/receive) unstructured explicit knowledge documents with their colleagues (Figure 35). This question was arranged around the respondents expressing the frequency of using each of the four main methods previously identified during the earlier stage discussions. The ranking scales ranged from **1** – used infrequently, to **3** – used regularly, and **5** – used very frequently.

Sharing of PD files and Documents

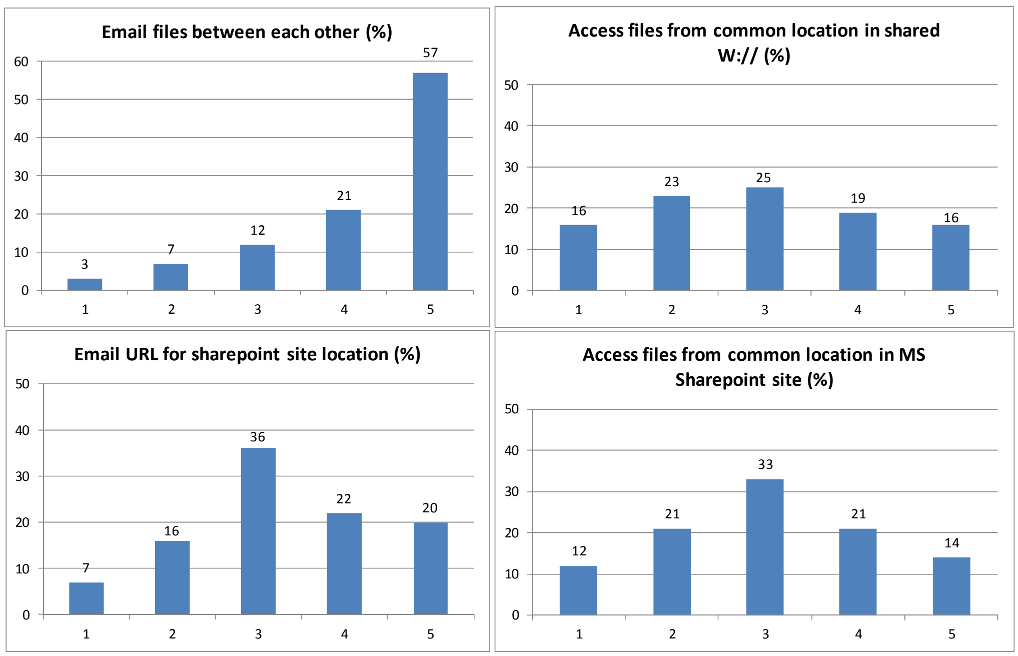


Figure 35. Sharing of PD files and Documents – Survey Response

The most popular and common method for sharing knowledge documents is to attach the file to an email, with 57% of PD engineers using the system very frequently. The high use of emailing the URL for the location of files within SharePoint® site folders, or accessing directly from SharePoint® sites was also popular.

Having led the survey participants through the main questions regarding the storage and sharing of both informal and formal explicit knowledge documents, as well as the use of various corporate CMS's, it was anticipated that the respondents had undergone a period of reflection regarding general KM practices.

The fifth and sixth questions were therefore simply directed to solicit the participants' immediate viewpoints on 'Corporate Memory Loss' and their support for a unified single 'Global Standardised Tool' to help combat continued memory loss in the future. At this point a straight forward YES or NO response was requested.

Corporate 'Memory Loss'

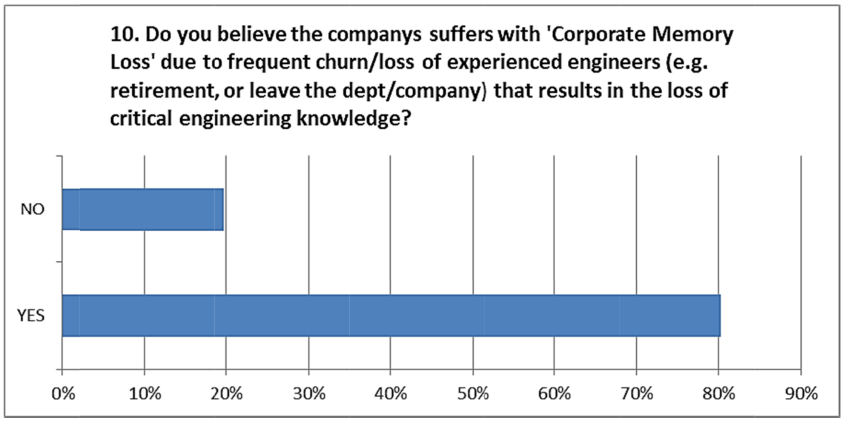


Figure 36. Corporate 'Memory Loss'- Survey Response

80% of participants (290 responses) agreed that the company suffers with 'Corporate memory loss' (amnesia) as a result of the dynamic PD workforce (Figure 36). Exactly the same response was received in support for a global standardised tool to help improve against continued future corporate memory loss (Figure 37).

Support for a Global Standardized Tool

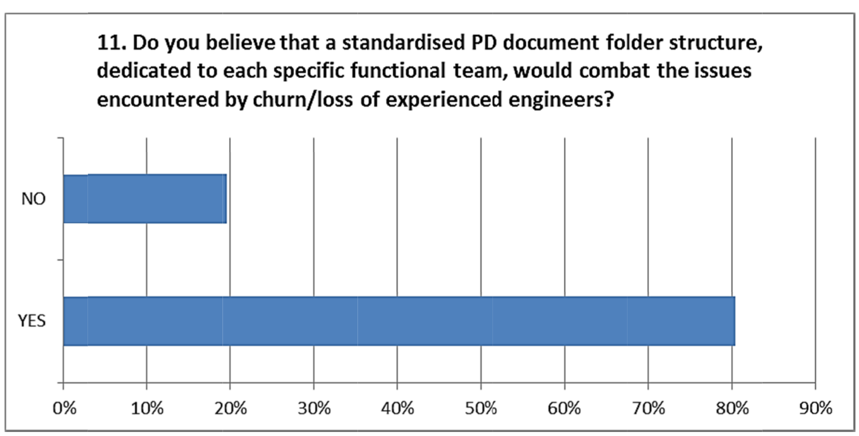


Figure 37. Support for Global Standardized Tool – Survey Response

The penultimate question sought to understand how frequently PD engineers accessed the full comprehensive list of available Corporate Tools and Websites during the course of normal PD Program delivery (Table 13). The underlying aim of this question was to ascertain the degree of familiarity and utilisation the global PD workforce exhibited in respect to the eclectic array of web-based tools that had been developed in-house and evolved organically over the recent decades.

Frequency of Accessing Corporate CMS Tools

(%)	Never	Occasionally			Frequently
FordDoc - 2D Drawings	10	10	14	23	43
AIM Issues	10	10	20	26	33
TeamCentre - 3D Models	17	12	18	20	33
WERS on the Web (WoW)	15	10	20	21	33
AVBOM - Part Complexity Bill of Materials	25	18	21	17	19
Integrator - Program Deliverable Assessments	31	16	22	14	16
BSAQ - Quality Metrics (TGW/ CPU / R/1000)	27	27	23	8	15
eFDVS (Vehicle T&D plan)	22	20	24	19	15
FSMS - Ford Standards Management System	27	15	21	22	15
CETP's - Corporate Eng. Test procedures	17	20	28	22	13
DURIS (Proving Ground Incidents)	24	19	27	20	10
Global 8D System	19	25	29	18	9
myRPS - Prototype/Part ordering	31	20	28	12	9
GPDS Homepage	18	29	32	13	7
LFMA - Quality Foundation Documents i.e. DFMEA, DVP&R	30	23	26	14	7
PeBoD (Design Rules)	48	17	21	7	7
ETiS - Service Workshop Procedures	47	23	17	7	6
FACTS - Competitor Benchmarking	29	27	26	13	5
WCR's Trustmarks - Worldwide Customer Requirements	42	26	20	9	4

Table 13. Frequency of Accessing Corporate CMS Tools – Survey Response

The final survey question posed was a completely open-ended request for each participant to provide a free-text response giving their general feedback on challenges, issues and experiences regarding knowledge management within the company.

A total of 96 legible written responses were received, representing 27% of the 362 survey participants and 9% of the total population that received the survey. Several more responses were received but were subsequently removed as they were not legible or could not be easily understood or interpreted in the context of the survey.

The full list of written responses can be found in **Appendix H**.

The underlying themes from the written responses are summarised together with the general findings from the survey in the next section.

4.8.3 Summary of the Multinational Survey

The multinational PD survey on knowledge management practices, as described in section 4.8, focused on soliciting responses from industrial PD practitioners against several key aspects which are now discussed;

The demographic profile of the survey participants was gathered to ensure a statistically viable number for responses were achieved, and that all aspects of regional location, number of years PD experience, and sub functions within the Powertrain team divisions were all fairly represented. However, the results showed that North America was under-represented whereas and Asia Pacific (particularly India) was over-represented. Equally, the survey was mostly represented by Powertrain engineers, with far fewer responses from the other commodity teams. It is not believed that this greatly skewed the results, but in retrospect it may have been insightful to also analyse results of the subsequent main survey questions according to each sub population within the demographic profile of respondents. This aspect is discussed later in the final further work chapter.

The first main survey question tackled the subject of storage of informal technical program files, to ascertain where engineers place all unstructured explicit knowledge documents that are created during the course of new PD programs and ongoing product development. The overwhelming response for local PC hard drive (84%) was followed by the use of email folders (48%) and central network server location (43%). There was also a reasonable utilisation of MS Sharepoint® 'Team' sites (30%) and 'Department' sites (26%). The results showed there to be significantly less utilisation of personal Sharepoint sites (5%) and portable memory drives (4%).

The logical structures for organising PD knowledge and preferences for taxonomies and classification approaches showed the key preferences for program codes (74%), component part description (50%), type of issue (38%), and SE knowledge document type (32%). The findings regarding preference for hierarchical taxonomies will be harnessed to form the central development of the proposed KM framework and structure of the envisaged prototype ICT tool.

The storage of formal technical and program file types, that represent structured explicit knowledge documents generated as part of the systems engineering process, were found to be predominantly held on small scale independent program / team / department type MS Sharepoint® sites (57%). This demonstrated that the SE community is at least already partially acquainted with the use of the MS Sharepoint® software platform. Beyond these, the results suggested a fairly equitable use of the eight main in-house CMS's for storing formal technical or program knowledge documents for each PD knowledge domain (Figure 34).

The methods that PD engineers use to exchange and share PD knowledge files between the various teams and individual employees was found to be dominated by attaching files to emails (57%) which demonstrates the inefficiency and security risks posed by current practices. The use of central server locations was found to be limited, but the results instead suggested a growing tendency towards emailing the URL hyperlink for the file location within a local MS Sharepoint® site.

The global PD community strongly agreed on the subject of 'Corporate memory loss', and systemic failure to capture essential PD knowledge effectively (80%). Similarly there was also consensus on the business need for a potential global standardised tool with an embedded PD document structure that could provide wide spread access to all geographically dispersed teams working on collaborative innovation.

The utilisation of the current eclectic array of the top 25 in-house CMS's was dominated by those containing 2D drawings and 3D models, Issues tracking (reliability failures), part numbering and part usage complexity, and NPD process outcomes and test results. There was also a high frequency of usage of CMS's related to core knowledge on test procedures and design standards, problem solving reports, and failure mode avoidance tools (Table 13).

The multinational survey findings have confirmed that the KM challenges surrounding current practices and adequacy of tools can, with reasonable confidence, be generalised across all regions of the extended enterprise as there were no apparent conflicting views between the participating regions. The possibility to improve the confidence level in this respect is also discussed in the further work chapter.

4.9 Limitations and Threats to Validity

The investigation was purposely limited to Ford Motor Company and a small number of direct purchased part suppliers. This constraint was consciously imposed as it was anticipated that competitor OEMs would be unwilling to participate or reveal confidential information. However, the lack of wider participation prohibits the generalisation of the findings as applicable across the complete automotive industry. This aspect is discussed further in the future work chapter at the end of this thesis.

The main obvious threat to validity is the potential risk of introducing *researcher and respondent bias* due to the researcher and participants being embedded within the industry. To mitigate this risk a 'triangulation strategy' was adopted that utilised multiple independent sources of evidence (***Yin*** 2013). This was primarily achieved through the five stage investigation approach (Figure 19) which progressively extracted the main KM concerns from initial small scale informal discussions and local semi-structured interviews, and then broadened the generalisation of findings through the use of a large scale multinational survey with a far larger population of diverse participants.

4.10 Proposed Automotive Extended Enterprise Architecture Model

The general findings of the industrial investigation equally informed the research with the various knowledge transactions between the different divisions of the Automotive Extended Enterprise (EE), which are first summarised below, and then depicted in the automotive EE architecture model which is proposed in the subsequent section.

4.11 SE Knowledge Transactions

Each new vehicle program commences with scoping the engineering definition for the product functional performance attributes, technology feature content and exterior and interior styling themes. The program initially starts with the inputs from the collection of teams that collate the ***Global Insights***, which focus on the wants/needs/expectations of the target customer population for the particular vehicle platform model. Additionally, legislative and regulatory requirements such as emissions and safety targets are also incorporated.

The product planning teams then define the product description book which communicates all of the content that the new ***Vehicle PD Program*** must deliver. The vehicle program team cascade the vehicle program definition to the numerous ***NPD*** teams to engage them in commencing the design process. The ***NPD*** teams each represent a group of functional part technology types known as 'commodities'.

The initial task for the ***Core*** engineers is to interpret the functional targets and attributes into engineering transfer functions and design requirements to describe how the overall vehicle requirements may be achieved. The ***Core*** engineers then supplement the technology design requirements with additional specifications, rules, and lower level sub system functional targets to compile the complete set of stakeholder requirements which are then issued to the network of external design and manufacturing supplier's specialist in each respective vehicle technology.

The ***Supplier Product Development*** teams use the engineering design requirements and transfer functions as the inputs into the design calculations and selection process, and then offer the design solution proposals to the ***Core*** and ***NPD*** team. The preferred design solution is chosen and the selected supplier is awarded the new business to participate in the product development program (with the intention to eventually supply the manufactured parts into full scale production). Once all the initial design detail has been finalised the initial CAD models are supplied for package check. Prototype parts are procured and tested on supplier rigs and prototype vehicles.

Upon successful completion of the Design Validation (DV), the production tooling is manufactured for all components and sub-assemblies at each tier level supplier. The Tier 1 ***Supplier Manufacture*** plant then assembles the final end-item sub system to be delivered to the ***Global Vehicle Assembly*** plants. Production Verification (PV) parts are produced, quality checked, and tested.

The ***Global Vehicle Assembly*** plants, in all multinational regions, receive the end-item sub-assemblies for all the different technologies and build each vehicle according to the customer order specification that was originally placed at the OEM ***Dealership***. Each completed vehicle is then delivered to the respective ***Dealership*** where it is then handed over to the ***New Customer***. The customer collects the new vehicle and only returns to the ***Dealership*** for regular service interval checks or if a functional fault develops that results in a customer complaint during operational service (e.g. engine failure).

The ***Dealership*** attends to the appropriate repair necessary to remedy the functional fault and then records the details of the problem and the service parts required to repair the vehicle in the warranty claim which is loaded into the global warranty database. The ***Global Vehicle Assembly*** plants and the ***OPD*** engineers are able to interrogate the database and monitor the warranty claims data to build reports which display Pareto's and graphs to profile any emerging patterns of high frequency repairs.

The ***OPD*** engineers then work with the ***Dealerships*** to recover the failed parts back to the ***Supplier Manufacture*** team for investigation. The teams then employ problem solving techniques to establish the root cause of the failure, and to define the appropriate corrective action and Prevent reoccurrence actions. The SE knowledge transactions that occur within the OPD domain form the basis of the research findings presented in the detailed case study in chapter 5.

4.12 Automotive Extended Enterprise Architecture – Proposed Model

The descriptions of the knowledge transactions in the prior section are now adopted to form the basis for the automotive extended enterprise model in Figure 38 below.

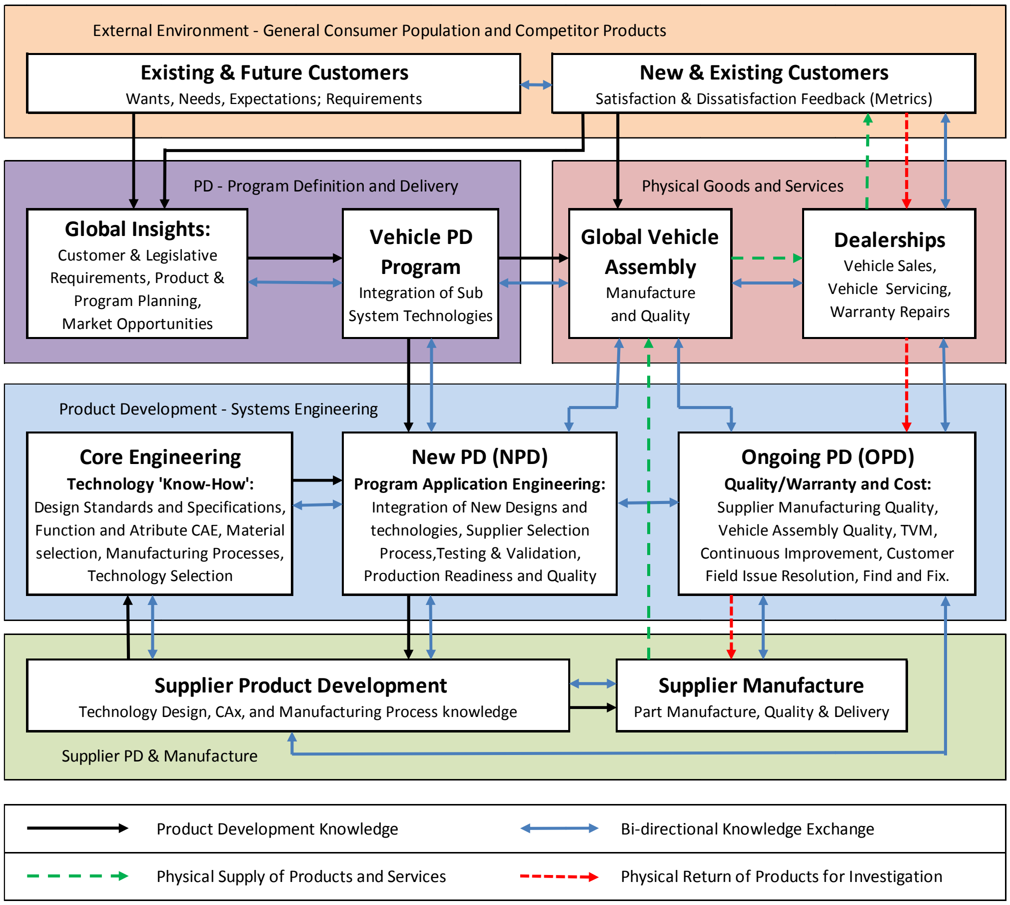


Figure 38. Automotive Extended Enterprise Architecture Model

The automotive EE architecture model depicts the major knowledge transactions between the different internal and external members of the extended enterprise. The generalised model is purposely not constrained to geographical location, vehicle program, or part technology type and is therefore ubiquitously applicable to all multinational PD and manufacturing operations. The model also clearly identifies the discretely separate roles of the CORE, NPD and OPD teams and how they interact with different parts of the complete automotive EE.

The development of the Automotive EE architecture model (Figure 38) satisfies research objective 2 (Table 2).

4.13 Summary of the Exploratory Industrial Investigation

The main research findings from the five stages of the exploratory industrial investigation (Figure 19) are listed below;

The *first stage* reviewed the corporate documentation to ascertain the KM complexities surrounding product, people and processes. This initial secondary research revealed a multi-layer suite of product technology naming conventions, a wide array of engineering divisions and departments, and a vast number of PD processes that all complicate establishing any one particular holistic vision for KM.

The *second stage* centred on a series of preliminary informal face-to-face discussions with PD engineers based in the Ford Dunton PD centre. In this phase the key factors that negatively affect knowledge management were found to be as follows;

- Organisational churn due to restructuring, captive offshoring, attrition, retirement, and promotion, which results in business discontinuity when knowledge is lost or transferred without context.

- Lack of any formal naming convention for files and folders resulting in missing meta-knowledge to signify the value of the file contents.

- Proliferation of files when exchanged via large email distribution lists, which also undermined document version control.

In the *third stage* a series of semi-structured interviews were conducted with a number of Ford engineers and external supplier engineers. The key issues that were identified were as follows;

- Both informal and formal unstructured knowledge documents are generally collocated within poorly organised folder systems, and may end up being simultaneously stored in a wide number of different CMS's.

- The lack of any formal taxonomy to facilitate the creation and storage of explicit unstructured knowledge documents results in a wide range of non-homogenous approaches which are frequently counter intuitive to other users.

- The lack of facility for the extended enterprise to actively participate in capturing and accessing centrally stored user generated knowledge documents.

The *fourth stage* set about exploring the current KM practices in far greater detail by examining the archival records of engineers from several different global PD centres. Three dominant KM classification viewpoints emerged from the review and an abstract model was presented to illustrate the complications of establishing a single common taxonomy suitable for all stages of the vehicle product lifecycle.

The *fifth stage* collated all of the findings from the preliminary four stages as the basis for a multinational survey that was issued to 1,065 engineers across several Ford PD and Manufacturing regional facilities. In total 362 responses were received representing a 34% response rate. The analysis of the results supports the ability to generalise findings as many of the KM challenges revealed in the European teams were underlined and echoed as also being strongly present in other global regions. The results also demonstrated that 80% of the multinational survey respondents agreed they have strong concerns regarding corporate knowledge loss, and similar overwhelming support for a centralised knowledge management support tool.

An automotive extended enterprise architecture model was then presented to illustrate the knowledge transactions between the different stakeholder operations to facilitate the construct for the remaining research. The definition of the knowledge inputs and outputs for each PD domain (Core, NPD, and OPD) lays the foundation for the subsequent research chapters and the notional requirements for the KM framework.

According to the combined findings from all stages of the exploratory industrial investigation (chapter 4), the following DRM *Reference* model was developed. The discrete DRM model describes the refined understanding of the *existing* situation and the ramifications to the wider automotive business operations.

4.14 DRM – Final Reference Model

The refined final DRM ***Reference*** model in Figure 39 below was developed to provide a graphical representation for the purpose of this research project.

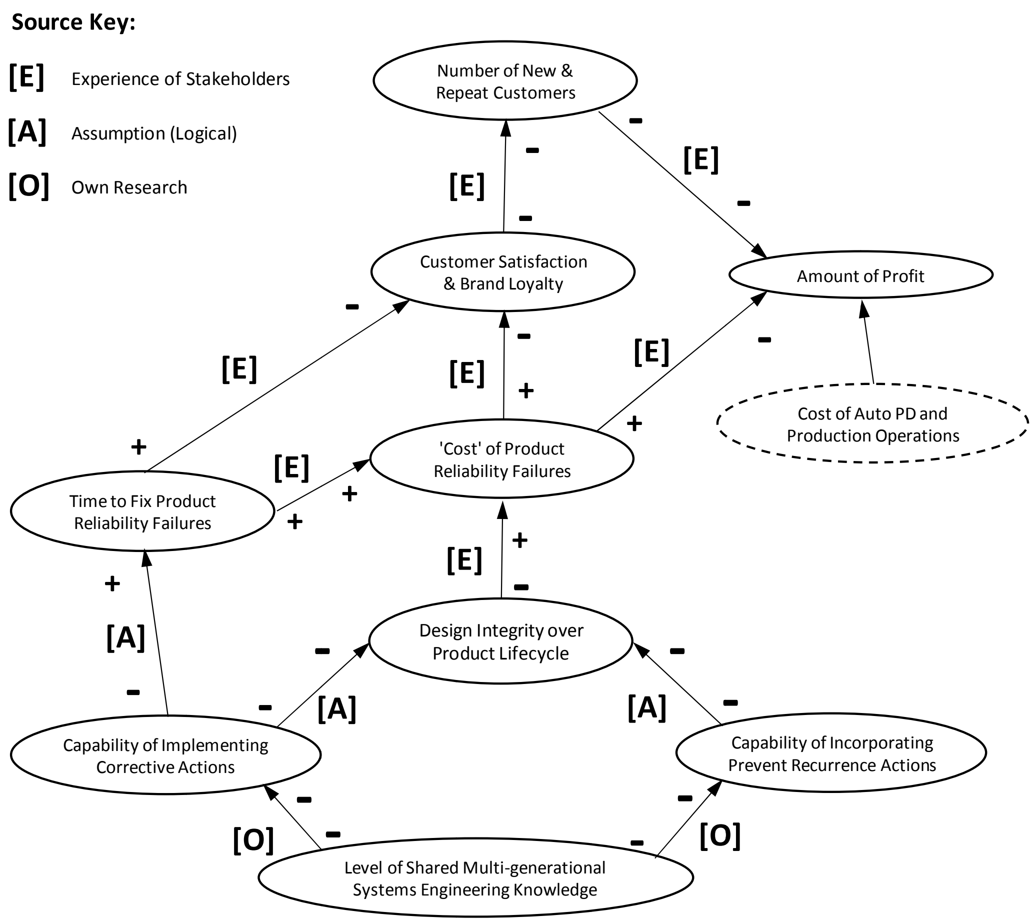


Figure 39. DRM 'Reference' Model - Representing the Existing Situation

The *Reference* model reflects the existing situation that suggests the current lack of an appropriate mechanism for centralising and sharing all multigenerational SE knowledge *(See Figure 10 for DRM Notation),* which leads to;

i) Sub-optimal capability of implementing corrective actions in the instances where OPD engineers have no pathway to access knowledge generated during the NPD phase on each vehicle program. This undermines the ability of the OPD engineering teams to understand the original stakeholder requirements used as SE inputs in the original design process, and subsequent outputs from executing the NPD process.

ii) Sub-optimal capability for the effective incorporation of Prevent Reoccurrence Actions (PRA), where countermeasures and mitigation actions taken to resolve product reliability failures are not appropriately captured in the suite of FMA tools in the CORE PD knowledge domain. This has an undesirable negative effect due to the potential risk of not ubiquitously eliminating the failure mode to prevent reoccurrence on all subsequent future multigenerational vehicle programs.

The completion of this chapter signifies the completion of the *first* part of the *'DRM - Descriptive Study I'* as shown in step 3 of Figure 11.

The next chapter presents the *second* part of the *'DRM - Descriptive Study I'* as shown in step 4 of Figure 11. The chapter focuses on powertrain reliability failure investigations that form the central construct for the SE knowledge transactions that occur within the ***OPD*** domain in Figure 38.

5 AUTOMOTIVE POWERTRAIN RELIABILITY FAILURES

5.1 Introduction

In chapter 3 the literature review revealed the key importance for OEMs to adopt a continuous improvement strategy as part of their Quality Operating System. A fundamental principal of a robust continuous improvement strategy is to monitor product functional performance in operational service and to prioritise investigating the root cause for any reliability failures and developing appropriate countermeasures. In this respect it is imperative that all new SE knowledge learned from any such investigations is then effectively captured within the corporate failure mode avoidance tool set to avoid costly reoccurrence in future multigenerational vehicle programs. This chapter presents the methodology employed in the case study review of a significant number of automotive powertrain reliability failures to classify the types of SE knowledge utilised in these types of investigations and new knowledge learned.

This phase of secondary research was undertaken in order to establish an appropriate meta-knowledge classification scheme in respect to the SE knowledge utilised and generated in the process of investigating and correcting PT functional reliability failures including fault categorisation, root cause, and the subsequent Corrective And Preventative Actions (CAPA).

Although the significant number of test cases were closely reviewed in fine detail, due to the volume of content the specific investigations are not presented individually. Furthermore, no cases involving sensitive information were included in order to protect corporate confidentiality. However, irrespective of this the findings presented are most significant when aggregated to represent the array of issues encountered, and the knowledge employed in resolving them, rather than the particular details of each individual case.

This phase of secondary research was vital to ensure that the requirements for the KM framework, presented in the subsequent chapters, was well informed in advance. The chapter then finally presents the overall findings and conclusions from the case study review, including the recognised potential threats to validity in the results.

5.2 Case Study Methodology

This section describes the range of questions to be answered by the case study, how the specific cases were selected, and the analysis method employed in rigorously examining each individual case for critical knowledge content.

5.2.1 Case study Questions

The case analysis sought to answer several questions to underpin the development of the KM framework and ascertain the meta-knowledge classification requirements for the subsequent prototype ICT tool. The key questions in this respect were as follows;

Q1. What is an appropriate classification scheme for the different types of powertrain faults on vehicles, and the subsequent distribution within the population of cases?

Q2. What classification scheme is appropriate to depict the perceived impact of powertrain failures on customer vehicles?

Q3. What types of supporting systems engineering knowledge are required to investigate the wide spectrum of powertrain failures?

Q4. What is the frequency of use of the various different root-cause analysis tools employed within the systems engineering problem solving process?

Q5. What internal and external system conditions are deemed to have influenced the range of powertrain failures?

Q6. What corrective actions comprise the type of fixes available for the range of powertrain failures?

Q7. What are the antecedent factors that led to the faults being missed during product development or subsequent production manufacturing and assembly?

Q8. Where within the PD program or production manufacture should the fault have been identified and corrected before escaping to the end customer?

Q9. What actions were taken to prevent the reoccurrence of the root cause for the failure on future multi-generational vehicle programs?

Q10. Which Failure Mode Avoidance (FMA) tools required update or modification as a result of identifying the root cause and prevent reoccurrence action?

The next section discusses the process employed in the selection of the appropriate individual test cases.

5.2.2 Powertrain Reliability Failure Cases – Selection Criteria

This section discusses the criteria applied in the selection of the specific test cases. The case studies needed to be a thorough examination of automotive powertrain failures prevalent on full scale production cars that had already been launched and sold in high volume to external general public customers, thus precluding any failures encountered during the normal course of product development as part of prototype vehicle testing.

The aim of the case study was to examine reliability failure investigations on production parts which escaped discovery during the PD program, or failures caused through manufacturing variation or defects that escaped detection as part of the manufacturing quality control plan.

The system exhibiting the failure in service should be part of the powertrain, as other vehicle systems such as electrical, chassis or body systems are out of scope as mentioned in section 1.8.

Additionally, the failures needed to have been investigated and analysed in depth to the extent that the verifiable root cause for the failure was already established and the countermeasures had already been identified, and if possible also successfully implemented.

Furthermore, where possible, the prevent reoccurrence action should have also been identified, or there should be sufficient information to at least infer what appropriate prevent reoccurrence action (PRA) should be pursued and implemented.

Within the wider field of engineering there are many variations of different problem solving methods and techniques available. A comparison of the most popular approaches is shown below in Table 14.

PDCA	DMAIC	A3/PPS	8D/PSP	Focused Improvement
Plan	Define	Clarify the Problem	1. Create Team and Collect Information	1. Select Focus Area
				2. Organise Project Team
	Measure	Breakdown the Problem	2. Describe Problem	3. Understand Present Losses
		Set Target	3. Define Containment Actions	4. Set Theme and Target
				5. Draft Improvement Plan
	Analyse	Analyse the Root Cause	4. Analyse the Root Cause	6. Analysis and Countermeasures
		Develop Countermeasures	5. Define Possible Corrective Actions	
Do	Improve	See Countermeasures Through	6. Implement Corrective Actions	7. Implement Improvements
Check	Control	Evaluate Results and Processes	7. Define Actions to Prevent Recurrence	8. Confirm Results
Act		Standardise Success	8. Congratulate the Team	9. Prevent Recurrence
				10. Horizontal Replication

Table 14. Common 'Problem-solving' Approaches (Sahno & Shevtshenko 2014)

However, within the case study company there are three primary problem solving approaches employed for investigating failures, each of which was provisionally explored to decide if they met the selection criteria;

A number of 8D reports (***Quality-One***, 2017) were initially reviewed but these were generally considered too superficial as they lacked the required depth to ascertain the specific SE knowledge utilised to resolve the case issues. Similarly, 'Prevent Action Closure' papers which constitute a highly involved 14D process were briefly reviewed but these were immediately ruled-out as unsuitable in the interest of non-disclosure of confidential information, such as potential safety related issues.

The eventual source of information nominated as suitable for this research was DMAIC-R reports. This format of problem solving report is used widely within the company for issues that are central to the weekly quality review meetings chaired by the Powertrain Quality Manager and attended by the Powertrain Director.

Commensurately the depth of SE knowledge employed within the problem solving and issue resolution process was found to be extremely comprehensive in respect to meeting the requirements of the case selection criteria. DMAIC-R reports employ data-driven problem solving techniques to systematically identify the cause for variation in performance attributes, and product functional failures.

As such each report provides a detailed description of the issue and its impact on the customer vehicle, the problem solving tools used and analysis undertaken to establish the design or manufacturing process related root cause, and the final corrective and prevent reoccurrence actions.

Finally, there should be a sufficient number of cases to support the validity of the findings. The target number of cases to be retrieved was provisionally defined according to the approximate percentage of annual warranty ($USD) as observed on average for each PT sub system in 2013/14/15 as shown in Table 15.

Powertrain Sub System	**% Annual Warranty**	**Target # Projects**
Engine	40%	20
Transmission and Driveline (TDE)	35%	18
Powertrain As-Installed (PTI)	15%	7
Calibration, Controls and NVH (PCCN)	10%	5

Table 15. Target Distribution of DMAIC-R Projects by Sub System

A notional target of 50 test cases in total was deemed sufficient to provide significant insights to support the subsequent analysis. The provisional target number of projects for each PT sub system is also shown in Table 15.

The following descriptions explain the general approach and content found within each section of a standard DMAIC-R project report. A more detailed and comprehensive review of the problem solving process steps can be found in ***Erdogan and Canatan*** (2015).

Define – the key issue to be addressed is defined in detail in respect to the extent and severity of the problem according to the number of vehicles affected and impact to the business in respect to quality metrics such as ‘voice of the customer’ survey data, and the number of repairs per thousand vehicles. Another key metric is the amount of warranty costs incurred as a result of the material and labour costs involved in paying dealerships to repair the failures. This data is used to initially ‘frame’ the problem.

Measure – In this phase the team, typically comprised of experts from PD and manufacturing, in both the OEM and Supplier, revisit the quality foundation documents such as DFMEA and PFMEA and collectively decide which key engineering design or manufacturing parameters are most pertinent to the root cause based on the gathering of initial evidence such as photos or physical specimens of the failed parts. The team then agrees on a priority order for collecting key data to develop the initial root cause theories. This phase typically also attempts to reproduce the failure under controlled conditions to demonstrate the association between the nominated main effects. The team may then construct a ‘Design of Experiments’ (DoE) aimed at systematically studying each of the main CTQ factors that may ultimately lead to understanding the underlying root cause.

Analyse – The data collected in the measure phase is often analysed using statistical calculation methods and tools to establish trends and relationships between parameters and variables that may explain changes in performance or function. The conclusion of this phase should then provide high confidence that the root cause is understood in detail and can be explained and, if needed, controllably reproduced.

Improve – Once the measured data has been analysed the team makes recommendations on which parameters or combination of variables need to be better controlled or adjusted to eliminate the root cause for the failure. The initial physical embodiment of the solution is implemented within an initial small batch of new manufactured parts (prototypes) containing the recommended design change or adjustments in manufacturing process. These parts are then tested against the predefined Design Verification Method (DVM) to demonstrate the root cause has been eliminated.

Control – This phase ensures the recommended corrective action is rigorously introduced into production with adequate quality control methods. The quality performance data metrics are then monitored closely to gauge the degree of success the corrective action has towards eliminating future field failures on customer cars.

Replicate – The final DMAIC-R phase in the context of CAPA is for the team to decide how to prevent reoccurrence of the issue in future PD programs. This often requires the teams to employ techniques such as asking the set of '5 Whys' questions to drill into how the failure mode escaped. The team then works to implement changes in the appropriate design requirements and rules, or manufacturing control plans to ensure failures do not reoccur, so the entire organisation benefits from the new learning and knowledge.

An initial vast number of DMAIC-R reports were collected by directly approaching the OPD engineers within each of the PT sub groups and copying the electronic files onto a portable memory stick as most file sizes were far too large to send as an email attachment. All individual reports had been published in MS PowerPoint (.ppt) format to present in the PT Director Quality Review meeting. The project file names lacked the required information to identify the contents, and the contents contained a range of unidentified multimedia such as photos of part failures and embedded graphic images.

After an initial screening exercise a total of 48 DMAIC-R reports were selected as suitable for inclusion, representing 993 pages of knowledge generated by Ford engineers and managers, and across 35 different technology suppliers of externally purchased parts. Each project team typically consisted of at least one qualified 6 sigma black-belt engineer, functional chief engineer and manager, subject matter experts and technical specialists from both design and manufacture, OPD and Core engineers, quality data analysts, and test engineers.

5.2.3 Case Study Analysis Method

In order to maximise the reliability and repeatability of each DMAIC-R case study examination it was imperative to establish a standard pathology to categorise the key knowledge harnessed and utilised in each failure investigation. The definitions were drawn from the fields of systems engineering and failure mode avoidance and aligned beneath each of the DMAIC-R steps as shown in Table 16 below.

DEFINE	Distribution of PT Failures	1	Project Classification
	Impact of PT Failures	2	Error States
MEASURE	Failure Investigation	3	Root Cause Analysis Support Tools
		4	SE Support Knowledge
ANALYSE	Primary Failure Mechanism	5	Noise Factors
IMPROVE	Issue Resolution	6	Corrective Actions
CONTROL			
REPLICATE	Future Prevention	7	Antecedent Factors
		8	Escape Points
		9	Prevent Reoccurrence Actions
		10	Failure Mode Avoidance Tools

Table 16. DMAIC-R Case Study Examination Pathology

A total of 10 sub categories were established as the framework for the examination pathology. Each DMAIC-R project was then examined to capture the specific features and knowledge embedded into the investigation as evidence within the project report.

The analysis was then conducted by examining each case page-by-page, identifying the knowledge content type, and entering the classification of the findings into a Microsoft Excel spreadsheet which facilitated tabulating the results and providing graphical output.

The MS.xls spreadsheet also formed the basis for the ***DMAIC-R Directory*** element of the web 2.0 groupware support tool which is presented in chapter 7.

The PT reliability case study classification methodology is presented in the next sections.

Distribution of Powertrain Failures – Project Classification

A key finding of the research conducted in chapter 4 was that the classification of knowledge ownership is a major priority when establishing the taxonomy for any potential KM system. Knowledge that is improperly captured or incorrectly stored is highly likely to become latent and remain undiscovered for future use, thus rendering it redundant.

The first step in the DMAIC-R case study analysis was to pre-screen and sort the projects. This involved a bottom-up analysis to classify each project according to the taxonomy and hierarchy previously defined in Table 5 and Figure 25. The full list of fifteen classification elements is shown in Table 17.

1	Project Title	Basic Project Identifiers
2	Date	
3	Number of Pages	
4	Team Members / Names	
5	Supplier Name / Location	
6	PT Sub QB	PT Technology Group Identifiers
7	PT System	
8	PT Sub System	
9	Vehicle Line Description / Code	Vehicle / Powertrain Identifiers
10	Vehicle Build Plant Location	
11	Engine Type / Size	
12	Engine Name Description	
13	Transmission Type / Code	
14	Customer Complaint Symptom	Description Keyword Identifiers
15	Root Cause Description	

Table 17. DMAIC-R Project Classification Scheme

Additional classification elements were then added to capture the main keywords used in the subjective description of the customer complaint symptom and the root cause.

The above project classification scheme was then used in the subsequent analysis to answer question 1 in section 5.2.1.

Impact of Powertrain Failures – Error States

Each DMAIC-R project initially lists the 'Voice of the Customer' as a word description of the symptoms that the customer experienced when the failure occurred. This is originally captured on the warranty claim form in the native language of the country in which the repair was conducted, and so has to be translated into English language. Since there is no strict lexicon the categorisation was drawn from the existing 4 Error State definitions according to the industry standard Parameter diagram (Fritzsche 2006). Each error state category describes the nature of undesirable system performance from the customer perspective. A system may in fact maintain its primary function but in the presence of undesired secondary side-effects e.g. unusual noise, difficult to operate, water or oil leakage etc.

Full Failure – this category is used for all the failures where the vehicle was completely immobilised or inoperable. In context this equates to cases where the engine would not start, or the vehicle would not move. These types of failures generally require the customer vehicle to be recovered by roadside assistance.

Partial /Degraded Function – This category is used when the customer symptom implies the vehicle was still operable but with a persistent degradation in function or attribute. This equates to situations such as a partial loss in engine power or torque transfer from the engine to the road wheels somewhere within the drivetrain system.

Intermittent Failure – This category is used where the reported issue is non-persistent and not easily reproduced when the vehicle is presented to the dealership. These failures are often associated with electrical wiring or control system sensor faults.

Unintended Failure – These types of failures are often triggered by a mismatch in the control strategy software logic or false sensor values suggesting certain parametric values have shifted outside of an acceptable range or exceeded a permissible threshold.

Allocation of the above error state type to each project was used in the subsequent analysis to answer question 2 in section 5.2.1.

Failure Investigation - Root Cause Analysis Tools

Once the ‘Define’ stage has been completed there is then a wide array of RCA tools available to support the team in deciding where to focus the resources and effort in the ‘Measure’ stage of a DMAIC-R project. The literature review in chapter 3 revealed a number of key RCA tools that are commonly utilised, which are shown in Table 18.

1	Cause and Effect Analysis
2	CTQ Analysis Y=f(X)
3	Design of Experiment (DoE)
4	Pareto / Histogram of Failures
5	Is / Is-Not
6	Reliability Hazard Plot
7	5 Why's Statements
8	Statistical Process Control (SPC)
9	Customer Questionnaires
10	Benchmarking

Table 18. Root Cause Analysis Tools

Each RCA tool reflects the collective corporate knowledge and critical thinking from the technology Subject Matter Experts (SME’s). Once completed for a single project the essence of each tool may be subsequently re-used as the starting point of departure for similar future investigations.

As such, each tool may be used generically to provide some initial direction and prioritization of the logical and sensible hypotheses that should be pursued in order to demonstrate replication of the failure mode under controlled conditions, and thus prove the root cause theory.

The above approach was used in the subsequent analysis to answer question 3 in section 5.2.1.

Failure Investigation - Systems Engineering Support Knowledge

The categorisation process to ascertain the different knowledge types was bottom up and iterative. Each knowledge class identified was first grouped by type or general engineering discipline.

The class assigned was subjectively inferred according to the nature of the knowledge rather than the specific Powertrain sub-system from which it was derived. This approach was required since although the identified current knowledge may be domain specific its position within a generic KM hierarchal taxonomy needed to be identified to facilitate a structure that will accommodate all potential future new knowledge. The main groups were initially defined and the categories then developed from within each group.

The first group of categories pertain to the physical form of the failed parts. This includes 2D Drawings and cross sections, 3D models and installation schematics, and photos of failed parts. These categories were only applicable where physical hardware faults were involved rather than control system software or calibration issues.

The second group of categories were derived from the results and controls defined according to the execution of the FMA plan during PD prior to production launch. These categories included the design validation and production verification test results, the manufacturing and assembly processes and associated quality controls plans including; manufacturing capability and detection stations according to the measurement system analysis.

The third group of categories relate to knowledge derived from different engineering disciplines that inform the failure investigation with critical insights regarding the design capability within the vehicle application in which the failure occurred. These categories include CAE / FEA design capacity analyses, material property analyses, thermal and aero data, operating load condition data. Noise, Vibration and Harshness data (NVH) was also a candidate for this group since this class of data is often required to explain customer complaints that lead to part replacements caused by disconcerting noises within a vehicle such as knocking and vibrations.

The final category is Diagnostic Fault Codes (DTCs). This knowledge class is specific to failures that can be pin-pointed to a change or loss in functional performance that is monitored through the array of sensors within vehicle control system architecture. The driver is typically presented with a visual warning message on the instrument cluster. These types of warning message can relate to both hardware and software or calibration issues and so knowledge regarding the fault signal is highly important in interpreting the root cause for complex powertrain failures.

The above categorisation scheme was used in the subsequent analysis to answer question 4 in section 5.2.1.

Primary Failure Mechanism – Noise Factors

Through the course of the initial examination of the DMAIC-R projects it became evident there was no standard lexicon utilised to define the primary root cause of the failure, which was prohibitive to classifying the projects by failure type. To overcome this the word description was instead subjectively aligned to the appropriate Noise Factor according to the standard Parameter diagram definitions (Fritzsche 2006).

Noise factors are non-controllable and may occur at random. Consequently they may have an undesired effect on the system output response.

- Internal noises are piece-to-piece variation and change-over-time aspects.
- External noises are customer usage, external environment, and system interaction

Noise 1: Piece to Piece Variation

This category considers the natural variation within the permissible range of all the manufacturing processes. The isolated effect of manufacturing variation on single components may be acceptable, but the combined effects once the components are assembled into sub assembly systems may cause undesirable side effects.

Noise 2: Change Over Time

This category considers the degradation of a design attribute due to damage accumulation over time which can lead to a performance limitation or in worst case a loss of a system function. Examples of this kind of noise factors are: corrosion, fatigue, wear and physical degradation over time/mileage/duty cycle.

Noise 3: Customer Usage and Duty Cycle

This category considers everything that a customer can do with the product during its useful life period. Instances of customer usage and duty cycle are: Carrying or towing heavy payloads, excessively high mileages, frequent starts / stops, off-road driving.

Noise 4: External Environment

This category considers the effect of external factors that are not generated by the design or transmitted by adjacent systems. The external environment defines the operating conditions under which the system must deliver and maintain all intended functions and attributes without degradation or failure. Typical examples for external environment are: water and snow, mud, dust, stone impact, road salt, extreme hot and cold ambient temperatures, high altitudes.

Noise 5: Internal Environment

This category considers potential system inter-actions with the affected neighbouring systems or package to surrounding parts. e.g. heat, vibrations, high torque and shock force, electromagnetic interference.

The above classification scheme was used in the subsequent analysis to answer question 5 in section 5.2.1.

Issue Resolution - Corrective Actions

A primary categorisation requirement in the context of KM is to define what corrective action was taken to eliminate the root cause of the failure. The manifestation of the corrective action could in reality take many forms depending on the technology and manufacturing techniques employed.

For the purpose of classifying each project three different instances of corrective action were selected as shown in Table 19. The first two classes pertain to physical hardware parts, and the third was reserved for changes specifically associated to the powertrain control strategy and calibration.

1	Design Change
2	Manufacturing Process Change
3	Modified Control Strategy / Diagnostic

Table 19. Identified Classes for Corrective Action Types

The above classification scheme was used in the subsequent analysis to answer question 6 in section 5.2.1.

Future Prevention - Antecedent Factors

Antecedent factors are those which inadvertently allowed a failure mode to remain latent and escape the PD engineering sign-off and manufacturing quality controls until ultimately being detected on a customer vehicle. There should instead be a close coupling between the point in the PD or manufacturing process where the potential failure mode was inadvertently incorporated and the point where it should be detected before escaping.

1	Inadequate Design Capability	Group 1	Design Phase
2	Inadequate Sign off - Function / Attribute	Group 2	
3	Inadequate Design Validation		
4	Inadequate Production Verification	Group 3	Production Phase
5	Quality Control - Manufacturing Variation	Group 4	
6	Quality Control - Manufacturing Defect		

Table 20. Groups and Classes of Antecedent Factors

The process of establishing the six Antecedent factors shown in Table 20 was iterative and bottom up by scanning through each DMAIC-R project and inferring which sub element of the PD or manufacturing process should have discovered the failure mode. This was done in combination with a working knowledge of the corporate PD process.

The six instances of different antecedent factors were then aligned within one of four groups, and additionally against either the design or production phase of the PLC. These were then taken in context with the escape / detection points highlighted in Table 21 in the next section.

The above classification scheme was used in the subsequent analysis to answer question 7 in section 5.2.1.

Future Prevention - Escape / Detection Points

A key question that must be asked when looking to implement prevent reoccurrence actions is; what was the earliest point within the PD process (robustness failures) or Manufacturing process (failures due to defects) where the potential for the non-conformity should have reasonably been detected?

As advanced by McMurran (2014) it can be argued that perfect foresight and complete specifications would suggest that all potential failure modes should be identified within the DFMEA (Design) or PFMEA (Manufacturing and Assembly).

However, the reality is that there are multiple additional points throughout the PD and manufacturing processes where the lack of design robustness or presence of defects could also be identified before allowing the issue to escape to the customer. Through the broad examination of the 48 DMAIC-R projects a primary bottom-up classification scheme was derived that established 10 possible detection/escape points as shown in Table 21.

1	Design Requirements (SDS)	Group 1	Design Phase
2	Design Specification		
3	Design Capability Model		
4	Component / Unit DV Test	Group 2	
5	System DV Test		
6	Vehicle DV Test		
7	PPAP / PSW	Group 3	Production Phase
8	Component Manufacturing Test	Group 4	
9	EoL Supplier Function Test		
10	EoL Vehicle Manufacturing Test		

Table 21. Identified Detection/Escape Points

The above classification scheme was used in the subsequent analysis to answer question 8 in section 5.2.1.

Future Prevention - Prevent Reoccurrence Actions

The secondary categorisation exercise in the context of CAPA was to define what prevent reoccurrence action was taken to eliminate the potential to repeat the same type of failure mode on future vehicle PD programs as shown in Table 22 below.

1	Design Requirement / Rules Updated	Design Phase
2	FMA Documentation Updated (Incl. D/PFMEA)	
3	Design Verification Method Updated	
4	Update Manufacturing SCCAF / MCP	Production Phase

Table 22. Classes and Phases of Prevent Reoccurrence Actions

The above classification scheme was used in the subsequent analysis to answer question 9 in section 5.2.1.

Future Prevention - FMA Tools

The final categorisation method was to examine each test case and ascertain which of the standard suite of FMA tools may have inadvertently missed the specific root cause for the failure mode. Pin-pointing which tool/s required update finalises the workflow to complete the closed loop CAPA process and provides the linkage between each DMAIC-R project and the FMA tools repository. The suite of FMA tools available were derived from the various publications examined during the literature review as shown in Table 23 below.

1	System State Flow Diagram	Function Analysis	Pugna et al. (2016) Erbiyik and Saru (2015) Erdogan and Canatan (2015) Henshall et al. (2014) Campean et al. (2013) Honda (2011) Fritzsche (2006)
2	Function Tree		
3	Boundary Diagram		
4	Interface Matrix		
5	DFMEA	Function Failure analysis	
6	PFMEA		
7	P-Diagram	Robust Countermeasure	
8	Fault Tree Analysis		

Table 23. Types of Failure Mode Avoidance Tools

The above classification scheme was used in the subsequent analysis to answer question 10 in section 5.2.1.

5.3 Case Study Results and Analysis

The following sections present the results and analysis from the examination of the 48 individual DMAIC-R projects in line with the methodology outlined in section 5.2.

5.3.1 Distribution of Powertrain Failures – Project Classification

The prevalence of powertrain failures within each of the four powertrain system groups is shown in Figure 40.

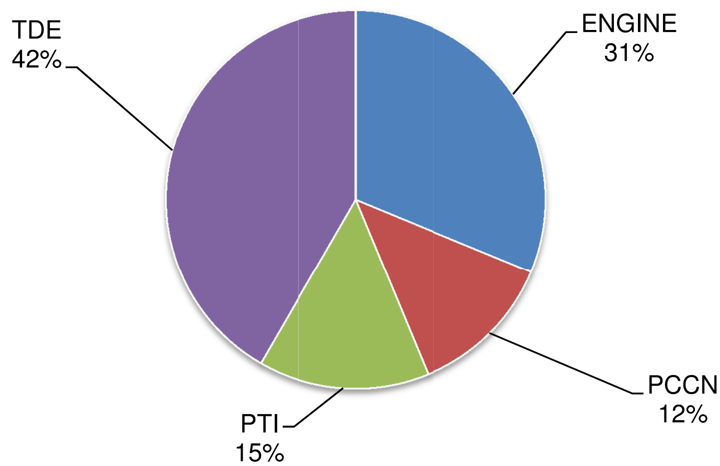


Figure 40. Distribution of DMAIC-R Projects by Powertrain System

Section 5.2.2 described the intention to review a significant number of PT failure investigation projects across the range of different PT technology groups.

The number of projects sought from each major PT sub system was approximated according to the annualised warranty spend (Table 15.). Figure 40 supports that a satisfactory number of projects were retrieved in this respect.

The detailed classification of powertrain failures according to sub-system, beneath each of the four main powertrain system groups, is shown in Figure 41.

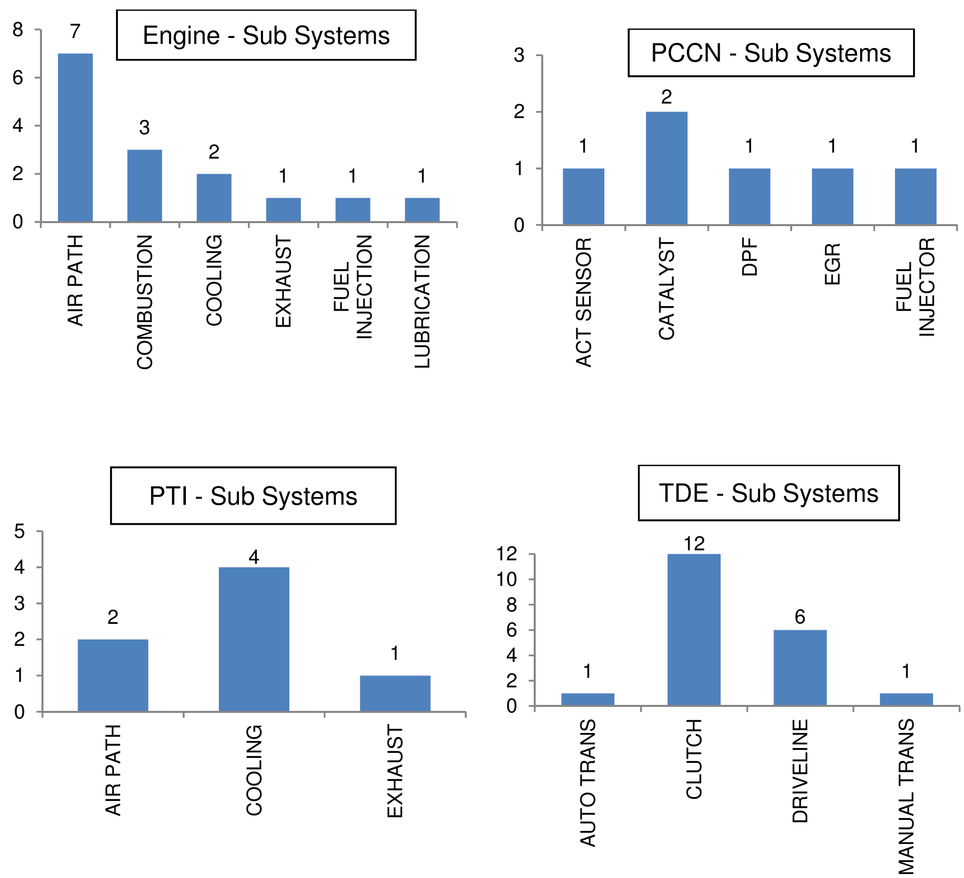


Figure 41. Distribution of DMAIC-R Projects by Powertrain Sub-Systems

This stage of the research sought to formulate a meta-knowledge classification scheme so there was no intention to infer any statistical or scientific conclusion based on the distribution of the population of projects. Equally it could not be claimed that the dataset is complete since it does not represent the entire population of projects published within any particular time bound period. Within the distribution of projects by PT sub system it can be seen that there are a greater number of clutch and air path projects. This bias within the distribution is purely a consequence of which engineers were approached and how willing they then were to locate and volunteer the subsequent electronic files that were then included in the case study analysis.

5.3.2 Impact of Powertrain Failures – Error States

The impact of powertrain failures according to each of the error state categories is shown in Figure 42.

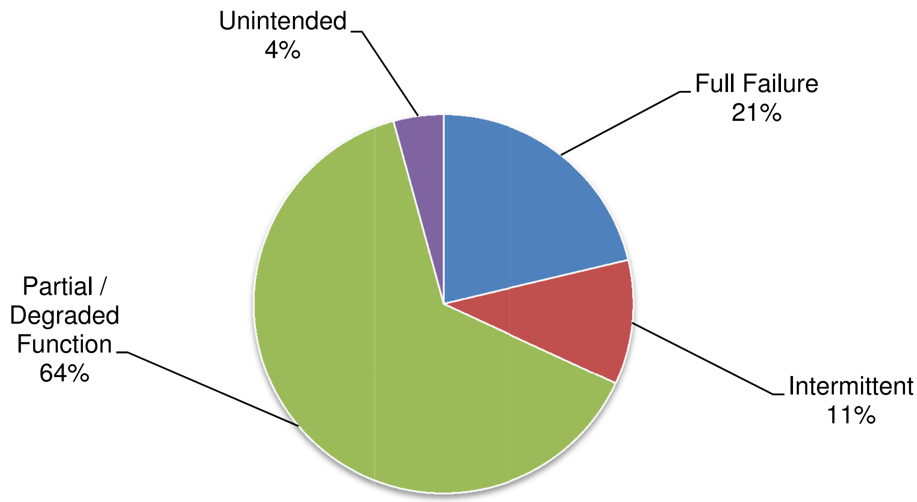


Figure 42. Distribution of DMAIC-R Projects by Error State Type

The majority of the projects examined were according to investigations on customer vehicles with partially degraded powertrain function (64%). Complete powertrain failures that rendered the customer vehicle immobilised represented the second largest group of projects reviewed (21%). Intermittent failures represented the third largest group (11%).

As discussed in section 5.2.3 this category represents a particularly challenging set of circumstances whereby the customer complaint may no longer be present, or may be difficult or impossible to reproduce.

Unintended failures such as a false instrument cluster message or 'Malfunction Indicator Lamp' (MIL) was the smallest group (4%). This category is strongly related to the PCCN sub system group of technologies, so the low percentage is a commensurate reflection on the small number of PCCN projects that were retrieved.

5.3.3 Failure Investigation - Root Cause Analysis Support Tools

Table 24 shows the results of the examination of the 48 DMAIC-R projects to determine the distribution of root cause analysis tool utilisation.

1	Cause and Effect Analysis	36	75%	High Utilisation
2	CTQ Transfer Function Analysis Y=f(X)	14	29%	
3	Design of Experiment (DoE)	17	35%	
4	Pareto / Histogram of Failures	27	56%	
5	IS / IS-NOT	25	52%	
6	Reliability Hazard Plot	1	2%	Low Utilisation
7	5 Why's Statements	1	2%	
8	Statistical Process Control (SPC)	2	4%	
9	Customer Questionnaires	3	6%	
10	Benchmarking (Customer / Vehicle)	6	13%	

Table 24. Distribution of RCA Tool Utilisation

The utilisation of the initial five RCA tools was found to be high across all 48 DMAIC-R projects. The second set of 5 tools collectively represents significantly lower utilisation.

Although there is a clear bias in the popularity of certain tool types, this is explained by the fact that most DMAIC-R projects simply need to employ the tools from the first suite to define the basic issue, but only the more challenging projects progress to use the second suite of RCA tools to fully understand the complex cause of the failure mechanism.

It cannot be stated that the second suite of tools are any less useful but rather they are probably used in a more specific and targeted way, whereas the first suite of tools are applied more generally to all investigations.

5.3.4 Failure Investigation – Systems Engineering Support Knowledge

Table 25 shows the distribution of different Systems Engineering knowledge types utilised across the 48 DMAIC-R projects.

2D Drawing and Cross Section	Comparison of the Intended design with the observed and measured failed part (hardware)	11	23%
3D Model and Installation Schematic		28	58%
Photos of Failed Parts		34	71%
Failure Inspection Report (OEM/Supplier)		15	31%
DVPR Test Result Reports	Results and Controls Defined via the Failure Mode Avoidance Process	8	17%
Manufacturing and Assy Process / Controls		15	31%
SCCAF / MCP		8	17%
MSA / VSA		9	19%
CAE / FEA Design Capacity Modelling	Design Functional Capability and Attribute Performance Analysis	15	31%
Material Lab Analysis		19	40%
Thermal Heat Management Data		4	8%
Operating Condition Data (RLD)		9	19%
NVH measurements		6	13%
Diagnostic / Complaint Codes (DTC / CCC)	Dealer / Customer	17	35%

Table 25. Distribution of SE Knowledge Utilisation

The results from this element of the analysis form the core of the research as it demonstrates the full range and utilisation of the number of complex knowledge types involved in the PT failure investigation process.

The findings portray a mix of knowledge from the output of the preceding PD program, as well as new studies conducted specifically for the investigation using the same techniques and methods typically employed in the early phases of NPD.

In many cases the original methods used to confirm design integrity may be revisited to reassess if the assumptions for the original input data are still valid, or if the latest understanding based on the latest real world measured data possibly means that the operating or boundary conditions need to be altered within the Design Verification Method (DVM).

5.3.5 Primary Failure Mechanism – Noise Factors

The findings regarding the noise factor categories associated to the failure modes for the 48 projects are shown below in Figure 43.

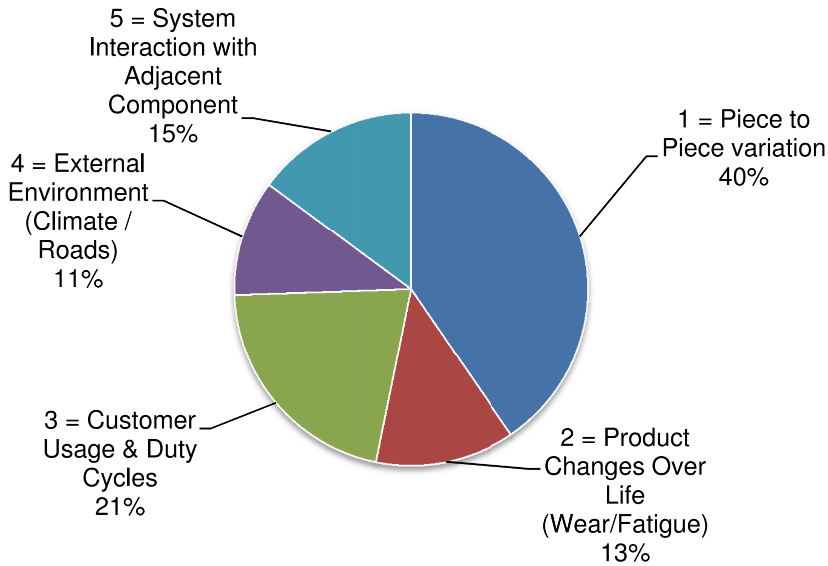


Figure 43. Distribution of DMAIC-R Projects by Noise Factor Types

The full definition for each noise factor type was discussed in section 5.2.3. The results found that the majority of failure modes within the 48 projects were designated to noise factor type 1, suggesting a high occurrence of failures due to manufacturing piece to piece variation.

Throughout the remainder of the projects a reasonably fair distribution was observed between noise factor types 2 to 5.

5.3.6 Issue Resolution - Corrective Actions

The findings according to the distribution of corrective action types are shown below in Figure 44.

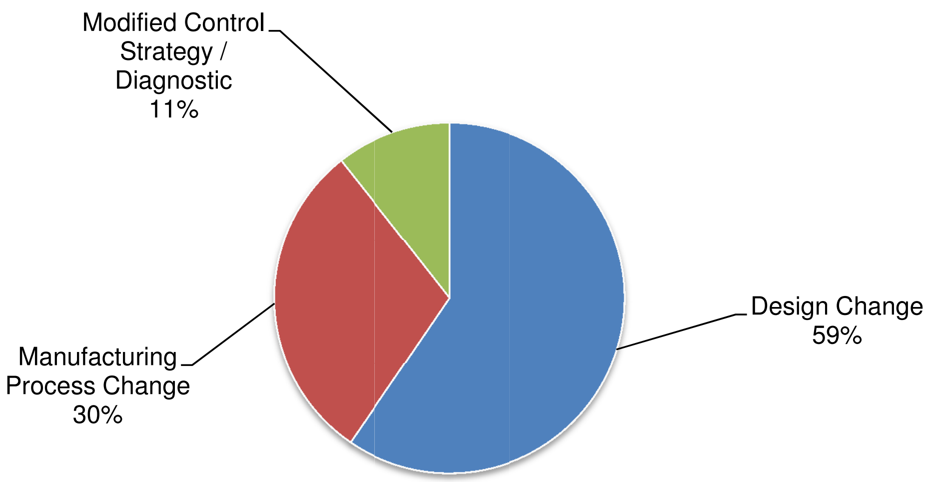


Figure 44. Distribution of DMAIC-R Projects by Corrective Action Types

It can be observed that the majority of corrective actions resulted in some form of design change. These results may seem counter intuitive given the higher proportion of noise factors related to manufacturing piece to piece variation found in section 5.3.5.

However, this can be explained by the fact that many of the design changes were implemented to make the design more robust / less sensitive to manufacturing variation. Manufacturing process changes were observed as the corrective action in 30% of the cases, and the remaining 11% were associated with changes to the powertrain control system through modified calibration or software strategy.

5.3.7 Future Prevention - Antecedent Factors

The subjective interpretation of the antecedent factors that ultimately allowed the failure mode to escape detection during the PD or manufacturing processes is captured in the distribution shown below in Figure 45.

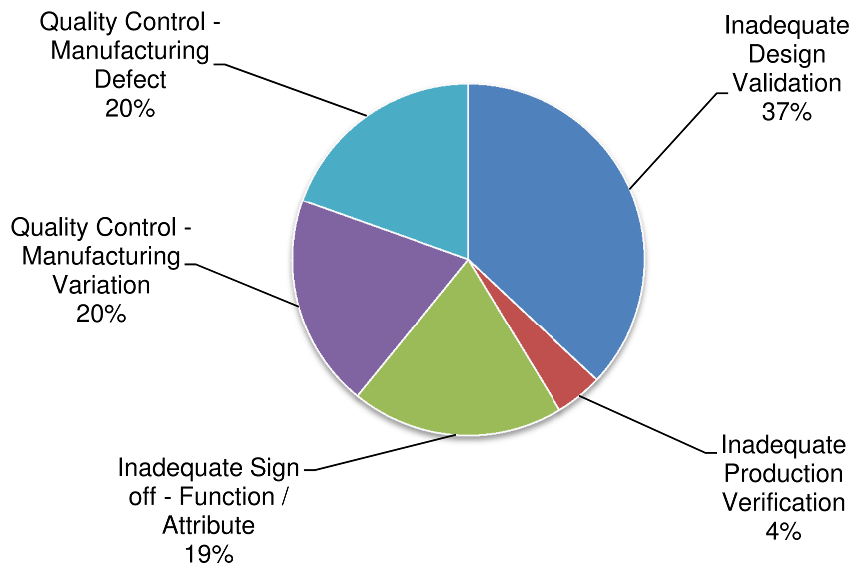


Figure 45. Distribution of DMAIC-R Projects by Antecedent Factors

The majority of the test cases reviewed found that the key antecedent factor that led to the primary root cause was due to inadequate design validation (37%). This suggests that either insufficient design validation was conducted or the design validation test methods were not adequate to find the latent failure mode. The second and third largest categories for antecedent factors are associated to manufacturing variation and manufacturing defects. Both of these categories are directly linked to the SCCAF and MCP elements of the Failure Mode Avoidance process, which provides a strong indication to which FMA tools require update as part of the PRA process.

The fourth category of inadequate sign off of the design function or attribute (19%) accounted for nearly one fifth of the projects. The fifth category of inadequate production verification (4%) represents the smallest group of antecedent factors where there was suggestion of insufficient or inadequate verification testing to assure the expected quality of parts is maintained when produced in high volume through the full scale manufacturing and assembly processes.

5.3.8 Future Prevention - Escape / Detection Points

The subjective interpretation of the points in the PD or manufacturing processes where the failure mode should have been detected before escaping to the end customer is captured in the distribution shown below in Figure 46.

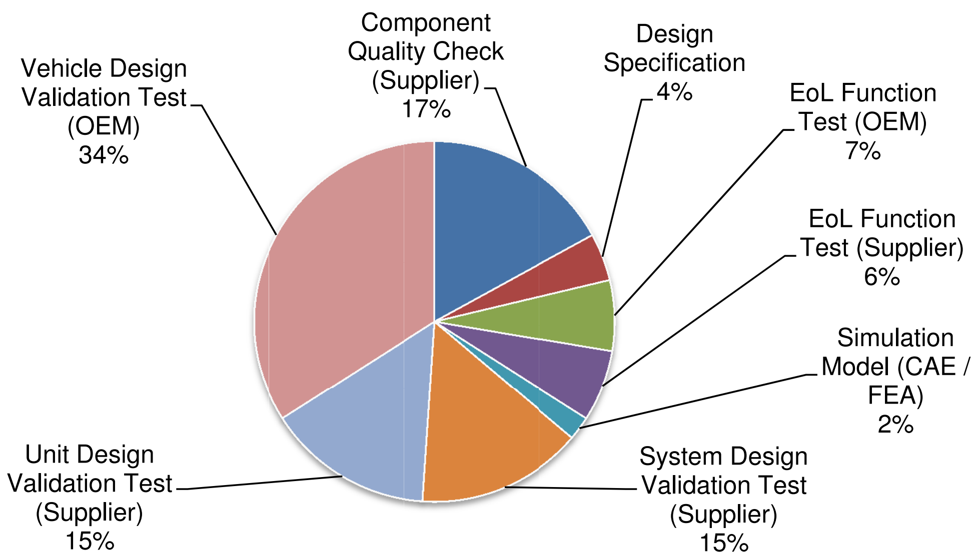


Figure 46. Distribution of DMAIC-R Projects by Escape / Detection Points

It can be observed from the wide array of possible escape / detection points that there are many opportunities to detect the possibility for failure before it should ever reach the end-customer. The sub categories broadly fall into either the design or manufacturing phase of the product lifecycle.

The strongest opportunity to catch any issues was during the fully integrated vehicle design validation test phase at the OEM (34%), which strongly correlates to the findings in the previous section on antecedent factors. The next key areas however relate to responsibilities within the supplier network whereby the unit design validation test (15%) or system design validation test (15%) should have detected the problem. The EoL function tests at either the OEM on a full vehicle (7%) or at the supplier on the System before it was supplied (6%) were also key opportunities.

5.3.9 Future Prevention – Prevent Reoccurrence Actions

The distribution of the prevent reoccurrence actions according to the examination of the 48 projects is shown below in Figure 47.

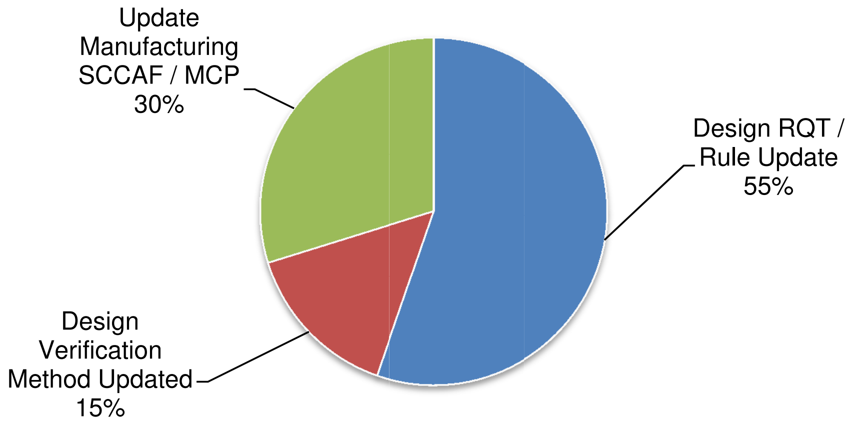


Figure 47. Distribution of DMAIC-R Projects by Prevent Reoccurrence Actions

As briefly mentioned in section 5.3.7, although inadequate design validation testing may be an antecedent factor in allowing a latent design issue to escape, simply modifying the approach on validation testing somewhat defeats the object as it will solely reveal inherent design flaw as a DV test fail on future vehicle programs.

Consequently, the distribution of prevent reoccurrence actions actually demonstrates that in the majority of cases it was the upstream design requirements or rules (55%) that were updated to prevent the potential for the failure from being embedded in the design in the first instance. There was a much lower incidence of cases where only the design verification test method was actually amended (15%).

The remainder of the test cases, which were more associated to issues caused by variation or defects in manufacturing, were linked to a commensurate update to the manufacturing quality control plans (30%).

5.3.10 Future Prevention - FMA Tools

The subjective interpretation of the appropriate Failure Mode Avoidance tools that require update as part of the prevent reoccurrence process is captured in the distribution shown below in Table 26.

System State Flow Diagram	Function Analysis	5	10%
Function Tree		5	10%
Boundary Diagram		3	6%
Interface Matrix		21	44%
DFMEA	Function Failure analysis	14	29%
PFMEA		10	21%
P-Diagram	Robust Countermeasure	10	21%
Fault Tree Analysis		12	25%

Table 26. Distribution of FMA Tool Utilisation

It should be noted that any number of FMA tools could be implicated depending on which tools may have missed considering any aspect of the risk of each failure mode.

The objective of the FMA process is that the engineering teams should apply critical thinking to the upstream FMEA so the subsequent design validation and production verification test plans then confirm all potential failure modes are not present within the vehicle system (***Henshall et al.*** 2014).

So, in principle, the root cause for any failure that does escape should be traceable back to the content in at least one of the FMA tools (***Henshall et al.*** 2015).

5.4 Limitations and Threats to Validity

This section briefly considers some of the limitations and threats to validity of the methods and findings associated with the case study research into powertrain functional reliability failures.

The quantity of test cases that were retrieved is the first area of consideration. The absence of any existing complete database dictates that the population of retrieved DMAIC-R projects realistically only represents a fraction of the total population of PT reliability failure investigations. The test cases that were used in the subsequent analysis cannot therefore be assumed to represent any significant statistical pattern. However, the classification systems established for each category were verified across a diverse number of different PT technology groups and failure types. This mitigates the lack of statistical significance, and instead supports the generalisation that sustained use of the approach could overtime build up significant patterns of interest.

The knowledge content pathology used to examine the test cases is the second area of consideration. The lengthy and detailed process of thoroughly examining all 48 projects was intended to establish the meta-knowledge classification scheme which could then be used within the subsequent prototype KM ICT support tool. Since this research project is primarily concerned with KM as the unit of analysis, rather than the application of problem solving techniques, the key objective was to establish the full spectrum KM categories and classes. On this basis the findings are considered suitable for forming the meta-knowledge construct within the requirements for the SE KM framework.

It was previously defined within the scope of the research in section 1.8 that only powertrain failures were to be considered. In this respect it is important to note that there may be possible limitations such that the scheme developed may not be entirely suitable for non PT technology systems. Equally, the data used was only derived from a single vehicle manufacturer and so there is no claim that it is representative of the wider automotive industry. However, since the majority of the supplier technologies are non-proprietary it can be reasonably argued that similar equivalent issues are probably prevalent across the broader population of OEM vehicle applications.

5.5 Powertrain Reliability Failures Investigation – Summary

In chapter 4 an initial exploratory industrial investigation was conducted to understand the general KM practices and challenges within the multinational automotive OEM environment. However, due to the general nature of the exploratory study, it did not reveal sufficient insights into the specific knowledge utilised in investigating and correcting product functional reliability failures.

In this chapter a targeted case study was conducted to better understand the KM implications in the context of PT reliability failures and the CAPA process, with a view towards establishing a meta-knowledge classification scheme to satisfy objective 3 (Table 2). To frame the case study a series of ten fundamental questions were compiled in section 5.2.1.

The first question the case study set out to answer was what is an appropriate classification scheme for uniquely re-identifying the many different types of PT failures within the population of test cases? The need to classify knowledge according to a large number of different identifiers was found to be critical due to the complexity in organisational structure and technology types. The bottom-up analysis of the 48 DMAIC-R projects revealed that for just the PT group of technologies a minimum of 15 unique identifiers are needed to fully classify any particular project so that it can be accurately relocated for future reuse. However, it could also be argued that several more identifiers may also be beneficial in pin-pointing specific attributes.

It was proposed that the impact of powertrain failures could be classified according to the four error state categories in accordance with the industry standard parameter diagram definitions. This approach supported the extension of the project classification scheme to allow the incorporation of error state meta-knowledge.

The utilisation of root cause analysis tools used in supporting the PT failure investigations was found to be polarised between tools with high and low popularity. However, the full spectrum of available RCA tools was used, so the provision of a formal mechanism and meta-knowledge classification scheme to store and retrieve all commodity specific examples for future reuse is essential.

The bottom-up examination of the 48 DMAIC-R projects established 4 main categories containing 14 different types of SE knowledge that were found to be frequently used during the investigations (Table 25).

- Knowledge of observed and measured failed part evidence and the subsequent comparison with the intended part geometric design and specification.
- Knowledge derived from the original vehicle NPD program failure mode avoidance plan, such as DFMEA and DV test results, PFMEA and PV test results, and manufacturing quality control plan check methods.
- Knowledge of the intended system functional capability and attribute performance, in conjunction with the original design targets and requirements.
- Knowledge from the dealership indicating the nature of the system failure as described in terms of symptoms experienced by the customer.

The subsequent meta-knowledge classification scheme also incorporated the outcomes of the DMAIC-R project investigations as follows;

The distribution of primary failure mechanisms found within the population of test cases was established through assigning the failure mode type to one of the five categories of noise factor (Figure 43) in accordance with the industry standard parameter diagram definitions (Fritzsche 2006).

The corrective action types implemented to resolve each PT failure mode was assigned to the respective category depending on whether the fault was found to relate to hardware design, hardware manufacture, or within the engine control software strategy or calibration (Figure 44). Further linkage to the corporate change management ‘release’ identifier would also be beneficial in this respect to facilitate traceability between different released design levels.

The case study found that five different classifications are required to define which antecedent factor ultimately allowed the failure mode to escape detection during PD or manufacturing (Figure 45).

A further 8 escape/detection points were identified as adequate in identifying where further opportunity may have lay to have prevented the failure reaching the end customer (Figure 46).

In regard to Prevent Reoccurrence Actions (PRA) three key themes were used in classifying the projects. The majority of actions were addressed through either creating or updating design requirements or rules. Further actions were classed as either updates to the manufacturing quality control plans, or updates to the design validation test methods, or production quality verification methods (Figure 47).

Finally, the linkage between the eventual root cause and the originating FMA tool that may have inadvertently missed the potential for the failure was classified against the 8 different tools found within the failure mode avoidance literature (Table 26).

All of the different categories and sub classes of knowledge types collectively form the meta-knowledge classification scheme which then forms the central construct for the OPD domain within the SE lifecycle KM framework advanced by this research.

This meta-knowledge classification scheme is deemed to work well in respect to providing the necessary closed-loop approach to ensure lessons learned are captured within the corporate engineering FMA tools for the longer term benefit on all future multigenerational vehicle platform programs.

Centralising all such knowledge should then benefit engineers in all three PD knowledge domains in all engineering divisions across the extended enterprise.

5.6 DRM – Final Impact Model

The final DRM '*Reference*' model of the existing situation was presented in Figure 39. According to the combined findings of the exploratory industrial investigation case study (chapter 4), and PT reliability failures case study (chapter 5), the following DRM *Impact* model (Figure 48) describes the desired future situation, which might be achieved with the proposed support tool *(See Figure 10 for DRM Notation).*

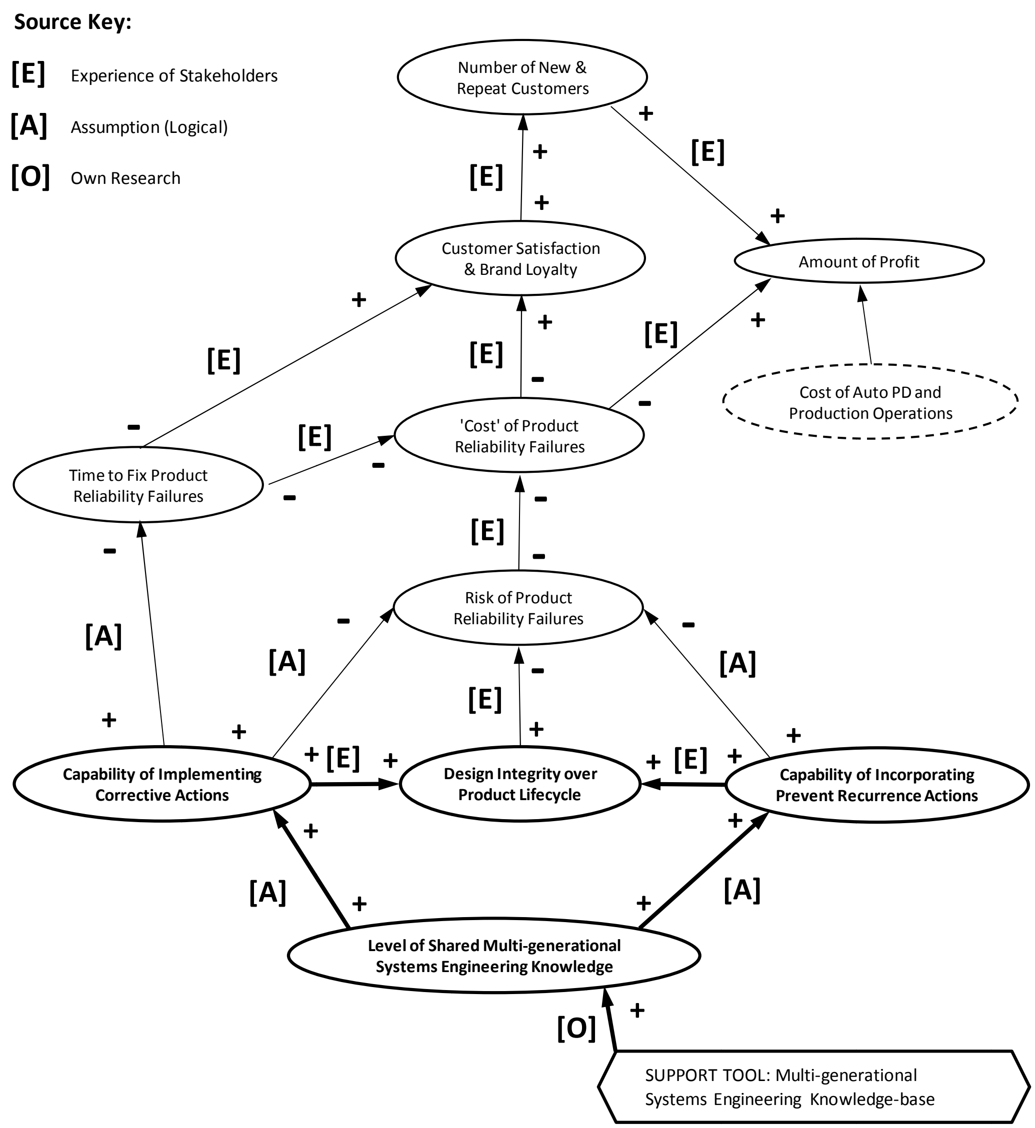


Figure 48. DRM 'Impact' Model – Representing the Desired Situation

The completion of chapters 4 and 5 signifies the completion of '*Descriptive study I*' (steps 3 and 4 in Figure 11). The next chapter now focuses on the 'Prescriptive Study' (step 5 in Figure 11) to develop the KM framework and subsequent *Support Tool*.

6 PROPOSED KM FRAMEWORK

This chapter utilises the understanding of current KM practices and challenges (chapter 4) in combination with the findings from the PT reliability failure investigation case studies (chapter 5) to propose the requirements for a KM framework to support the automotive systems engineering lifecycle.

6.1 KM Framework Requirements

In this section the main requirements for the KM framework to support the automotive system engineering process are presented. The general requirements are applicable to all technology types on all multigenerational vehicle platform programs;

RQT 1. The framework should capture the vehicle product definition and program specific requirements used by suppliers as the basis for developing technical design proposals.

RQT 2. The framework should provide access to the original full set of stakeholder requirements, including both internal and external requirements, compiled and issued by the OEM to the supplier as input into the design process.

RQT 3. The framework should provide access to all supplier design proposal responses including the initial modelled capability of the design to demonstrate meeting all of the stakeholder requirements.

RQT 4. The framework should provide a suitable mechanism for access to FMA tool set, and a suitable mechanism for the capture of new FMA plans aligned to the subsequently demonstrated results.

RQT 5. The framework should capture and provide traceability to all of the system engineering inputs and the commensurate outputs that result from executing the different phases of the NPD process including test reports and end of test part inspection and analysis results.

RQT 6. The framework should provide a standardised meta-knowledge classification scheme for recording new PT reliability failure types and provide a mechanism to link to the associated detailed DMAIC-R investigation reports in the OPD knowledge domain.

RQT 7. The framework should provide a mechanism to search all historical PT reliability failure investigation reports (output), coupled with all knowledge documents (input) used in the Product Quality Improvement Process.

RQT 8. The framework should provide a linkage between recognised failure symptom types and the implemented corrective and preventative actions to facilitate new DMAIC-R investigations on future multi-generational vehicle PD programs.

RQT 9. The framework should provide a link between the Prevent Reoccurrence Actions, the updated FMA tools, and systematic incorporation into future NPD programs.

All of these requirements are based on the findings from chapter 4 and 5, and collectively form the foundation for the proposed KM framework presented in the next section.

The proposed KM framework is presented in Figure 49, and is then followed by the detailed explanation.

6.2 Proposed KM Framework and Description of Key Elements

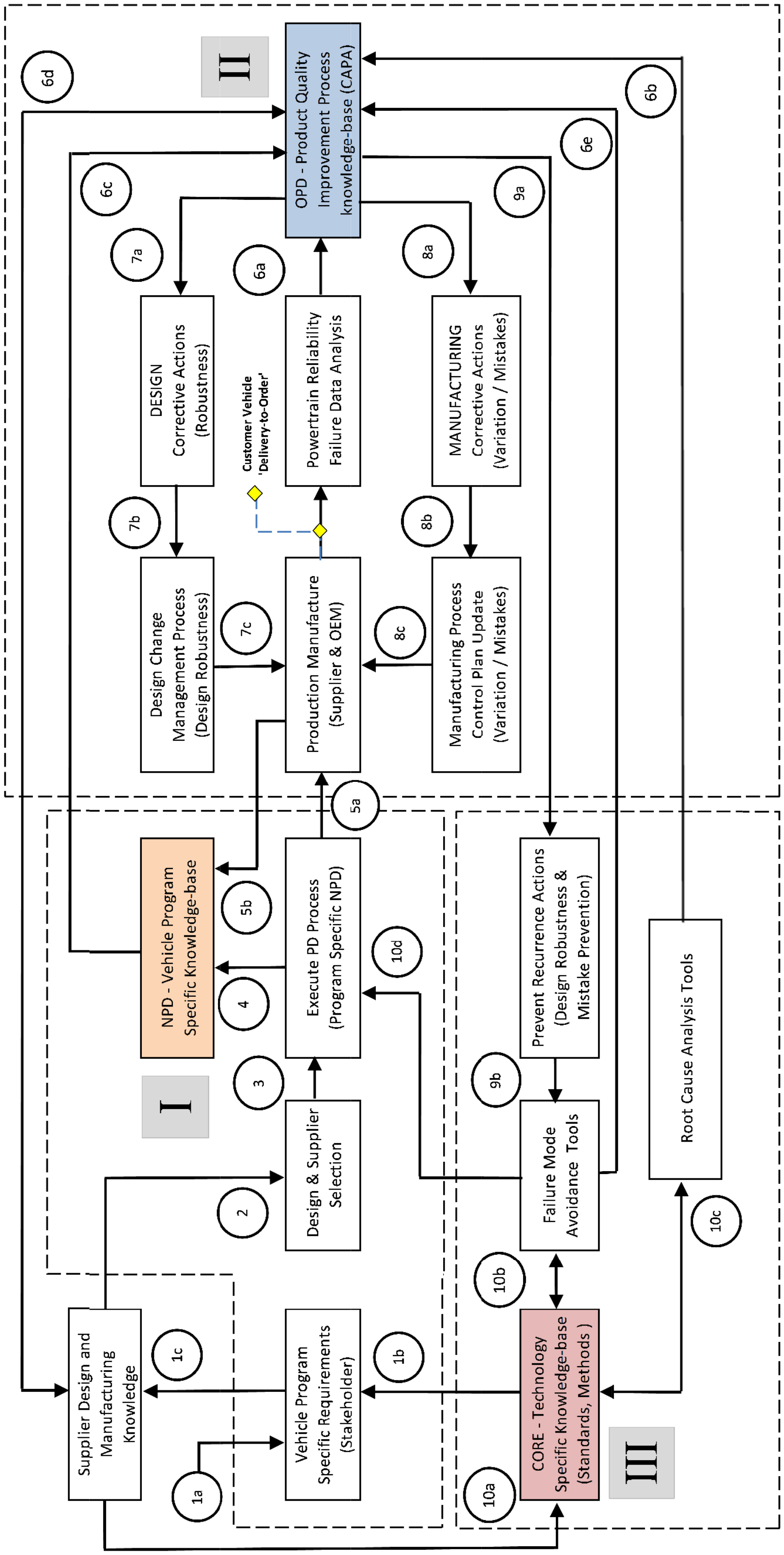


Figure 49. Proposed KM Framework to support the Automotive SE lifecycle

The main processes and examples of the specific types of SE knowledge inputs and outputs that support the PD decision making process at each stage within the proposed KM framework (Figure 49) are now discussed.

6.2.1 Group I - NPD

The KM framework assumes that the OEM organisation separately conducts the market research activities, including competitor vehicle benchmarking and consumer insight clinics, as a parallel continuous work stream outside of the framework boundary. This set of activities establishes the high level cycle plan definition for each vehicle platform program which subsequently feeds into the starting point activity below. The starting point for entry into the KM framework is at point 1a on the left side of Figure 49.

Vehicle Program Specific Requirements (Stakeholder)

Process description: First stage of the requirements analysis defines the powertrain line-up complexity and functional performance targets specific to the new vehicle program. Other key considerations are confirmed including program timing, the markets where the vehicles will be sold into, and the intended OEM vehicle build assembly locations. The second stage of the requirements analysis is to incorporate the technology specific domain knowledge and governing design rules and principals to generate early phase concept proposals. The stakeholder requirements are combined with the technology domain specific knowledge into a consolidated program definition document which is issued to a number of suppliers that specialise in the design and manufacture of each technology type. The supplier PD engineering team is asked to refine the design proposals and evaluate manufacturing feasibility.

SE Knowledge Inputs: (1a) Vehicle Program definition (Quality, Cost, Weight and Functional performance and attribute targets. Manufacturing build location strategy, program timing). (1b) Technology specific design rules and specifications.

SE Knowledge Outputs: (1c) OEM Program Definition Document (stakeholder requirements).

Supplier Design and Manufacturing Knowledge

Process description: In the functional definition stage the supplier design and manufacturing teams review the OEM program definition documents. Initial design calculations and CAE are conducted to allow the supplier to make a design proposal. The OEM makes a preliminary FMA analysis to assess the feasibility of the proposal.

SE Knowledge Inputs: (1c) OEM Program definition document (stakeholder requirements).
SE Knowledge Outputs: (2) Supplier design solution proposals, initial FMA assessment, Complexity matrix, Design transmittal, material specifications.

Design and Supplier Selection

Process description: Suppliers provides a set of functional design proposals and commercial quote response. The OEM considers the relative merit of each proposal and selects which supplier design to proceed with and carry into the NPD process. The functional definition is finalised and adopted into the PD program.

SE Knowledge Inputs: (2) Supplier design proposal (Functional).
SE Knowledge Outputs: (3) Physical design definition (CAD).

Execute PD Process (Program Specific NPD)

Process description: The SE technical processes defined within ISO/IEC 15288 (ISO sections 5.5.1 to 5.5.9) are embedded with the automotive PD process. The stage-gate definition for the program gateways and milestones are aligned to the calendar dates by which the engineering teams need to have completed the various stages of engineering design and manufacturing development. The knowledge output from the completion of each stage form the input to the next section.

SE Knowledge Inputs: (2) Functional Definition, (3) Physical definition, (10d) Failure mode avoidance tools.
SE Knowledge Outputs: (4) Design Validation, (5a) Production Verification.

NPD Specific SE Knowledge Database (KB-I)

The PD teams collate the SE evidence (inputs and outputs) from each stage of the PD program to demonstrate and confirm that all the PD processes have been completed.

Initial BoM complexity is established and part numbers are assigned within the design and release change management database. Designs are checked for compliance to all design rules and standards. FMA plan has been followed. 3D models are completed and uploaded into the corporate PLM CAD management system. Configured virtual vehicle is constructed within the CAD environment, and static and dynamic package clearance checks are conducted. CAE analyses are conducted to confirm functional requirements are met for performance, structural integrity, crash safety, and NVH modal behaviour and interactions. 2D drawings are completed with full GDT detail, material specifications and processes that have been agreed with Tier 1 supplier manufacturing and tier 2 components suppliers. The 2D drawings are uploaded into the OEM CAD environment aligned to the 3D model through version control.

Preliminary DV rig tests are conducted by the technology suppliers to demonstrate compliance with DFMEA DVM's. The results are documented and the end of test parts inspected and the condition reported. Any design failures or deficiencies are resolved as early as possible, the design changes are validated and the 2D/3D updated before continuing.

First physical prototype vehicles are built and DVPR tests are conducted on the proving ground. The end-of-test parts are returned to the technology suppliers for teardown and inspection reports are collated. Program/Supplier specific manufacturing process flow plans are documented, manufacturing quality control plans are finalised, and the production verification tests are conducted and the results authored and published. Engineering Sign-off templates are completed by the PD engineers to confirm compliance with requirements and program deliverables at each program gateway. These are reviewed with the commodity Chief and managers and any open issues reported. The PD engineers and suppliers develop recovery work plans to modify the design and repeat any necessary tests to get back on track with the vehicle program timing.

SE Knowledge-Base Inputs: (1c) OEM Program definition document, (2) Supplier Functional Definition, (10d) Failure mode avoidance tools, (3) Physical definition, (4) Design Validation results, (5b) Production Verification results.

Production Manufacture (Supplier and OEM)

Production manufacturing capacity and quality verified according to SCCAF and MCP. PV test results and teardown inspection reports verify the product still performs as intended when manufactured and assembled during continuous high volume manufacturing production as part of the final APQP elements for PSW. On successful demonstration of this on all technologies across the complete vehicle the PD and Manufacturing teams concur and complete the vehicle program integration sign-off. Vehicle production then commences followed by vehicle sales to customers.

SE Knowledge Inputs: (3) Physical definition, (5a) Production Verification plan.
SE Knowledge Outputs: (5b) Production Verification Results.

6.2.2 Group II - OPD

Once the NPD program launches and vehicle production commences the KM framework assumes vehicles orders are placed by customers at the dealership and the Vehicle Operations manufacturing plant then builds to order. The completed vehicle is then delivered to the dealer and handed over to the customer. However, if the customer experiences any quality problems with the car they may return to the dealer to have the fault investigated and corrected. The dealer then diagnoses the problem, conducts the appropriate repair, and then records the fault details and repair within the warranty database. There are sufficient categories within the database to allow the data to be interrogated by the OPD engineers which initiates the Powertrain reliability data analysis process, which then feeds into the OPD quality product improvement process at point 6a of the KM framework in Figure 49.

Powertrain Reliability Failure Data Analysis

Process description: Dealership repair data is extracted from the corporate warranty claims database (AWS) and analysed by technology type and prioritised according to leading key indicators such as; number of repairs per thousand vehicles built/sold, average cost per unit, and associated warranty costs by repair type in $US dollars. OPD quality *data analysts* focus the attention on priority issues by issuing regular quality performance analysis reports to the OPD *quality engineers*.

SE Knowledge Inputs: External Quality data (dealership repair metrics).
SE Knowledge Outputs: (6a) Powertrain Quality Data Analysis (reports).

OPD - Product Quality Improvement Process Knowledge-base (KB-II)

Process description: OPD engineers for each technology type focus attention on the priority failures reported in the quality performance analysis reports. Failed parts are requested back from the dealer and inspected and analysed by the supplier, and an inspection report is issued with the findings. The OPD engineers retrieve the NPD Specific SE knowledge captured from the original program, and build up the initial DMAIC-R by incorporating the appropriate FMA tools and RCA tools retrieved from CORE Technology specific knowledge-base (KB-III). The root cause analysis investigations establish the required corrective actions for either design robustness improvement, or manufacturing defect and mistakes. The corrective actions are validated and incorporated into the continuous production manufacturing process as a 'running change'. Prevent Recurrence actions are identified and incorporated into the FMA tools to benefit future PD programs.

SE Knowledge Inputs: (6a) Quality data and analysis reports, (6c) NPD Specific SE knowledge, (6e) FMA tools, (6b) RCA tools, (6d) Supplier Design and Manufacturing knowledge (direct involvement in supporting the root cause investigation).

SE Knowledge Outputs: (7a) Design Corrective Actions, (8a) Manufacturing Corrective actions, (9a) Prevent Reoccurrence Actions (recommendations).

Root Cause Analysis Tools

Process description: Root cause analysis tool templates, based on the tool set in Table 24, are created and maintained by the CORE engineers and stored within CORE – KB-III (Technology Specific Standards, Methods).

SE Knowledge Inputs: 10c RCA tools (constructed and stored in KB-III).

SE Knowledge Outputs: 6b RCA tools (extracted from KB-III to support OPD).

NPD specific SE Knowledge

Process description: All of the NPD knowledge originally compiled during vehicle program is stored within the NPD Knowledge-base (KB-I). The knowledge can then be extracted from KB-I to support 'new' DMAIC-R investigations by the OPD teams.

SE Knowledge Inputs: (4) Design Validation, (5b) Production Verification.
SE Knowledge Outputs: (6c) NPD – Vehicle Program Specific Knowledge.

Supplier Design and Manufacturing Knowledge

Process description: The technology supplier for the specific part failure at the centre of the investigation is requested to provide direct support for the root cause investigation. The supplier is asked to perform a material inspection analysis on the recovered failed parts and report on the findings, including an assessment of the possible failure modes according to the supplier DFMEA and PFMEA. As part of the DMAIC-R process the supplier may also lead key initiatives to deduce the root cause theory through CAE simulations and Design of Experiments (DoE). The supplier may also need to revalidate that the load cases in the vehicle that failed are as expected according to the original program definition document used to derive the design. A great deal of knowledge shared by the supplier originally only exists within the supplier knowledge domain, so provision is required to formally capture the knowledge within the OEM knowledge domain within KB-II and KB-III.

SE Knowledge Inputs: (1c) Vehicle program definition document.
SE Knowledge Outputs: (6d) Supplier failed part inspection reports, (10a) Applied use of FMA tools for RCA investigation as constructed by the supplier to support the DMAIC-R project.

Design Corrective Actions (Robustness)

Process description: The OPD and supplier teams jointly conduct the DMAIC-R process and reach a conclusion on the root cause. A recommendation is made for the required corrective design action (and once all potential manufacturing root causes have been ruled out).

SE Knowledge Inputs: (7a) Proposed corrective ***design*** action (DMAIC-R output).
SE Knowledge Outputs: (7b) Validated corrective ***design*** action proposal.

<u>Design Change Management Process (Design Robustness)</u>

Process description: Once the recommended corrective ***design*** action has been validated it must then be introduced through the vehicle operations and supplier manufacturing change management processes. This process involves demonstrating the collective understanding of the root cause and validated corrective action/s to the engineering management teams by presenting the compiled findings of the DMAIC-R project. Once final approval to proceed with the recommended actions is given the OPD teams complete the change management process and introduce the change, together with the supplier, into current part manufacture and vehicle production.

SE Knowledge Inputs: (7b) Validated corrective ***design*** action proposal.
SE Knowledge Outputs: (7c) Industrialised corrective ***design*** action**.**

<u>Manufacturing Corrective Actions (Variation / Mistake)</u>

Process description: The DMAIC-R process may alternatively conclude that the design is indeed capable, and the source of the root causes instead lies with an undesirable variation in manufacturing or a mistake in the manufacturing process such as machine setup or material handling. As with the design robustness corrective actions all recommendations for manufacturing corrective actions must also be validated through the use of techniques to replicate the root cause and failure mode through CAE modelling and/or testing under controlled conditions.

SE Knowledge Inputs: (8a) Proposed ***manufacturing*** corrective action (DMAIC-R).
SE Knowledge Outputs: (8b) Validated ***manufacturing*** corrective action proposal.

<u>Manufacturing Process Control Plan Update (Variation / Mistakes)</u>

Process description: Once the recommended ***manufacturing*** corrective action has been validated it must then be introduced through the vehicle operations and supplier manufacturing change management processes. This process involves demonstrating the collective understanding of the root cause and validated corrective action/s. Once final approval to proceed is given the process control plan updates are introduced into current part manufacture at the supplier and/or OEM vehicle production plant.

SE Knowledge Inputs: (8b) Validated ***manufacturing*** corrective action proposal.
SE Knowledge Outputs: (8c) Industrialised ***manufacturing*** corrective action.

6.3.3 Group III - CORE

The output from the OPD Product quality improvement process generates new organisational learning that must then be appropriately captured in the CORE Technology specific knowledge-base (KB-III) to the bottom left hand side of the KM framework in Figure 49.

Prevent Reoccurrence Actions (Design Robustness and Mistake Prevention)

Process description: Prevent Reoccurrence Actions (PRA) are identified as the last step in the DMAIC-R projects as part of the OPD Product quality improvement process. The specific PRA recommended by the team is sent the CORE technology SME/TS's for consideration to then make the necessary updates to the corporate foundation documents (Design Rules, Specs, FMA tools etc.). The team also considers how the PRA is shared with the supplier network to prevent reoccurrence on future vehicle programs.

SE Knowledge Inputs: (9a) PRA recommendations from each DMAIC-R project.
SE Knowledge Outputs: (9b) FMA tools updated according to the SME/TS's.

Failure Mode Avoidance Tools

Process description: The technology specific SME/TS's update the FMA suite of tools according to the recommended PRA's that results from the OPD DMAIC-R projects. Once the FMA tool update has been made they are stored within KB-III for future reference and re-use.

SE Knowledge Inputs: (9b) FMA tools updated according to PRA recommendations.
SE Knowledge Outputs: (6e) Updated FMA tools available to support future OPD DMAIC'R projects, (10d) Updated FMA tools for incorporation into future NPD vehicle programs.

Root Cause Analysis Tools

Process description: The successful application of RCA tools within the OPD DMAIC-R projects may be usefully extracted and stored within KB-III for reference and reuse to support future OPD investigations.

SE Knowledge Inputs: (10c) RCA tools extracted from DMAIC-R projects.
SE Knowledge Outputs: (6b) Example RCA tools reused to support future projects.

<u>CORE – technology Specific Knowledge-Base (KB-III)</u>

Process description: The technology specific SME/TS's maintain KB-III with the up to date product specific design and manufacturing knowledge best practices regarding standards, methods, tools and processes.

SE Knowledge Inputs: (10a) Supplier design and Manufacturing knowledge, (10b) Updated FMA tools, (10c) RCA tools application within DMAIC-R projects.

SE Knowledge Outputs: (1b) Technology specific design rules and specifications – latest best practices published to guide the design process on future vehicle programs.

The KM ***requirements*** (section 6.1) are now aligned to the various framework ***elements*** of the KM Framework (Figure 49) in Table 27 below.

		Knowledge Management Framework Elements																								
KM Framework Requirements		I - NPD								II - OPD												III - CORE				
Applicable to all technologies / suppliers and all vehicle platform programs.		1a	1b	1c	2	3	4	5a	5b	6a	6b	6c	6d	6e	7a	7b	7c	8a	8b	8c	9a	9b	10a	10b	10c	10d
RQT 1.	Capture the Vehicle program specific requirements used as the basis for arriving at the adopted supplier design proposal.	X	X																							
RQT 2.	Provide access to the traceable record of the original compiled program definition issued by the OEM to the supplier.			X																						
RQT 3.	Provide access to the traceable record of the accepted design proposal provided by the supplier to the OEM.				X	X																				
RQT 4.	Provide acess to the FMA tools and a suitable mechanism for the capture of the FMA plan aligned to the subsequent demonstrated results.						X	X	X																	X
RQT 5.	Accommodate traceability to all additional pertinent system engineering outputs that result from executing the PD process including DV/PV test reports .						X	X	X																	
RQT 6.	Provide a standardised scheme for classifying new customer reported PT failures and provide a mechanism to link to the associated detailed investigation reports.									X																
RQT 7.	Provide a linkage to all historical PT failure investigation reports (output), coupled with all knowledge documents (input) used in the Product Quality Improvement Process.			X	X					X	X	X	X	X										X		
RQT 8.	Provide a linkage between recognised failure symptom types and the implemented corrective and preventative actions.									X					X	X	X	X	X	X						
RQT 9.	Provide a link between the Prevent Reoccurrence Actions, the updated FMA tools, and systematic incorporation into future NPD programs.		X																		X	X	X	X	X	X

Table 27. KM Requirements vs Framework Elements

6.3 KM Framework Utilisation - Case Study

This section describes a real-world case study example to demonstrate the utilisation of the KM framework, per objective 4.2 (Table 2), and illustrate its value in an industrial context.

The key aim of the case study is to demonstrate how geographically dispersed teams of PD engineers are currently challenged to organise and share the wide array of different knowledge types encountered during a typical program lifecycle. This is achieved by working through the real-world experiences of a multinational team over the duration of a single specific vehicle program lifecycle. This then subsequently lays the foundation for the web 2.0 groupware developed later in chapter 7.

6.3.1 Approach

The industrial case study presented involves the product development timeline of a past vehicle program within Ford Motor Company from concept to launch, and a subsequent detailed powertrain reliability failure investigation.

The particular case study presented was selected based on the following inherent SE KM challenges;

i) Longitudinal study - Concept to launch on a major new vehicle platform program, including a significant program delay and a postponed vehicle production launch, covering +5 years.

ii) Global collaboration – Involving geographically dispersed teams of engineers based in 6 different countries, and including a significant change in OEM organisational responsibilities and a loss of knowledge continuity.

iii) Complex manufacturing supply chain network – Including Tier 1 supplier operations in Poland, Tier 2 operations in Germany, and Tier 3 and Tier 4 operations in China.

iv) Product functional failure – Component failures that required an in-depth investigation using the DMAIC-R problem solving approach to determine the failure root cause, corrective actions, and prevent reoccurrence actions.

The details presented were ascertained through direct discussions and email exchange with the multiple engineers that worked on the product development of the front-wheel-drive Driveshaft sub system on the specific model 'X' vehicle program.

This involved direct face-to-face discussions, and remote WebEx audio conferences, with key engineers based in the UK, Germany, Poland, Turkey, North America, and China. The engineers were specifically selected based on their direct involvement in the original Driveshaft product development, and the subsequent failure investigation. The next section presents the vehicle program background.

6.3.2 Background

The vehicle program adopted for the case study was the new replacement Ford Model 'X' in Europe which commenced with the first issue of the proposed program content in August 2008. Once all the initial trade-off discussions had completed the program strategy was confirmed in May 2009, and the intended future production launch of the vehicle was announced as being April 2013. The European version of the vehicle program was to be engineered by the European product development teams based in Germany and the UK.

The preliminary CORE engineering PD work for the new vehicle program was conducted by a UK based team of driveline engineers, and the team completed all of the PD design and integration processes during 2010.

The first prototype vehicles were built in March 2011 and DV vehicle tests and supplier rig/bench tests were completed by December 2011. The subsequent verification prototype cars were then built in April 2012 with verification testing then due to commence.

On the 30th July 2012 there was a major strategic corporate decision to postpone the launch of the new vehicle due to an economic downturn, which moved the intended start of manufacturing production date from April 2013 to October 2014, representing a 1.5 year delay.

During the delay the planned vehicle assembly facility was changed from the original plant in Belgium to an alternate plant in Spain to support a reduction in labour costs. Verification testing of the prototype vehicles continued, but the initial vehicle production build phase was delayed to allow the new facility in Spain to make the necessary rearrangements of the assembly lines to accommodate the new vehicle platform.

Furthermore, in March 2013 the CORE and NPD responsibilities for the European driveline engineering team were disbanded from the UK PD centre and transitioned to a new team of engineers in an alternate PD centre in the USA.

The UK based team was originally also responsible for OPD oversight of product quality in Europe, but as the team was disbanded the responsibilities were transitioned to a new team of engineers within a PD facility in Turkey.

The OPD team assumed responsibility for the customer vehicle quality 3 months after the Start of Production (SoP) which commenced from January 2015. The timeline for the PD program is described in Figure 50 below.

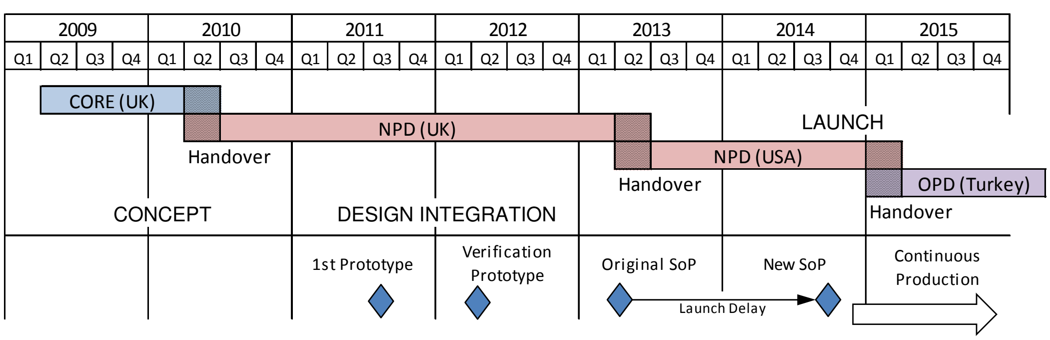


Figure 50. Case Study Program - PD and Manufacturing Timeline

The next sections describe the generalised account of events from the engineers involved with each stage of the product lifecycle and the associated NPD, OPD, and CORE knowledge domains.

6.3.3 Case Study – NPD Phase

The ***NPD*** knowledge generation cycle described in this section pertains to the PD activities shown in area 'I' in the SE KM framework (Figure 49).

On the specific Model 'X' vehicle program the UK based driveline engineering team were responsible for integrating the design solution for connecting the torque delivered from the engine, through the transmission, to the road wheels.

This is achieved on front wheel drive vehicles through the left and right hand side driveshafts as depicted in Figure 51 below.

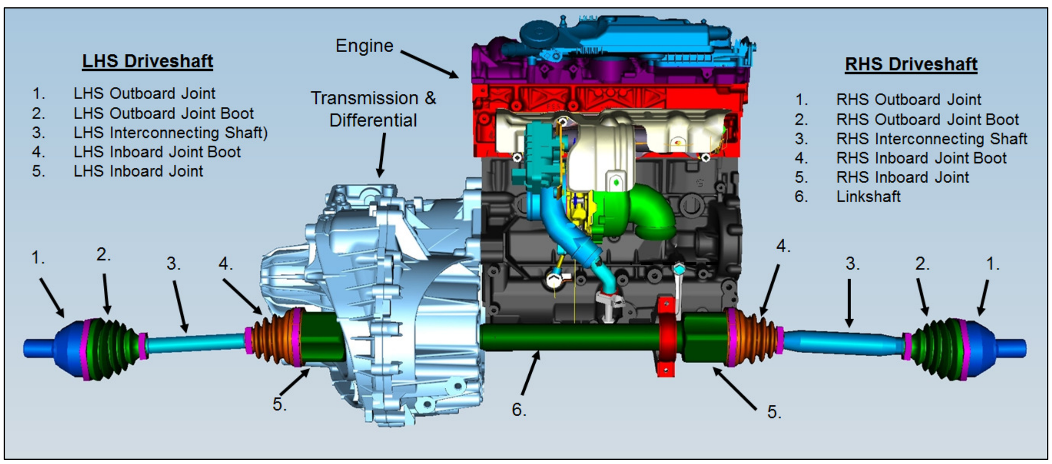
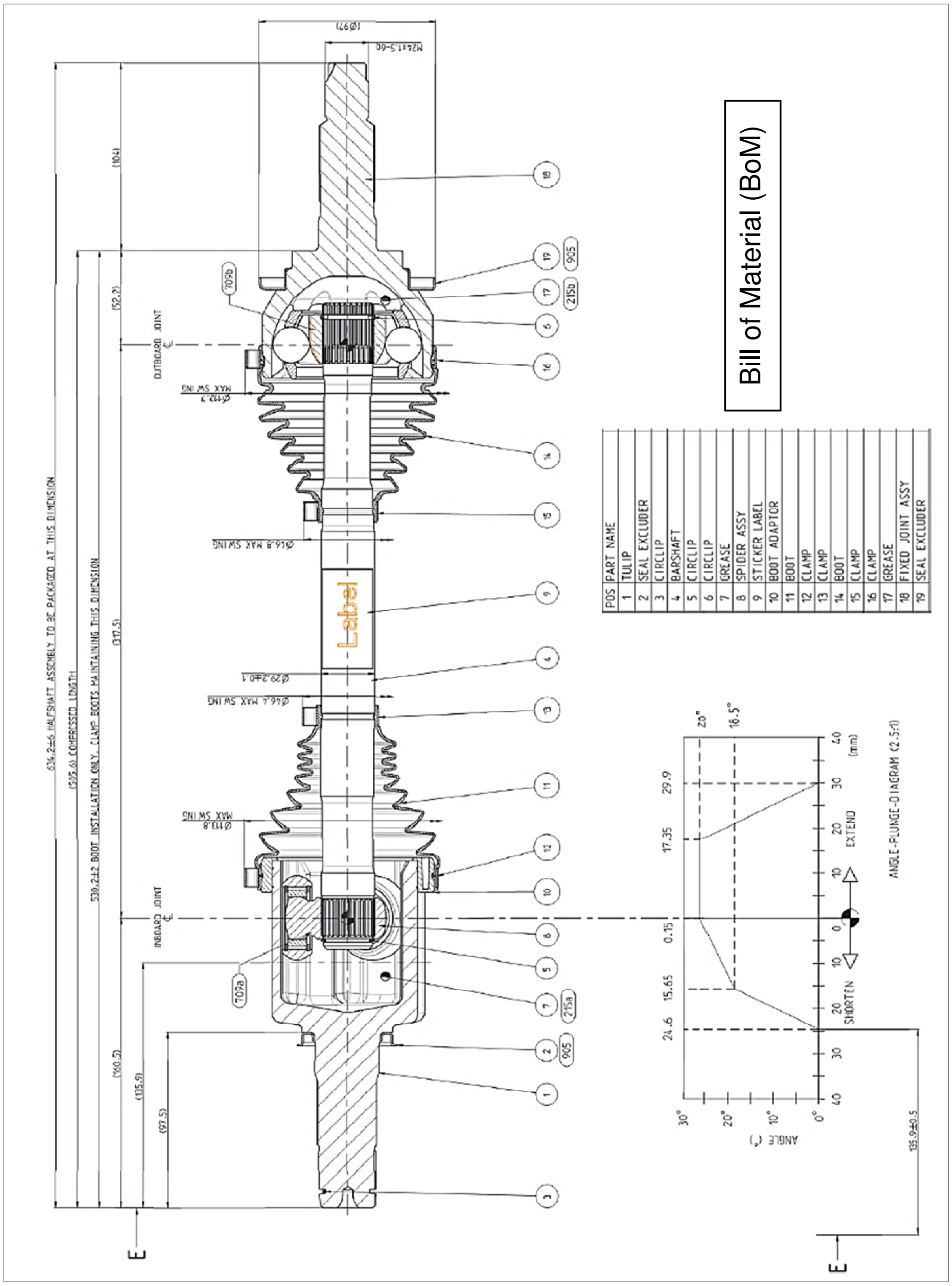


Figure 51. Powertrain Installation Schematic – Driveshaft

The Ford driveline team in the UK were responsible for integrating the complete driveshaft assembly into all new vehicle program applications. This includes ensuring that the part functions correctly under all engine torque operating conditions and through the full dynamic range of chassis suspension and steering movement. The driveline team also define the stem spline interfaces into the transmission differential side gear at the inboard end and the chassis wheel hub at the outboard end. The driveshaft functional and physical design is 'black-box' and design selection criteria is based on the stakeholder requirements provided as the SE inputs by the OEM driveline team. All of the internal driveshaft components are the sole responsibility of the Tier 1 supplier who also subsequently relies on lower tier sub suppliers.

The typical driveshaft component BoM is shown in the table in Figure 52.



POS	PART NAME
1	TULIP
2	SEAL EXCLUDER
3	CIRCLIP
4	BARSHAFT
5	CIRCLIP
6	CIRCLIP
7	GREASE
8	SPIDER ASSY
9	STICKER LABEL
10	BOOT ADAPTOR
11	BOOT
12	CLAMP
13	CLAMP
14	BOOT
15	CLAMP
16	CLAMP
17	GREASE
18	FIXED JOINT ASSY
19	SEAL EXCLUDER

Figure 52. Driveshaft System – Cross Section and Component List

On the specific Model 'X' the initial design integration work was done by the UK based NPD engineering team. The initial stakeholder requirements were compiled based on the program definition for engine power/torque, transmission gear ratios, geometric data for chassis suspension and steering dynamic movement, and vehicle payload data. The design requirements were augmented with the core engineering design specifications and rules, plus durability and quality targets. Finally, production build volumes and geographic vehicle assembly plant locations were also incorporated. The compiled set of requirements was then issued to a number of different potential suppliers as part of the request to quote process.

The suppliers were given an initial period to consider the stakeholder requirements and then asked to submit the design proposal responses back to the NPD team. Trade-off studies were done and the best functional design with preferred overall business case was selected. The physical definition of the designs were then completed by the nominated production supplier, and the 2D/3D CAD was supplied into the OEM CAD environment for virtual integration into the complete vehicle digital buck within the Teamcenter® PLM system, and then package clearance checks conducted. The FMA process was followed and the tool suite completed for the program. The DV test plan was developed from the DVP generated from the FMA process. The supplier rig testing and prototype vehicle testing completed. The driveshafts were removed from the vehicles at the end of test and the parts were disassembled and inspected by the supplier and confirmed as having met the test pass/fail criteria.

As mentioned in section 6.4.2, the CORE/NPD driveline team in the UK were responsible for executing all of the SE processes from the program start in August 2008 until March 2013 when the engineering responsibility was handed to the driveline team in the USA. During this 46 month period the responsible UK engineer accumulated 1.67GB of data/information/knowledge in the form of 1,260 unstructured electronic files dispersed within 133 folders within his personal windows explorer file manager on his PC hard drive. During the handover of responsibilities the files were transferred from the UK engineer to the new NPD driveline engineer in the USA via mass transfer upload to a central server location. In the proposed framework, presented in section 6.2 all of the NPD files generated through this single case study would have been uploaded into a centralised SE folder structure within the proposed NPD knowledge-base **KB-I** (Figure 49). The knowledge content within **KB-I** could then be easily relocated and made available for future reference to support the ***OPD*** knowledge cycle described in the next section.

6.3.4 Case study – OPD Phase

The ***OPD*** knowledge generation cycle described in this section pertains to the activities as shown in area 'II' in the SE KM framework (Figure 49).

Once the NPD program work had been satisfactorily completed, the mass production of the vehicle commenced at the vehicle assembly plant in Spain. Then, 90 days after the start of production, the ownership of the Driveshaft quality performance in operational service was transferred from the NPD driveline team in the USA to the OPD driveline team in the PD centre in Turkey.

The OPD team continuously monitored and analysed the corporate warranty reporting system and recognised an increasing number of driveshaft repairs on customer vehicles reported by dealerships across Europe. The warranty claim detail included technician and customer comments regarding complaints of driveline vibration at high speed during motorway driving.

The OPD team contacted the dealerships and coordinated the recovery of the failed parts which were then sent to the supplier for a more detailed closer inspection.

Once the supplier received the complaint Driveshaft they dismantled the inboard joint and inspected each of the three roller bearings (Figure 53) within the inboard joint forged housing (also see **Appendix I**).

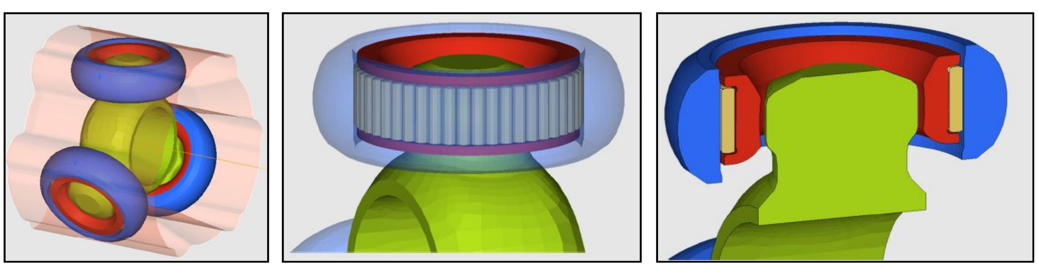


Figure 53. Driveshaft Inboard joint – Needle Roller Bearing Arrangement

The supplier immediately recognised there was damage to the inner race shoulder of the needle roller bearing as shown in Figure 54 below.

There are three roller bearings in each inboard joint of each Driveshaft, but damage was only found on a single bearing. The damage on the shoulder of the inner race is shown in Figure 54 below (also see **Appendix I**).

Figure 54. Needle Roller Bearing – Inner Race Fracture Photos

The number of vehicles reported as suffering with the high speed vibration issues, as a result of the same failure mode, continued increasing so the OPD team in Turkey initiated a new DMAIC-R project. In total the project assembled 15 active key team members representing; OEM and supplier PD managers and engineers, Quality engineers including 6 sigma black belt specialists, and manufacturing and assembly plant engineers.

The OPD driveline team in Turkey also enlisted the support of the NPD driveline team in the USA to verify all the SE process output from the original PD program. This required the engineers to 'sift' through the original design requirements and selection criteria files that had been handed over from the UK based PD team 1.5 years earlier.

The FMA tools that were originally used to define the Design Validation Plan (DVP) were re-examined in combination with the end-of-test teardown inspection reports that had been published by the supplier. The teams were unable to positively identify any shortfalls in the original DVP and confirmed all tests had been completed without any indication of the failure mode evident on any of the end of test parts.

Once the team had defined the problem they jointly worked on formulating the 'Cause-and-Effect' diagram (**Appendix I**) to structure the approach for systematically exploring all the different possible explanations for the root cause of the failure mode.

The only specific reference to this particular failure mode within the generic FMA documents was a link between over extension and excessive high angular articulation of the inboard joint, through mishandling during assembly into the vehicle, which was identified within the Tier 1 Driveshaft supplier DFMEA.

The OEM and Tier 1 supplier engineers visited the vehicle assembly plant and spent several weeks monitoring the assembly process and trying to simulate the sequence of mishandling which may have caused the bearing inner race shoulder to fracture, but were unable to confidently reproduce the failure under controlled conditions. A series of experiments (DoE) were devised and subsequently executed;

- CAE simulation of high angle + High torque combination events (USA)
- Simulated assembly mishandling (Spain)
- Simulated loading abuse onto the transportation lorry at the VO plant (Spain)
- Simulated customer abuse events on the vehicle proving ground (Belgium)

None of the above DoE's was able to successfully reproduce the failure mode.

In parallel the team of supplier manufacturing engineers turned its attention to devising a further DoE to study the axial strength variability of the inner race according to parts from known OK and Not Ok batches of bearings. A new vertical press test was developed to evaluate the axial strength of the bearing assembly on a machine at the Driveshaft assembly plant in Poland (**Appendix I**).

As the Driveshaft assembly is a Tier 1 'black-box' supplied part the Ford driveline team was not expected to specify an axial strength requirement at component level within the 'black-box'. Equally, the Tier 1 supplier was not aware of an axial force requirement and had only cascaded the requirement for radial strength and rolling durability equated to the anticipated maximum useful vehicle life mileage.

The hierarchy of the inner race within the component tier model is shown below in Figure 55.

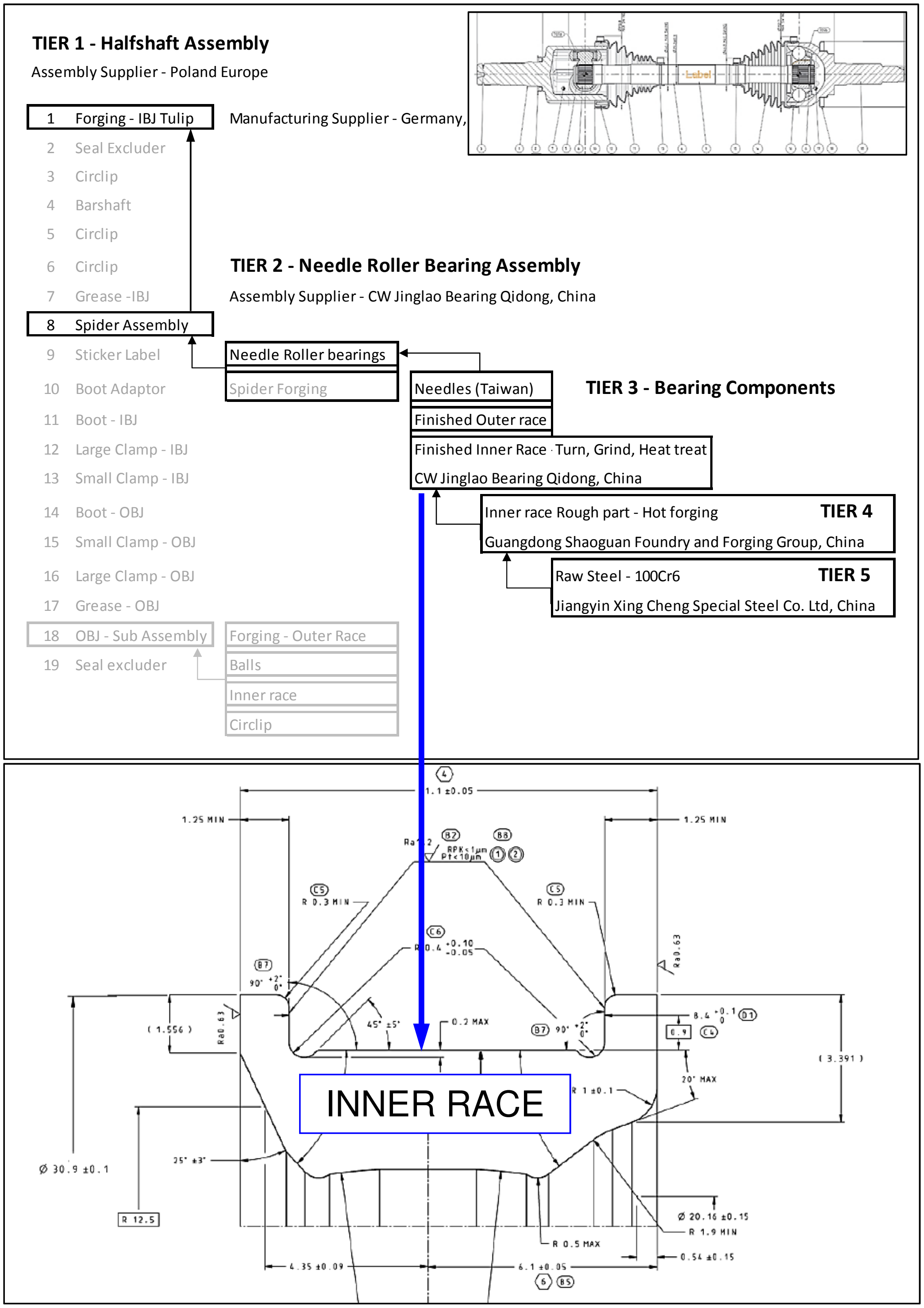


Figure 55. Driveshaft Assembly – Component Tier Model

As can be seen in Figure 55 the Tier 2 sub supplier of the needle roller bearing assembles three separate component types; the needles, finished outer race and the finished inner race, which are received from the Tier 3 finished component suppliers. The finished inner race is produced in-house from the rough part forging which they receive from the Tier 4 forging supplier also based in China. The rough part forging supplier received the raw steel from the Tier 5 material supplier also based in China.

It was necessary for the DMAIC-R project team to understand the complete manufacturing hierarchy through the supply chain in order to study the following parameters which may have contributed to the axial strength variability;

Tier 2 – Bearing assembly process; for any possible mishandling causing potential unnoticed 'pre-damage'. The Tier 1 quality engineering audit team visited the Tier 2 sub supplier to evaluate the processes and report the findings.

Tier 3 – Finished Inner race manufacturing processes; including machining variation caused through the turning and grinding operations, plus the material hardness variation resulting from the heat treatment process through the continuous conveyor oven. The variability in finished form of the inner race was measured using 3D scanning techniques, and the hardness variability checked in the materials laboratory.

Tier 4 – Raw steel supplier; for any possible batch to batch variation in composition or levels of undesirable impurities. Failed inner race samples were closely examined using an external specialist materials metallographic technology company in Germany who assessed the chemical composition, microstructure and hardness.

The DoE results for the vertical axial strength press test demonstrated that there was an unacceptable level of variability between maximum (>55kN) and minimum (<25kN) strength parts. Through Six Sigma Statistical methods the team also established that the specific minimum axial strength requirement was > 34kN for the worse case vehicle application.

The OEM quality data analysis team used 6 sigma statistical techniques to determine if the main effects for the variation could be identified and isolated. The team gathered data for all of the Critical-To-Quality (CTQ) factors from a large number of new sample bearings provided at each step of the supply chain. The bearings were then tested to failure on the new axial strength vertical press bench test.

The final conclusion of the team was that no single CTQ factor, or combination of CTQ factors, could be attributed to the variability in axial strength and consequently no recommendation could be made in regard to which dimensional tolerances or material characteristics should be better controlled or modified. The part design simply did not lend itself well to achieving the newly established axial strength requirement, and so the final conclusion was the root cause was due to a lack of consideration for *Design for Manufacture* (DfM).

An alternate bearing design was conceived and verified using CAE modelling that incorporated the increased strength requirement (**Appendix I**). Prototype parts were manufactured and tested using the vertical axial press method to validate the design strength exceeded the design requirement. The new design was progressed through the OPD Change Management Process for approval and introduced into full scale manufacturing at the bearing supplier which then flowed through into the driveshaft assembly and vehicle production.

During the course of the single failure mode investigation 1.18GB of data / information / knowledge was generated in the form of 267 unstructured electronic files which were stored within 47 folders on the OPD engineer's local PC hard drive. The majority of the files had been generated through the different DoE studies conducted by the many different members of the DMAIC-R project team which were subsequently shared by email to all the other active team members.

The output from all of the investigations was consolidated into a 27 page DMAIC-R project report as a 5.7MB MS PowerPoint presentation file with no meta-knowledge.
In the proposed framework, presented in section 6.2, all of the OPD files generated through this single case study would have been uploaded into a central OPD database (Figure 49). The knowledge content within **KB-II** could then be easily relocated and made available for future reference to support the ***CORE*** knowledge cycle described in the next section.

6.3.5 Case Study – CORE Phase

The ***CORE*** knowledge generation cycle described in this section pertains to the PD activities shown in area 'III' in the SE KM framework (Figure 49).

The team of global CORE driveline engineers resided in the North American PD team, so the critical learning from the DMAIC-R investigation needed to define the fundamental Prevent Reoccurrence actions. The Technical Specialist / Subject matter experts were able to derive following key areas requiring attention:

The assembly installation drawing which provides instructions to the vehicle assembly plant did mention that inboard joint articulation angle and extension force limits, but these were not listed on the 'Internal' Significant Characteristics Communication and Agreement Form (SCCAF). The SCCAF constitutes the instruction from PD to the manufacturing team to be included in the assembly process control plan. The SCCAF was subsequently updated and reissued to the vehicle plant.

The PD team also has an equivalent list of Significant Characteristics which are cascaded to the Supplier on the 'External' SCCAF document. This typically deals with measurement and control of interface dimensions and tolerances such as fit into the transmission side gear spline and wheel hub spline. However, the OEM PD team do not typically insist on any on the manufacturing control for dimensional tolerances or material properties of component parts internal to the black-box. The OEM PD team expected that the Tier 1 supplier should have cascaded a set of Significant Characteristic requirements to the Tier 2 and Tier 3 manufacturers of the bearing inner race so that manufacturing variation and its influence on axial strength was controlled at source. The only feasible way to ensure this aspect was captured as a prevent reoccurrence action for the future was to author a new design rule to add the feature as a significant characteristic on the supplier 2D drawing.

Further to the prevent reoccurrence actions, during the course of the investigation the following FMA documents were cited as requiring update;

DFMEA, Boundary and Interface diagram, Parameter Diagram, Fault Tree.

Furthermore, there was also essential learning derived from the application of the following root cause analysis tools;

- Ishikawa '*cause-and-effect*' diagram – for future generic reference.

- Design of Experiment methods derived to try and isolate the failure mode;
  - CAE simulation – Virtual test methods: articulation angle and over extension
  - Simulated customer vehicle abuse – new test event procedures.
  - Vertical axial strength – equipment, set-up, and test procedure.

The new design rule was published such that it would be cascaded to all future new vehicle PD programs. However, the updated versions of the FMA and RCA tools resided locally on the PC hard drives of the engineers involved in the project. This made it is far less likely to be re-used and referenced in future vehicle programs.

In the proposed framework, presented in section 6.2, all of the CORE files including FMA and RCA tools that were generated through this single case study would have been uploaded into a central CORE database (Figure 49). The knowledge content within **KB-III** could then be easily relocated and made available for future reference.

The next section summarises the development of the SE KM Framework.

The development of the proposed prototype web 2.0 groupware support tool is then presented in Chapter 7.

6.4 Proposed KM Framework - Summary

This chapter initially presented the main KM framework requirements derived from combined findings of the industrial investigation (chapter 4) and the PT reliability failure investigation case studies (chapter 5).

The framework requirements include the need to centrally store the commodity specific design requirements and supplementary program requirements that form the combined stakeholder requirements and represent the basis for the engineering input for all the sub system assemblies on each new vehicle program. Without a permanent traceable record of the program specific stakeholder requirements it is considered practically impossible to revalidate the functional performance of a system in relation to the operating environment and imposed loading conditions originally embedded within the CAE modelled capability of the system.

It was also identified that the demonstrated results of the DV tests, originally identified through the FMA process, and subsequent compliance with the expected functional targets are a pivotal element to the initial framing of all DMAIC-R investigations into new reliability failures on vehicles in operational service. The investigating OPD team needs to be able to locate the original set of functional targets that the system was designed to accommodate. This is critical since the system may have failed due to a change in any of the 5 different noise factors (Figure 43) that may have deviated from the design parameters assumed in the original program sign-off.

The framework requirements also called for the need to incorporate a standardised meta-knowledge classification scheme in order to provide a mechanism to extract and classify the copious volume of knowledge embedded within the envisaged centralised global DMAIC-R report document library and directory. The meta-knowledge classification scheme was seen as a key enabler to allow other members of the global PD community to search and find historical DMAIC-R projects according to the embedded knowledge content type, to help inform new reliability failure investigations on future multigenerational vehicle programs with the details about how similar problems were solved in the past.

The meta-knowledge enabled search function was considered critical to support the two key aspects of the DRM impact model (Figure 48) namely;

- Capability of implementing corrective actions
- Capability of incorporating prevent reoccurrence actions

Both of the above aspects in turn support the main proposition for increasing the likelihood of improving and maintaining the robustness of design integrity over the product lifecycle. This is achieved by primarily avoiding the reoccurrence of historical failure modes, or conversely resolving new reliability failures more swiftly through the identification of the appropriate corrective actions derived from previous similar experiences and countermeasures.

An overall KM framework which embodies the above requirements was then proposed (Figure 49). The main sub processes within the framework were then described, and examples of the SE knowledge inputs and outputs that support the PD decision making process within each of the different stages of the product lifecycle were presented.

Finally, a real-world longitudinal case study was presented to demonstrate the use of the proposed KM framework. The case study was used to illustrate the specific KM challenges encountered within an industrial PD environment by presenting the real-world experiences of a multinational team over the duration of a specific vehicle model 'X' program lifecycle. The case study was presented in a structured format beneath each of the three SE lifecycle knowledge domains (NPD, OPD and CORE), and demonstrated how the proposed KM framework could centralise the knowledge captured in each domain to support more effective sharing between geographically dispersed PD teams and future re-use.

Chapter 7 now presents the development and implementation of the proposed prototype ICT ***support tool***, which is the envisaged key enabler to achieve the 'desired' future state, as presented in the ***DRM final impact model*** (Figure 48).

7 DEVELOPMENT OF THE PROTOTYPE SUPPORT TOOL

In chapter 6 the development and validation of the SE KM framework was presented. This chapter now presents the work undertaken to develop a KM groupware tool, as an implementation of the KM framework (Figure 49), to support the Automotive SE lifecycle, thereby satisfying objective 5 in Table 2.

The following sections present the design and evaluation of the prototype groupware which represents the 'support tool' within the DRM Impact model (Figure 48). A groupware is a web-based tool which allows globally dispersed teams to upload user-generated content to a common centralised knowledge-base, enabling non collocated teams to collaborate. All knowledge documents that are uploaded within the groupware can be readily accessed by all permitted PD and Manufacturing engineers at any point within the automotive systems engineering lifecycle.

7.1 Prototype Support Tool - Requirements

Although the requirements for the KM framework were defined and aligned to the framework elements in Figure 49, the development of the ICT tool also needed to make consideration for the intended end-user and the operating environment. Small-scale informal discussions were held with local PD engineers, and according to the gathered feedback a further set of ICT tool requirements were generated as follows;

RQT 1: Users will need to access the groupware from all the corporate multinational facilities, including all the different regional PD centres and manufacturing operations. Therefore, the developed tool would need to reside inside the corporate IT security firewall in order to eventually facilitate demonstrating the groupware as part of the planned *support tool evaluation* (Figure 11, step 8).

RQT 2: The prototype version of the support tool will not develop all levels of the automotive ontology or taxonomical hierarchy, but should provide the complete outline knowledge-base structure so the full structure can be viewed in context.

RQT 3: The groupware should also be based on partitioned sub sites so that access and control of all knowledge documents could then be managed and administered at a local level. This feature should provide sufficient assurance to the different intended end user groups to instil confidence that all knowledge material was secure, and also to build a sense of equity which would then encourage user-contribution. This principle was considered critical to the success of tool as without the contribution of user-generated content the site would remain unpopulated which would hinder adoption and could potentially result in redundancy and long term rejection.

RQT 4: The groupware would need to accommodate a variety of file types including rich multimedia such as photos, videos and presentations as well as typical MS office document file types. The storage requirements will therefore grow over time to a considerable size, so the storage capacity should be expandable.

RQT 5: The groupware should also have an intuitive Graphic User Interface (GUI) so that the site structure can be easily navigated. The incorporation of corporate colour schemes, fonts and logos will increase the chances of acceptance and adoption.

RQT 6: The architecture sitemap of the groupware will need to reflect the main groups of the KM framework and be able to navigate between the NPD, OPD and CORE knowledge database repositories. The tool will need to incorporate the preferred taxonomies for each PD domain (section 4.7.1), and the meta-knowledge classification scheme for the PT reliability failures as developed in chapter 5.

7.2 PLM Software Platforms - Review

In order to inform a decision as to which software platform would be most appropriate to develop the prototype ICT tool a review of a host of Commercial-of-the-Shelf (COTS) PLM software tools was first conducted. The list of key features available on each PLM platform offering is shown in **Appendix J**.

The study revealed that Ford, Toyota, Nissan, Volkswagen, Renault and Volvo all utilise various modules of Siemens PLM®. Siemens Teamcenter® provides the capability to manage structured PD knowledge: Requirements, BoM and CAx Configuration, and PD processes.

Although there is a separate 'bolt-on' CAPA module available for Siemens Teamcenter® no real-world industrial cases studies could be found that specifically attempted to link the CORE technology product knowledge with unstructured NPD knowledge and OPD (CAPA) knowledge.

There is also the functionality within many of the PLM offerings to integrate product document management with the product development processes. However, although the capability exists the fundamental taxonomy and sub structures still need to be constructed and tailored to suit the particular KM requirements. For this reason it was decided to build the prototype ICT KM Support tool using MS SharePoint® 2010 as the basic platform and to build the complete site architecture and sub site hierarchy.

MS SharePoint was already available via the IT department within the case study company, thus avoiding any issues with the necessity to procure any expensive new software or associated commercial licenses. As the SharePoint® software could also be installed by the corporate IT team it had been verified as fully compatible with the PC desktop and laptops, and could be hosted on the corporate server without additional complications.

The corporate version of the software was also fully linked to the corporate user directory, which permitted the local application to connect with as many remote users as required by granting access permission within the SharePoint® software. The basic version of SharePoint® had all the envisaged in-built functionality required, but no structure or content. The next sections describe the development of the Support Tool within the Microsoft SharePoint® platform environment.

7.3 Prototype Support Tool - Architecture Sitemap

In order to develop the support tool within the MS SharePoint® environment the structure of the KM framework first had to be mapped into the groupware architecture sitemap. A hierarchical tree of the sitemap is shown below in Figure 56.

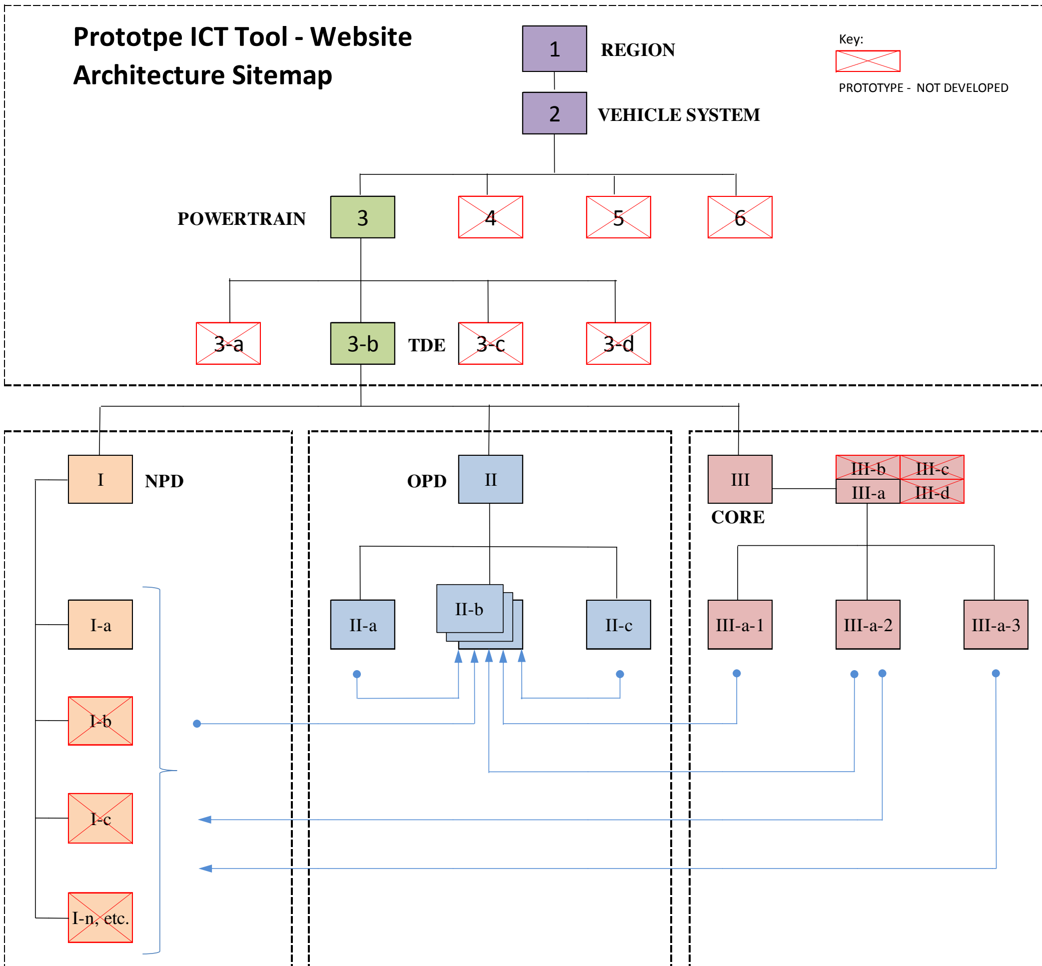


Figure 56. Prototype ICT Tool – Groupware Architecture Sitemap

For simplicity and clarity the function and purpose of each of the sites and sub sites shown in Figure 56 was purposely excluded.

The descriptions for each sub site in the sitemap hierarchy can instead be found according to the label notations in Table 28 on the next page.

The descriptions of the key sites, sub sites and pages within the groupware architecture in Figure 56 are shown below in Table 28. The 'greyed-out' areas represent the structure that was not developed in the prototype version of the tool.

Locator:	Level:	Navigate to:		Description:	Type:	Contains:	
1	Welcome Page (1)	Global PD	Regions	Site	Page	URLs	
2	Welcome Page (2)	Global PD	Vehicle Systems	Site Page	Page	URLs	
3	Homepage	Global PD	Powertrain Systems	Site Page	Page	URLs	
4	Homepage	Global PD	Body Systems	Site Page	Not Developed	URLs	
5	Homepage	Global PD	Chassis Systems	Site Page	Not Developed	URLs	
6	Homepage	Global PD	Electrical Systems	Site Page	Not Developed	URLs	
3-b	Homepage	TDE	PT Sub Systems	Page	List	URLs	
3-a	Homepage	Engine	PT Sub Systems	Page	List	URLs	
3-c	Homepage	PTAI	PT Sub Systems	Page	List	URLs	
3-d	Homepage	PCCN	PT Sub Systems	Page	List	URLs	
I	**Homepage**	**TDE NPD**	**Vehicle PD Programs**	**Page**	**List**	**URLs**	
I-a	Site	TDE NPD	B299 - Fiesta	Site	Document Library	Folders	
I-b	Site	NPD	C346 - Focus	Site	Document Library	Folders	
I-c	Site	NPD	CD391 - Mondeo	Site	Document Library	Folders	
I-n	Site	NPD	ext Platform / Program - et	Site	Document Library	Folders	
I-a-1	Sub Site	TDE NPD	0504_Halfshaft System	Document Library	Folders	Sub Folders	Documents
I-a-2	Sub Site	TDE NPD	0701_Automatic Trans	Document Library	Folders	Sub Folders	Documents
I-a-3	Sub Site	TDE NPD	0703_Manual Trans	Document Library	Folders	Sub Folders	Documents
I-a-4	Sub Site	TDE NPD	0800_Clutch System	Document Library	Folders	Sub Folders	Documents
II	**Homepage**	**TDE OPD**	**Continuous Improvement**	**Site**	**List**	**URLs**	
II-a	Site	TDE OPD	Quality Data & Analysis	Page	List	Folders	Documents
II-b	Site	TDE OPD	DMAIC Projects	Page	Document Library	Folders	Documents
II-c	Site	TDE OPD	DMAIC Directory	Page	List	URLs	
II-b-1	Sub Site	TDE OPD	0504_Halfshaft System	Page	Document Library	Sub Folders	Documents
II-b-2	Sub Site	TDE OPD	0701_Automatic Trans	Page	Document Library	Sub Folders	Documents
II-b-3	Sub Site	TDE OPD	0703_Manual Trans	Page	Document Library	Sub Folders	Documents
II-b-4	Sub Site	TDE OPD	0800_Clutch System	Page	Document Library	Sub Folders	Documents
III	Homepage	TDE CORE	DE Standards and Method	Site	List	URLs	
III-a	Sub Site	TDE CORE	0504_Halfshaft System	Page	Web Parts	URLs and Folders	
III-b	Sub Site	TDE CORE	0701_Automatic Trans	Page	Document Library	Sub Folders	
III-c	Sub Site	TDE CORE	0703_Manual Trans	Page	Document Library	Sub Folders	
III-d	Sub Site	TDE CORE	0800_Clutch System	Page	Document Library	Sub Folders	
III-a-1	Page	TDE CORE	Standards and Methods	Web Part	List	URLs	Corporate CMS's
III-a-2	Page	TDE CORE	Technology Knowledge	Web Part	Image Viewer	URLs	Sub Folders
III-a-3	Page	TDE CORE	Generic SE Templates	Web Part	Document Library	Folders	Sub Folders

Table 28. Prototype ICT Tool – Groupware Sitemap Description

The next section discusses the specific layout, page content and navigation around the different elements of the groupware architecture sitemap.

7.4 Prototype Support tool - Navigation Guide

This section discusses the website pages developed to represent the three knowledge-bases within the KM framework, as described in Figure 49 in order to illustrate the proof of concept for the overall prototype ICT groupware tool.

The starting point to locate the groupware tool is via a 'fuzzy' search on the corporate website homepage as shown in Figure 57 below.

Figure 57. Ford Corporate website homepage – 'fuzzy' search

Once the user has navigated to the Global PD site they are presented with the groupware welcome page. The user is prompted with the Step 1 option to select their respective region or commodity engineering team as shown in Figure 58.

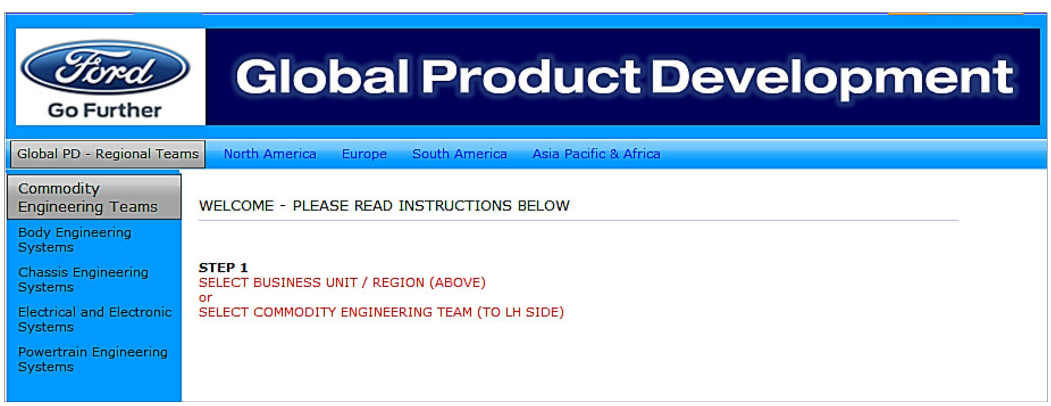


Figure 58. ICT Tool – Global PD Site – Welcome Page (1)

The layout of the welcome page was structured so the user can select their region via the tabs along the top ribbon or from the four main commodity engineering teams along the quick launch menu on the left hand side.

Once the user has navigated away from the welcome page to the selected region they are then presented with the commodity engineering team welcome page as shown in Figure 59 below. If the commodity engineering team was selected on the first welcome page, shown in Figure 58, the user actually circumvents navigating through this page and is instead taken directly to the page shown in Figure 60.

Figure 59. ICT Tool – Global PD Site – Welcome Page (2)

The layout of the commodity engineering team page was structured to show all four major vehicle commodity groups; namely Powertrain, Body, Chassis, and Electrical and Electronic systems.

As described in Table 28, only the Powertrain sub-sites were developed for the purpose of demonstrating the concept and principles of the groupware structure. The URL and Icon hyperlinks for the body, chassis and electrical and electronic systems were not developed as part of the prototype. At this point the user is only able to navigate to the Powertrain Systems page and sub sites.

Once the user has navigated to the Powertrain Systems page they are presented with the Step 2 option of selecting the respective PT sub system from the tabs in the ribbon along the top of the page as shown in Figure 60 below.

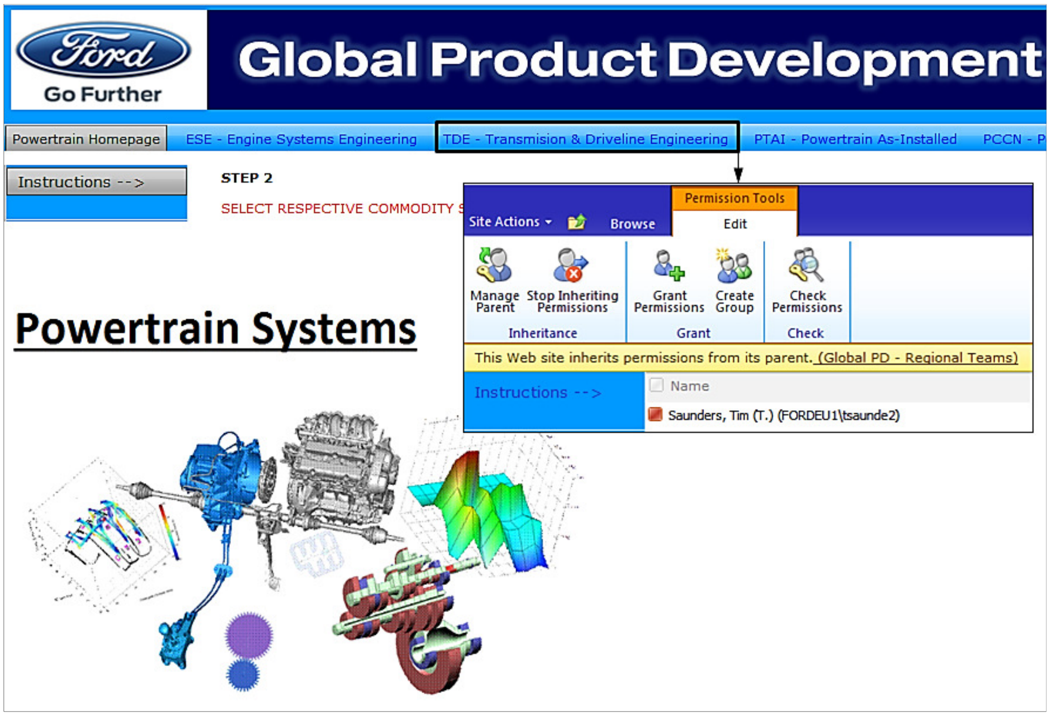


Figure 60. ICT Tool – Global PD Site – Powertrain Systems Page

Once again, for the purpose of demonstrating the working concept of the groupware, only the website sub structure for the TDE sub system was developed. For completeness the tabs for the Engine, PTI, and PCCN sub systems are shown in the ribbon along the top to show them in the context of the overall page layout in case the site is intended to be fully developed at a later stage.

All of the higher level website pages are open access and without any form of access restriction. This is permissible because the welcome and homepages only exist for the purposes of navigation to the appropriate commodity sub system, and as such they are effectively empty shells since they do not contain any SE content that must be secured from non-permitted user access. However, to navigate further beyond these pages, to the respective powertrain sub system pages, automatic access is blocked.

To navigate beyond this point the user must first request access via the screen prompt which then sends an automated email to the site administrator. The local level SharePoint® site administrator may then review the email request before granting access. Access may be given on the basis of read-only or contribute depending on the user needs.

Once the user has been granted access to the TDE Sub site they are then able to navigate to the homepage as shown in Figure 61 below, and also then have access to all the sub sites and pages found within this page.

Figure 61. ICT Tool – Global PD Site – TDE Systems Page

Within the TDE homepage the user is presented with the step 3 option where they are prompted to select one of the three respective knowledge-bases. The tabs in the ribbon along the top of the page, and the URL hyperlinks listed at the bottom of the page, provide the same identical function in selecting;

I NPD – Vehicle PD Programs

II OPD – Continuous Improvement

III CORE – Standards and Methods

The structure of the sub sites and pages for each of the above three knowledge bases are repeatable templates that can be re-generated from within the SharePoint® repository as the basis for creating the structure beneath all of the other Vehicle systems and sub systems (i.e. those not developed in the prototype groupware).

The following sections describe the steps required to navigate within each the TDE sub systems SharePoint® sites which were developed to illustrate the concept for each of the structured knowledge-bases within the prototype ICT groupware.

7.4.1 TDE NPD Knowledge-base (I)

The user is able to navigate to the ***TDE NPD – Vehicle programs*** Knowledge-base from the URL hyperlink on the TDE homepage as shown previously in Figure 61.

The TDE NPD sub site utilises a standard document library folder structure to store the array of SE knowledge document types which creates a recognisable structure for all users, as shown in Figure 62 below.

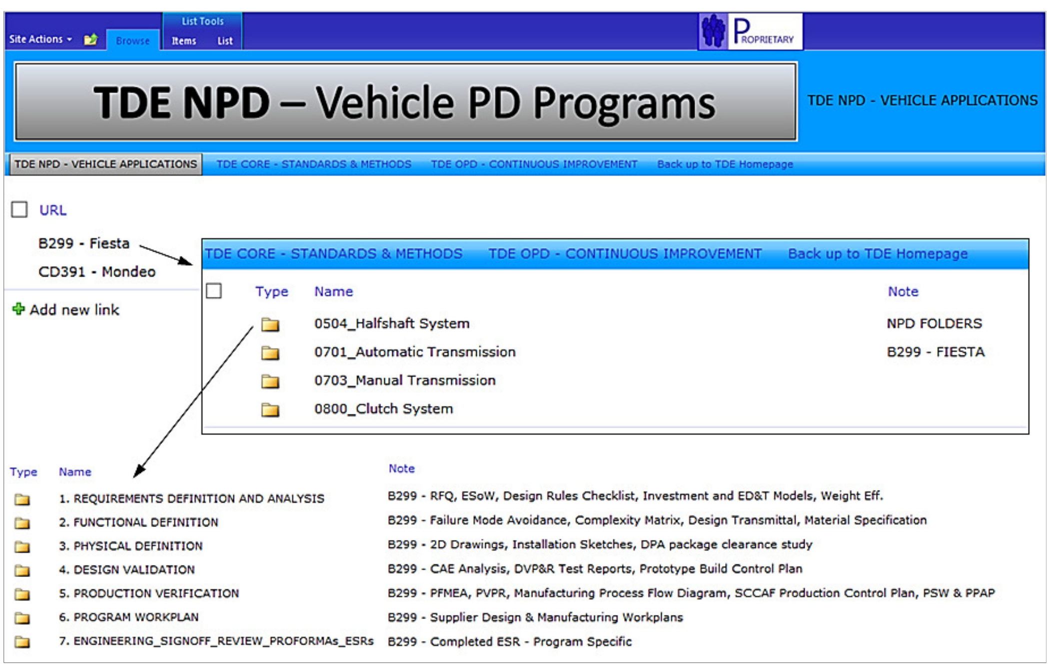


Figure 62. ICT Tool – TDE NPD Site – Vehicle PD Program Folders

The standardised document library format was created within the SharePoint® environment and then stored as a site template within the SharePoint® site repository. The document library structured format can be re-generated and assigned to as many different new vehicle programs as required. This also links intuitively to the Core SE knowledge document library described later in this section.

The groupware site administrator may then assign the appropriate level of access to the complete list of intended users by adding their corporate username ID within the MS SharePoint® site permissions area of the site actions menu. If an externally facing B2E type site was constructed the site administrator may then also add external email addresses and create a user ID profile for supplier engineers and assign access. The standard set of folders and sub folders provide the necessary framework to allow all potential users within the extended enterprise to recognise the structure of each knowledge-base and build familiarity with the location for each knowledge document type. Within each folder the standard set of sub folders are also structured in a standard format as shown in Figure 63 below.

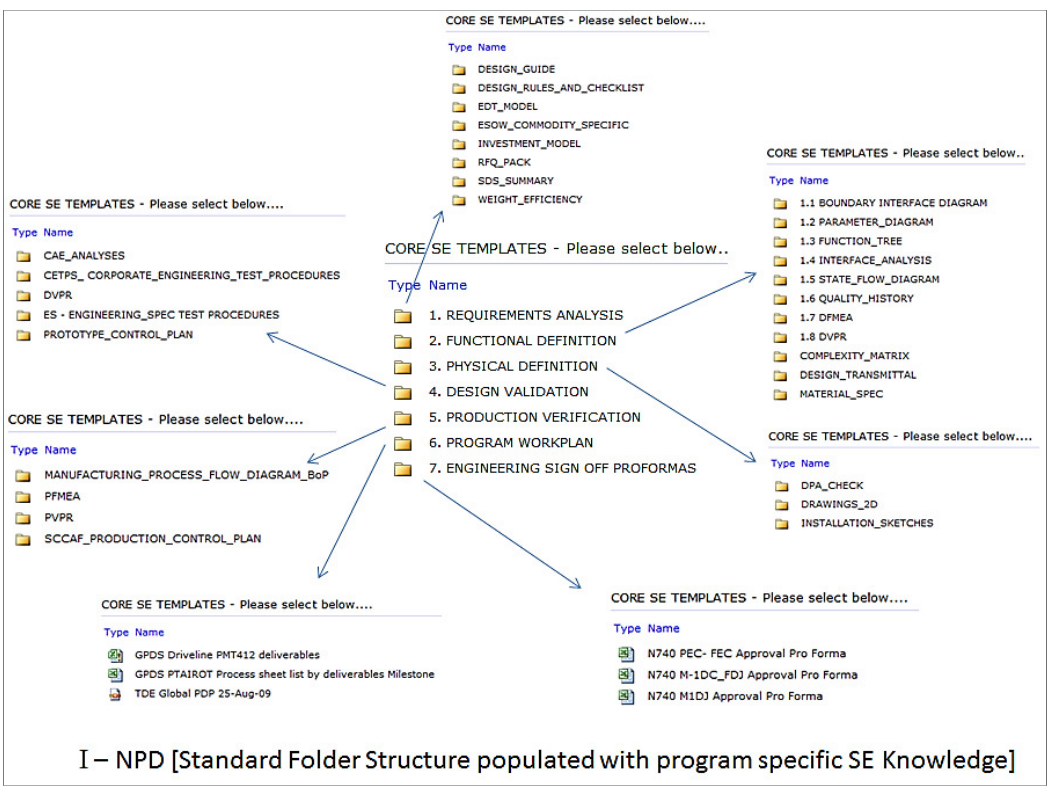


Figure 63. ICT Tool – TDE NPD Site – Vehicle PD Program Sub-Folders

Once the document library site template has been re-generated and assigned to the next vehicle program the site admin is able to add/delete/amend the folder names to tailor to the specific technology commodity group if needed.

7.4.2 TDE OPD Knowledge-base (II)

The user is able to navigate to the ***TDE OPD – Continuous Improvement*** Knowledge-base from the URL hyperlink on the TDE homepage as shown previously in Figure 61. Within the TDE OPD knowledge base there are two main web pages which are represented by the tabs along the ribbon at the top of the page;

1. DMAIC-R ***Directory***
2. DMAIC-R ***Reports***

The ***DMAIC-R Directory*** is a MS SharePoint® list constructed to represent KB-II (Figure 49) and is organised according to the meta-knowledge classification scheme as described in chapter 5. The individual meta-knowledge categories are used to identify the contents of all DMAIC-R reports as shown in the header of each column across the page. Each column may then be filtered according to the sub category as shown in Figure 64 below.

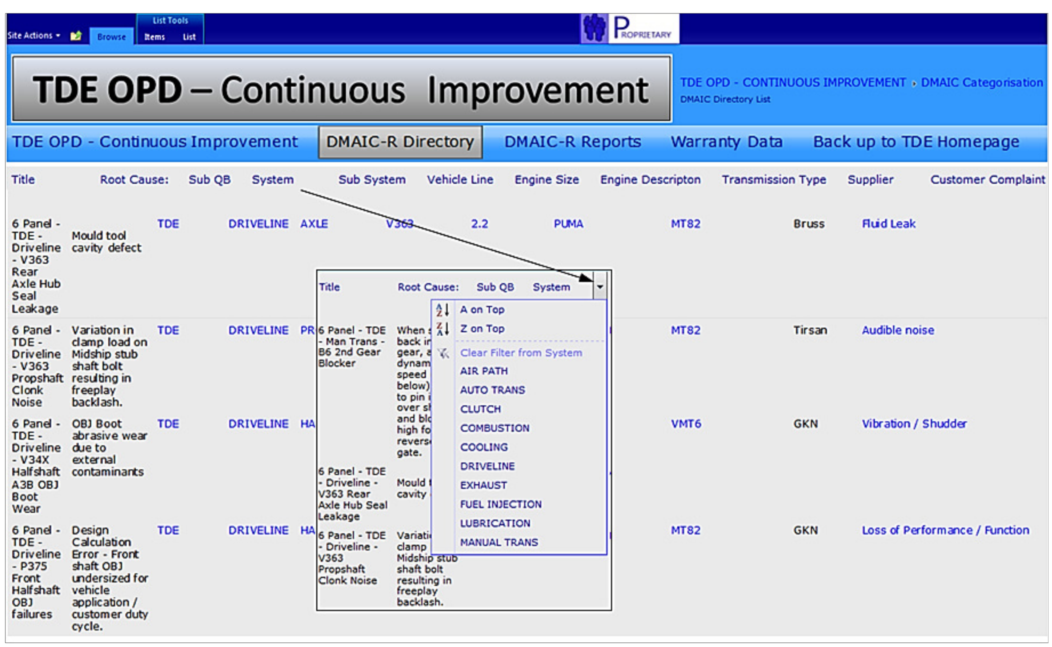


Figure 64. ICT Tool – TDE OPD Site – DMAIC Directory 'Filter and Search'

The user is able to determine what content there is to the DMAIC-R report and whether it supports a current investigation where they may be looking for past knowledge to help. If the user identifies any particular investigation case of interest the title heading on the left hand side forms a hyperlink to the full DMAIC-R investigation report. Conversely, the user may also upload a new DMAIC-R file into the database by clicking the '+ Add new item' at the bottom left hand side of the screen as shown in Figure 65 below.

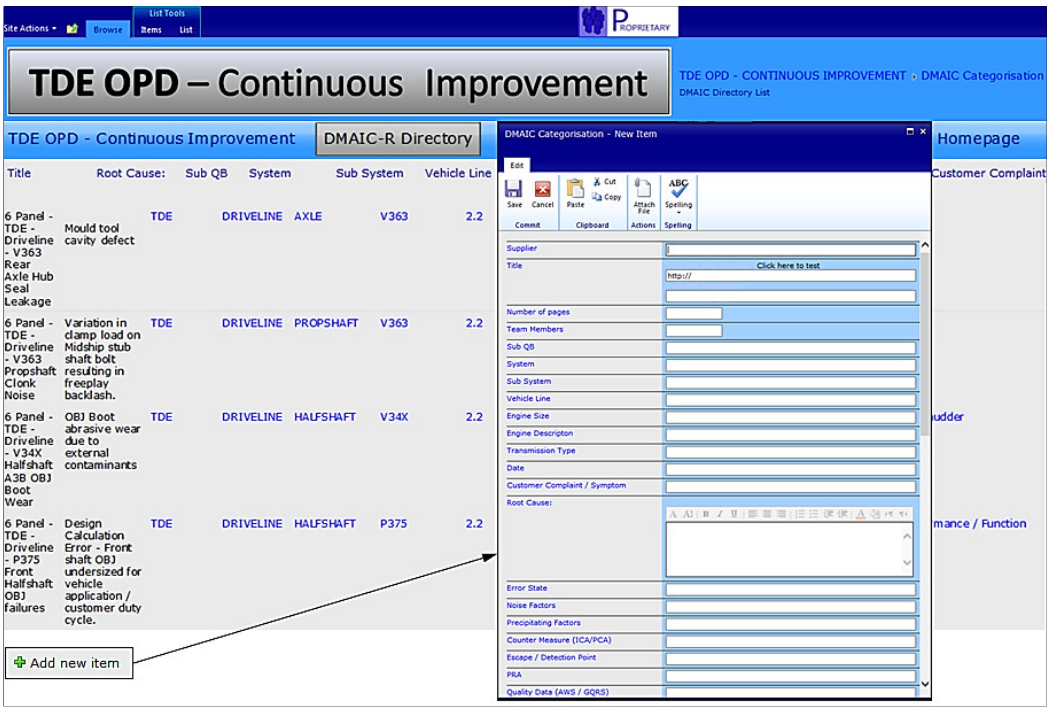


Figure 65. ICT Tool – TDE OPD Site – DMAIC-R Directory 'Add new item'

The user is then prompted to complete the details of the DMAIC-R contents in respect of all the main column headings ensuring all the meta-knowledge details are incorporated and transparent for future users when they search for knowledge within the directory. The screen prompt finally allows the user to upload the DMAIC report file, typically in .ppt or .pdf file extension format, which when attached to the database entry assigns the URL to the title in the SharePoint® list. In order to make sure that the URL hyperlink is always able to find the full DMAIC report a separate document library was created.

The second web page within the TDE OPD sub site is the ***DMAIC reports*** page which is a SharePoint® document library as shown in Figure 66 below.

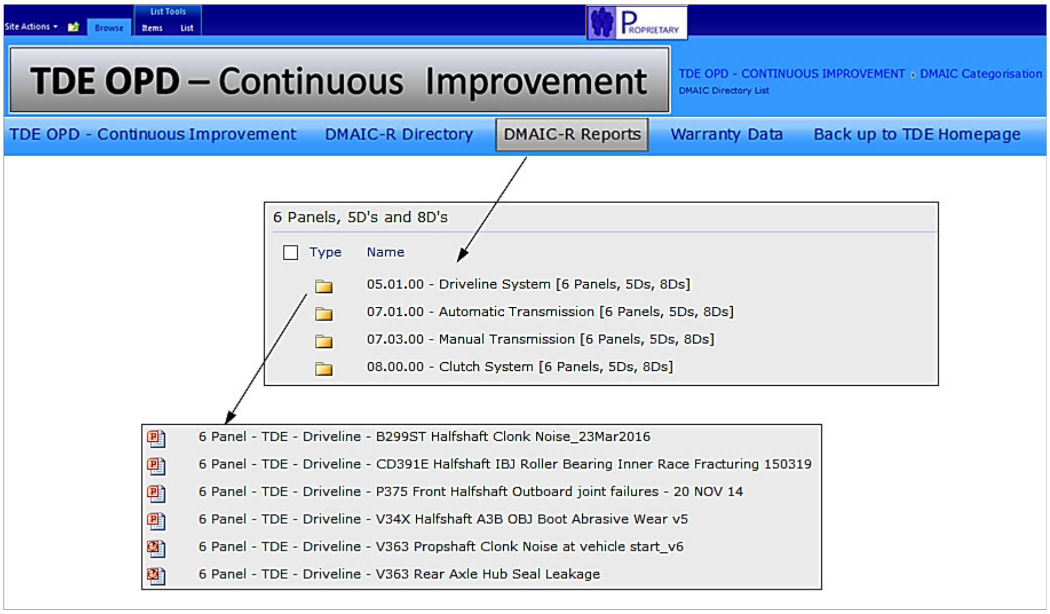


Figure 66. ICT Tool – TDE OPD Site – DMAIC-R Document Library

The folder structure presented on the page represents the same familiar TDE sub systems hierarchy.

For the purpose of the demonstration of the groupware concept this document library was fully developed in order to allow all of the 48 DMAIC-R reports used in the PT failures case study in chapter 5 to be uploaded.

Access to the folders beneath each TDE sub system may be restricted to a limited user contribution group, as maintained by the site administrator, to ensure that all confidential knowledge documents are secured. External users from other sub system teams may access the DMAIC-R report files from the DMAIC directory hyperlinks so they can then download a local 'read-only' offline copy. This protects the integrity of the original DMAIC-R files whilst allowing dispersed teams of collaborating engineers to access and share all prior knowledge captured within the OPD knowledge-base.

7.4.3 TDE CORE Knowledge-base (III)

The user is able to navigate to the ***TDE CORE – Standards and Methods*** Knowledge-base from the URL hyperlink on the TDE homepage as shown previously in Figure 59. The user is then presented with the option to select the specific TDE sub system they wish to navigate to via a URL hyperlink as shown in Figure 67 below.

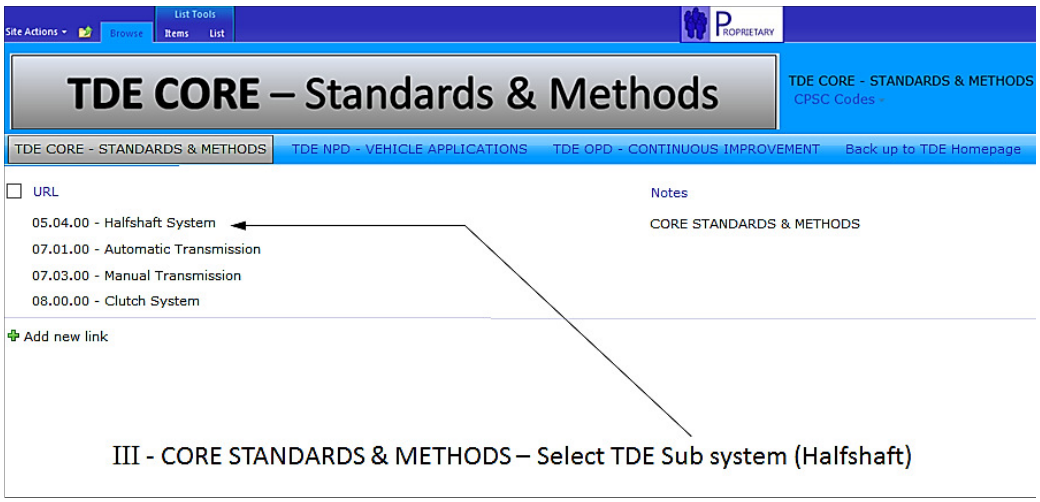


Figure 67. ICT Tool – TDE CORE Site – Sub System Structure

The user is then prompted to select whichever TDE sub system team they are interested in navigating to by selecting the appropriate URL hyperlinks from within the SharePoint® list. For the purpose of demonstrating the concept of the groupware the page was populated with URL hyperlinks to all four main TDE sub systems, but only the structure beneath 05.04.00 Driveshaft was completely developed. Once the user has selected the appropriate sub system link they are directed to the sub system page where they are then presented with three web-part areas, each of which is now discussed in turn;

The first web-part, on the right hand side of the web page, provides a further series of URL hyperlinks that allow the user to navigate to the existing corporate CMS's, as shown in Figure 68. The links allow the user to navigate to the respective Design Requirements and Standards as well as the Corporate CMS for the FMA tools and RCA tool examples which are held in separate document libraries.

The second web-part within the TDE Sub system page provides a generic schematic of the sub system assembly with the associated base-part-numbers for the assembly BoM components list as shown on the left hand side of the web page in Figure 68.

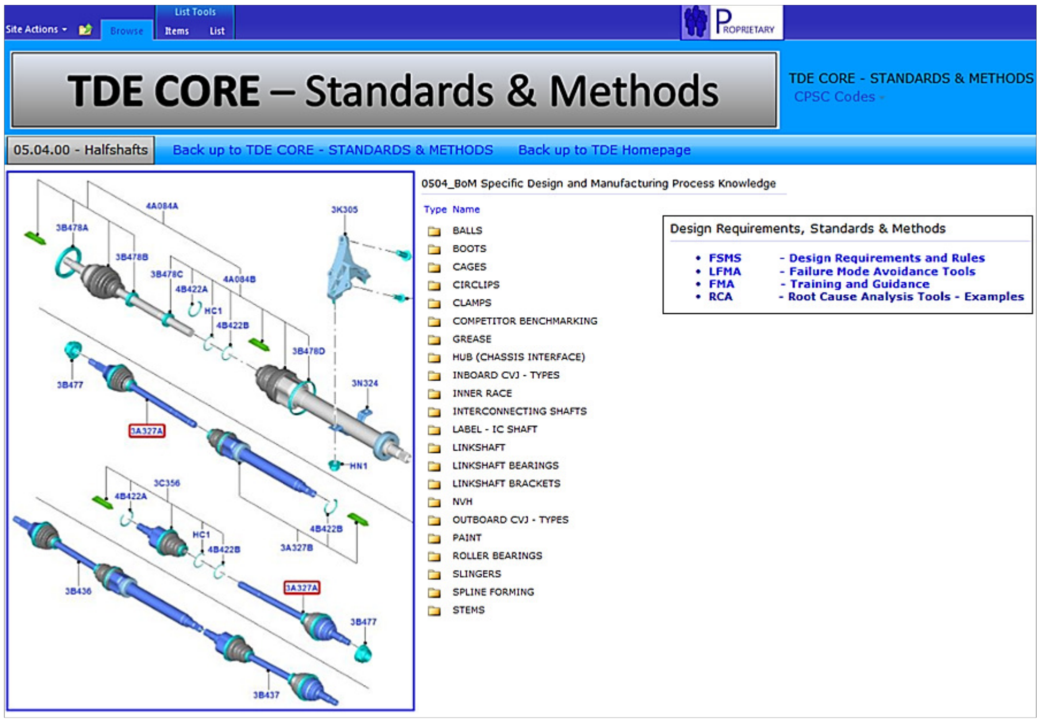


Figure 68. ICT Tool – TDE CORE Site – Product Knowledge Folder Structure

Alongside the image of the assembly schematic is a document library containing individual folders for each generic component type in the BoM where the Technical Specialist or SME for the system can upload key knowledge documents such as design specifications, material selection criteria, and calculation methods. These folders can then be accessed by all NPD and OPD engineers wishing to understand more details regarding design principles and manufacturing processes specific to each component type.

The third web-part within the TDE Core knowledge-base contains exactly the same document folder structure for SE knowledge documents as used within the TDE NPD – vehicle programs site (Figure 62 and Figure 63), as shown in Figure 69. However, at this level the folders are populated by the Subject Matter Experts (SME's) and Technical Specialists (TS's) with all the relevant knowledge documents pertinent to the current best practices and processes. The folders are then maintained over time with the expectation that the body of knowledge will grow organically.

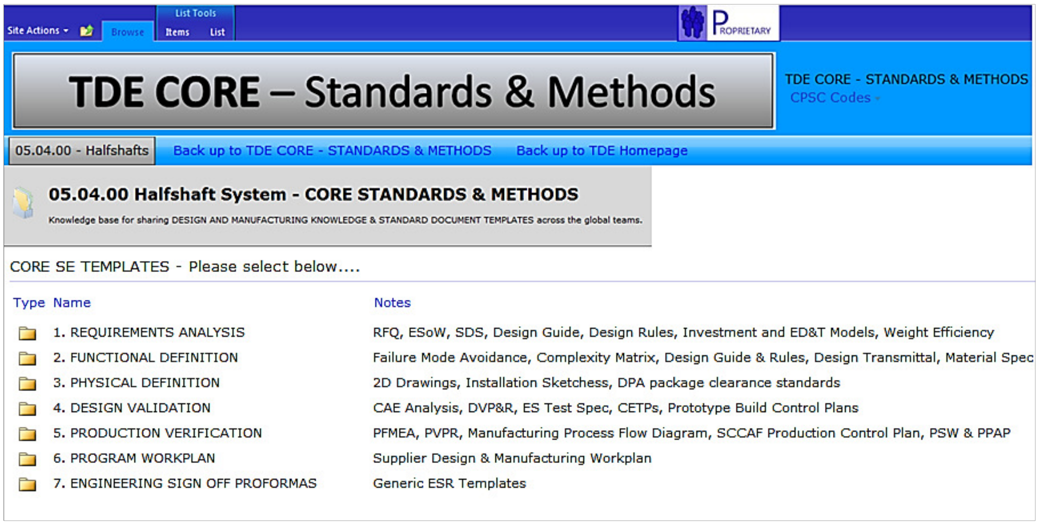


Figure 69. ICT Tool – TDE CORE Site – SE KM Folder Structure

The standards and methods knowledge documents, and process deliverable templates that support each part of the NPD process, can be located within the equivalent folder and sub folder structure as shown in Figure 70 below.

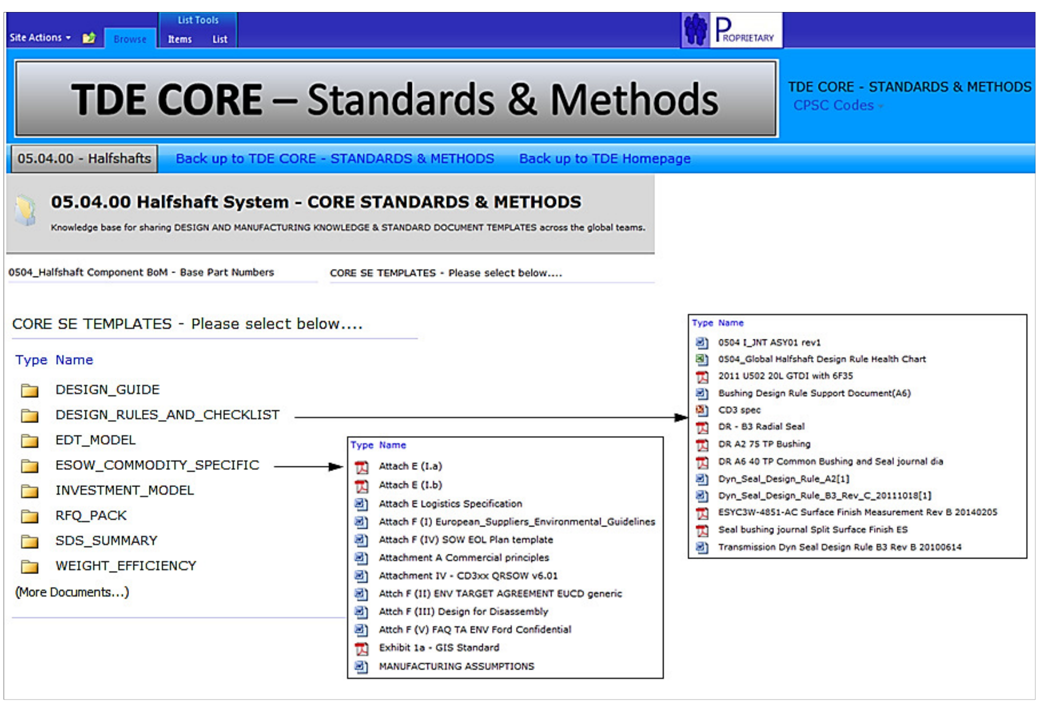


Figure 70. ICT Tool – TDE CORE Site – SE KM Sub-Folder Content

This chapter has so far described the user interface, navigation, and operation of the groupware tool. The next section now describes the evaluation of the prototype tool with a small group of industrial PD practitioners within Ford Motor Company.

7.5 Prototype Support Tool - Evaluation

This section describes a real-world case study example to evaluate the KM groupware support tool presented in the previous section, to satisfy research objectives 5.2 and 6.1 in table 2 (***Marxen and Albers*** 2012).

The first aim of this exercise was to evaluate the 'perceived ease of use' of the support tool by demonstrating the functionality of the groupware tool and explaining the navigation between the different sub sites within the tool architecture. The second aim was to evaluate the 'perceived usefulness' of the support tool by requesting feedback from PD engineers whether they recognised the potential KM advantages offered and the likelihood of adoption and utilisation of such a tool (***Davis*** 1989).

7.5.1 Evaluation Approach

As the nature of the evaluation was to solicit qualitative feedback, in the form of explanatory evidence from industrial practitioners, it was decided to adopt a case study approach. The case study method (***Robson*** 2002) involved four steps;

i. Develop interview questions
ii. Selection of participants
iii. Demonstrate support tool and conduct interview
iv. Analyse findings

Step one involved developing an open-ended questionnaire to capture the feedback from the participants. Open ended questions that elicited descriptive feedback were preferred to Likert scale ratings against predetermined answers as a more informative method from which to gather useful insights on perceived usefulness and ease of use. The full list of the interview questions may be found in **Appendix K**.

Step two initially established the criteria for selecting the participants for the exercise. The PD practitioners were selected on the basis of their prior involvement in more than just a singular domain within the groupware support tool. This was considered essential so that the participants had experience of the need to reference and link CORE knowledge together with the NPD process and OPD reliability investigations. It was anticipated that breadth of PD experience was more essential than depth. Additionally, for the initial evaluation of the prototype tool it was also decided that only a small scale qualitative study was required, as opposed to a large scale statistically significant study, since the nuisances around the undeveloped sub sites within the prototype architecture hierarchy could cause confusion and attract undue criticism which would detract from the intention of the exercise. In accordance with similar research involving *support tool evaluation* it was deemed sufficient to select three participants (***Bradfield*** 2007). It was also deemed sensible to interview local participants within the UK PD for ease and convenience of meeting face-to-face.

Step three was achieved by demonstrating the working prototype tool to the selected PD practitioners. This involved explaining the purpose of the tool, introducing the graphic user interface, navigation menus and working through the hierarchy and structure of the groupware. This was achieved by systematically working through each of three groupware knowledge-base domains and explaining the logic and linkages between the different kinds of knowledge generating activities associated with each type of engineering role. The demonstration covered the process of uploading new user-generated knowledge documents into the appropriate area, and also locating, retrieving and sharing knowledge documents of interest. Each demonstration was conducted in isolation to prevent open discussion between the participants which might introduce group bias. At the end of each demonstration the interview questions were provided. Each participant completed their responses and was asked to explain their thoughts. Each exercise lasted approximately 45 minutes.

The final step was to analyse the interview question responses and cross correlate for common themes and unique nuances according to the particular thoughts and impressions of each participant. This was then considered as part of the overall conclusions to the research project. The findings are presented in the next section.

7.5.2 Evaluation Exercise - Findings

Information regarding each participant is summarised below in Table 29:

Participant	PD Roles	Technology Type	PD Experience
P1	OPD + NPD	Clutch Systems	5 years
P2	OPD + NPD	Driveline Systems	9 years
P3	CORE + OPD	Manual Transmissions	3 years

Table 29. Tool Evaluation Participant Overview

The initial five questions relate to the ***perceived usefulness*** of the tool (**Appendix K**).

Q1 responses: All three participants responded favourably towards the potential for the tool to improve knowledge capture and sharing between non collocated PD team members, but concerns were raised regarding restricted access rights to each specific commodity area needing to be strictly monitored to prevent unauthorised access which could result in files being mistakenly removed or modified. It was also noted that SharePoint® was not an 'ISO' compliant tool, but program knowledge documents could be migrated to either EDMS or APDM after program launch as these are both recognised as the corporate ISO complaint websites.

Q2 responses: In terms of whether the tool would prove helpful in locating knowledge created and stored by engineers in other roles it was recognised that the tool would overcome the loss of knowledge when engineers leave the company. Clear partitioning of knowledge ownership by organisational role within each PD domain was also highlighted as a useful key to navigating through the sub-sites.

Q3 responses: The co-location of technology specific knowledge was also appreciated as a fundamental enabler to controlling access rights to recognised team members. It was also remarked that co-location of all generic program sign-off templates would increase the standardisation of file naming convention which would help.

Q4 responses: When asked about the likely willingness of engineers investing the time to populate the tool it was clear that there needs to be an incentive to increase personal equity and encourage a change away from current practices. It was suggested that the upload of program evidence documents within the NPD knowledge base domain might be encouraged if the tool was proactively used within the commodity manager program review meetings, and all documents were downloaded 'live' in the meeting, thereby exposing any missing documents required for the program review.

Q5 responses: The main challenges with encouraging adoption of the tool were envisaged as a lack of unawareness of the tools existence. It was suggested that this could be countered through widespread demonstration to illustrate the potential effectiveness of the tool as part of daily working practice, which may precede a pilot program before widespread roll-out.

The next 4 questions related to the ***perceived ease of use*** of the tool (**Appendix K**)

Q6 responses: The participants all agreed that the site structure and layout seemed intuitive, and one respondent particularly noted that structuring technology specific product knowledge within folders commensurate with the component bill-of-material beneath the commodity assembly was particularly useful.

Q7 responses: When asked if the participants thought that engineers would struggle to understand how to add new items into the correct sub sites and folder locations the general response was that everything looked quite straight forward. However, one respondent remarked that the systems engineering phase structure was not consistent with the corporate PD process milestones and engineering gateway notation scheme. Equally, the file naming convention adopted by different engineers would also create confusion if engineers used random non related terminology.

Q8 responses: Regarding any potential foreseeable issues with managing the site structure and content, one respondent raised the point about long term storage requirements which would increase over time as the site structure grew and more content was added. Additionally, the need for a dedicated program control engineer was suggested so they could monitor that all necessary program documents were completed and uploaded since most engineers need to be reminded in advance of the milestone and gateway reviews.

Q9 responses: The main weaknesses and areas for improvement centred on two different aspects. Firstly, certain key documents such as Design Validation Plans are generated early in the program as part of the FMA exercise, but are not completed until the testing is finished and the results are available. This could present issues around which folder location the files should be stored under, so possibly ending up in two locations. Secondly, the DMAIC-R directory provides the function to upload new investigation reports, but the SharePoint® tool requests input to identify the meta-knowledge content of the project which is an excessively long list of free-text entries. The proposal was to cut down the length of the list and also change from free-text to 'radio' buttons with predefined categories and sub classes that can be selected.

Q10 responses: The final comments included a suggestion to conduct a trial period so that more engineers had a chance to work with the tool and use it with real knowledge documents. This would give them a chance to 'play' with the tool and better understand any particular nuances. Another participant added that a 'How-to' guide or 'Single-point lessons' would need to be embedded within the tool to help demonstrate many of the key features, and to also specify particular critical aspects such as the need to adhere to a strict naming convention for file names, and content categorisation for folder names.

7.6 Prototype Support Tool – Summary

The initial section of this chapter defined the *requirements for the prototype support tool*. The main foundation of the support tool is based on the various sub elements of the KM framework developed in chapter 6. Crucially though, several additional ICT issues needed to be considered such as; hosting the software platform within a large multinational company which attracted concerns surrounding expensive software licenses, interoperability with existing network servers and PC hardware, and incompatibilities when operating inside the corporate IT security firewall.

A brief comparative review of the most popular commercial PLM software platforms revealed that several possessed the required functionality. However, Microsoft SharePoint® was ultimately selected to develop the prototype groupware because it was already an approved software platform recognised by the IT department within Ford Motor Company.

An *architectural sitemap* (Figure 56 and Table 31) was developed based on the key components of the *KM framework* (Figure 49). This laid the foundation for the subsequent development of the groupware sites and sub sites, and the necessary navigational menus and links between the different web pages. It also provided the developmental structure for populating the web pages with the appropriate taxonomy for folders, and creating template pages which could then be readily reproduced at different levels within the site hierarchy. A navigation guide was then built using screenshots for all levels of the groupware site architecture. The pictorial figures were augmented with descriptive text to explain the intent and purpose of each knowledge-base domain and the linkages between different elements of the groupware.

Finally, the prototype tool was demonstrated to a small group of PD practitioners within Ford Motor Company. The participants were selected based on sufficient breadth of experience in more than a single PD role as this was deemed necessary in order for them to have an appreciation of the all three knowledge-base domains. The participants were then requested to complete a short questionnaire regarding the *perceived usefulness* and *perceived ease of use* of the groupware as the basic means for provisionally evaluating the support tool, and the potential for user adoption.

8 DISCUSSION, CONCLUSIONS AND FURTHER WORK

This thesis presents the findings of the research to establish a knowledge management framework and prototype ICT groupware tool to support the capture, sharing and re-use of automotive SE knowledge throughout the complete vehicle lifecycle.

8.1 Discussion and Conclusions

The introduction to the thesis provided an initial general overview of the automotive industry. This highlighted that a key KM challenge faced by large automotive MNE's is the difficulty in managing new dynamic knowledge that is constantly updating in an environment of continuous collaborative innovation. The initial problem statement outlined how enormous volumes of intellectual capital in the form of critical design and manufacturing knowledge documents are distributed across the large extended enterprise rather than captured in well-organised central knowledge repositories.

The subsequent literature review revealed that the general motivation for improved KM practices is the mitigation of vital knowledge loss caused by the churn and attrition of the workforce during operational restructuring and captive offshoring, and the departure of experienced knowledge workers due to retirement. Furthermore, although a great deal of attention has been given in the literature to the early stages of the PD process, none has attempted to address the knowledge management requirements to support the complete automotive SE lifecycle. In particular, there is a dearth of attention in the extant literature towards capitalising on new SE knowledge learned during the investigation and resolution of product functional reliability failures on vehicles in operational service.

The *knowledge-based view of the firm* equally asserts that knowledge-based resources are the most strategically significant determinant to achieve sustained competitive advantage, and that effective KM enables more robust decision making, faster problem solving, and more efficient transfer of best practices. In this respect the literature review revealed insufficient insights into the typical SE knowledge transactions between the different divisions of the automotive extended enterprise to meaningfully inform the research with how this might be achieved, particularly in regard to compliance with the control of documents, and records retention management, as defined in ***ISO/ TS 16949*** (2009).

The literature review synthesis highlighted several *research gaps* summarised as follows; *A fundamental lack of empirical research to comprehensively inform a KM framework with the necessary insights from which to derive the requirements for developing an adequate support tool to improve the capture, sharing, and re-use of multigenerational automotive SE lifecycle knowledge.*

As a result, the need for further empirical research was argued, which prompted the following overarching research question (section 1.6);

What are the requirements for a knowledge management framework and tool to support the automotive systems engineering lifecycle?

The above overarching research question was decomposed into five further sub questions, the first of which asked; *what are the key KM challenges encountered across the extended enterprise within a typical large automotive MNE?* To address this first sub question an *exploratory industrial investigation* was conducted at Ford Motor Company. The industrial investigation progressed through five discrete stages, each aimed at improving and widening the generalization of issues found.

The first stage was an initial introspective review of the corporate documents pertaining to the SE technical processes as defined in ***ISO/IEC 15288*** (2008), the divisional organisation of operations and teams, and the architectural decomposition of the different technology groups that represent the complete vehicle structure. This was followed in the second stage by initial informal face-to-face discussions with local engineers, which helped to crystalize the outline schedule for the series of semi-structured interviews in stage 3 with both OEM and supplier engineers and managers.

The third stage gathered key insights regarding current KM approaches for capturing and sharing unstructured PD technical and program documents. The consensus of the participants regarding the adequacy of current KM practices suggests that current approaches are informal, random and ad-hoc.

In the fourth stage of the industrial investigation a number of the regional participants from throughout the extended enterprise were approached to gather deeper insights regarding the structure and content specific to their personal KM record archives. The key complexities were found to centre on the lack of a formal naming convention for electronic documents and folders caused by the proliferation in vehicle platform programs, technology types, and the interplay of approaches depending on engineering role within the different phases of the SE lifecycle. A proposed abstract model of the different PD knowledge classification viewpoints (Figure 26) was constructed based on the different preferences for KM taxonomies according to the functional design domain, vehicle product assembly domain, and the SE phase within the vehicle lifecycle.

There then followed a review of the corporate CMS's presently used for storing '*CORE*' knowledge regarding technology specific design methods, principles, rules, standards etc., and a parallel review of the top 25 general CMS's used during the normal course of conducting *'NPD'*. Although these were found to be generally well frequented by the participants the underlying sentiment was that the array of dedicated CMS's are disparate, and consequently the knowledge held within each is out of context with the remainder of the knowledge for the specific vehicle PD program.

Finally, in fifth stage of the industrial investigation the consolidated findings of the initial four stages of the industrial investigation were then utilised to inform a *Multinational PD survey* which was issued to 1,065 engineers across several Ford PD and Manufacturing regional facilities. In total 362 responses were received representing a 34% response rate. The survey was aimed at understanding if all the collated themes identified in the initial four stages could be generalised across all of the other company regional PD centres around the world.

The industrial investigation confirmed that there was an agreed lack of centralised provision for all regional members of the extended enterprise to actively participate in capturing and sharing user-generated SE knowledge documents generated during the course of new vehicle product development programs. It also confirmed that all regions shared similar concerns regarding the inadequacy of current KM practices, the frustration caused by the lack of access, and the risks posed by the potential loss of critical SE knowledge. In this respect the findings supported that many of the same fundamental issues were also prevalent globally throughout the company.

A concise architecture model of SE knowledge transactions throughout the extended enterprise was established to depict the flow of PD knowledge between the different divisional operations to represent the foundation for how a proposed KM framework might connect the different PD knowledge domains (Figure 38). As with the *Global R&D Organization* model based on the work of ***Zedtwitz et al*** (2004) in Figure 3, the EE architecture model proposed in this research (Figure 38) only represents the organizational layer within the overall envisaged KM framework.

The *DRM final Reference model* (Figure 39) was primarily based on the findings of the case study investigation into KM practices and challenges (chapter 4). The concise reference model describes the current 'as-is' *undesirable* situation implications and outlined the risks to design integrity over the product lifecycle. The main risks are posed by potentially repeating reliability failures caused by ineffective capture of prevent reoccurrence actions, and inefficiency in identifying and resolving new failures caused poor capability to reference lessons learned from historical reliability failure investigations

The second research sub question then asked; *what new SE knowledge is generated during the investigation of powertrain reliability failures on vehicles in operational service?* To answer this question secondary research material was gathered in the form of a significant number of DMAIC-R projects which were then examined in detail to establish the root-cause, corrective actions, and prevent reoccurrence actions. This stage not only found that 'virtual' cross-functional teams are typically assembled to combine their collective knowledge (*wisdom-of-crowds*), but also that a significant amount of untraceable valuable SE knowledge is typically embedded within each DMAIC-R report which is rendered redundant due to the lack of assigned meta-knowledge to facilitate discovery and re-use.

The third 'follow-on' research sub question asked; *how could the 'new' SE knowledge learned from reliability failure investigations be captured and shared more effectively?* The examination of the 48 test cases revealed 10 major categories and 64 sub classes that are required to comprehensively classify the SE knowledge held within a typical DMAIC-R problem solving project. The results of this study were used to establish a comprehensive meta-knowledge classification scheme which was then later embedded within the subsequent SE KM prototype ICT support tool.

The *final DRM Impact model* (Figure 48) was developed to juxtapose the *reference model* with the future 'to-be' desirable situation, and was based on the findings from the examination of the powertrain reliability failure investigation DMAIC-R projects (chapter 5). The Impact model describes the envisaged benefits that the subsequently proposed *DRM support tool* might bring about by providing a suitable mechanism for the capture and re-use of SE knowledge across multigenerational vehicle programs, thus underpinning the complete SE KM lifecycle.

The fourth research sub question asked; *what are the requirements for an automotive SE lifecycle KM framework to enhance knowledge capture, sharing and re-use capabilities?* To address this question a *Knowledge Management Framework to support the automotive SE lifecycle* was developed and proposed. The main requirements embodied within the proposed KM framework (Figure 49) were derived from the exploratory industrial investigation and subsequent examination of powertrain functional reliability investigations. The framework represents the continuum of knowledge transactions involved in the major SE activities within each of the three discrete PD knowledge domains, namely; NPD knowledge specific to new vehicle programs, OPD knowledge specific to product quality improvement, and CORE knowledge specific to technology design methods and manufacturing processes. The various elements and inter-linkages within the framework were then described in detail, followed by summary Table 27 which aligned the framework elements to the three PD domains identified in the *Automotive Extended Enterprise Architecture Model* (Figure 38).

The *real-world utilisation of the KM framework* was then undertaken through a single embedded case study example which presented the systems engineering lifecycle of a specific vehicle platform model 'X'. The single longitudinal case study described the main activities within each of the three PD knowledge domains for a particular technology on a specific vehicle program, from concept to launch and into operational service. The example provided sufficient confidence that the framework suitably depicts all facets of knowledge transaction types throughout the SE lifecycle, but the limited validation on a single case study only requires further attention as discussed in the further work chapter. The validated framework was then able to inform the website architecture of the subsequent prototype ICT support tool with the necessary insights to effectively link the SE Knowledge for each of the three discrete PD knowledge domains.

The fifth and final research sub question asked; *how might the KM framework be implemented, including appropriate methods and enabling tools, to realise the benefits?* To answer this question a prototype ICT support tool was developed on the Microsoft SharePoint® software platform to embody the three knowledge-bases depicted within the KM framework. The prototype groupware represents the *DRM Support tool* and incorporates the KM framework as the foundation for the web 2.0 architecture (Figure 56), and sitemap description (Table 28). A navigation guide was also presented using a series of screenshots from the graphic user interface of the prototype support tool.

The support tool was subsequently tested and evaluated with a small group of PD practitioners at Ford Motor Company to ascertain the *perceived usefulness and ease of use*. The participants provided general positive feedback towards the potential for the tool to address the highlighted KM issues, but the limited number of participants necessitates that a more thorough validation of the support tool is still required which is discussed in the final further work chapter.

8.2 Research Contributions

Through delivering all of the research objectives the aim has been achieved, and the key contributions of this research may now be summarised as follows;

- A detailed appraisal of the KM practices within a large automotive MNE that revealed the types of SE knowledge utilised, and the KM taxonomies employed, throughout the SE lifecycle on multigenerational vehicle programs.

- The development of an automotive extended enterprise architecture model to depict the knowledge transactions between the different geographically dispersed divisions of a typically large MNE and the network of sub suppliers.

- A thorough examination of a significant number of powertrain reliability failure investigations to establish an appropriate meta-knowledge classification scheme.

- The development of a suitable framework to address the current lack of KM support for the complete automotive SE lifecycle.

- The development and initial evaluation of a prototype web 2.0 support tool representing the implementation of the KM framework to support the automotive SE lifecycle.

8.3 Further Work

A key limitation of the research presented in this thesis is that only a single multinational automotive OEM was studied. However, the methodology developed within the initial exploratory industrial investigation (chapter 4) could also be applied across a host of other major automotive OEM's to gain a broader perspective of the wider industry and improve the robustness of the propositions that are asserted. Furthermore, the multinational survey could be deployed to a large number of automotive suppliers to embrace a much wider inquiry. This would require attention to the initial demographic profiling questions to make them more generic, plus the removal of any proprietary references to Ford Motor Company CMS's and Software tools. Additionally, the exploratory multinational survey was conducted at the very preliminary stage of research, and there are now a host of further questions that could be derived from the findings from chapters 4 – 7 which could also be included.

The secondary research conducted in chapter 5 presented the findings of the examination of 48 DMAIC-R projects. However, in reality, the resultant meta-knowledge classification scheme was only founded on a limited number of powertrain test cases which meant that no statistical significance can be drawn from the findings. It is therefore proposed that a possible future research direction could explore a greater number of test cases to draw statistically significant conclusions regarding certain patterns that might emerge from a much larger data set. To achieve this, the meta-knowledge classification scheme could be expanded to include an examination of reliability failures across the other major automotive technology groups.

In the original scope it was consciously declared to constrain the research to the powertrain group of technologies, and so this belies the greatest opportunity for further work. The possibility to expand the research to non-powertrain technologies feeds forward through all the remaining paragraphs;

The KM framework validation was based on a single longitudinal powertrain case study. To reinforce the validation it is suggested that several more cases studies could be explored to increase the number of cases, and equally that the research would benefit from a broader cross section of technology types. However, the true benefit of the KM framework is best understood when taken into the context of the SE knowledge lifecycle over long program durations; from concept to launch and then into operational service. However, the research upholds that the KM framework can only be robustly validated with longitudinal test cases, which prohibits the ability to contrive real-world examples over short duration programs that focus on NPD only.

Equally, the prototype KM support tool was derived from the KM framework based on Powertrain research only. A fully developed tool will also need accommodate the other automotive technology groups. The tool would also benefit from a more in depth evaluation exercise, with a much larger group of participants, to determine whether the proposed groupware is effective in enhancing the long term organisational capabilities to incorporate the outcomes of the CAPA process across a significant number of future DMAIC-R projects. This would then also inform the measurable success criteria regarding improvements in long term design integrity over the product lifecycle. It is envisaged that this would also require a significant longitudinal research study to first establish a suitable quantitative baseline for the current performance, and then comparatively measure the enhanced performance benefits derived from the groupware support tool.

Furthermore, the present research focused on the translating requirements of ISO/IEC 15288 Systems Engineering – System Lifecycle Processes (***ISO/IEC*** 2008) in the context of capturing new knowledge learned from reliability failures during vehicle operational service. Future work could therefore focus on the potential to extend the framework to incorporate ISO 26262 – Road Vehicles Functional Safety (***ISO*** 2011). This would be of particular interest to anyone wishing to adapt the research for electrical and electronic systems. Due to the highly sensitive nature of vehicle safety related failures this was consciously placed out of scope for this research thesis.

Finally, the prototype version of the ICT groupware tool could be fully developed as a major undertaking by any corporate IT department as it is entirely feasible that non-automotive industries could possibly also benefit from adopting the methodologies and concepts presented within this thesis.

REFERENCES

Adenfelt, M. and Lagerstrom, K. (2005) 'Enabling Knowledge Creation and Sharing in Transnational Projects', *International Journal of Project Management*, 24, 191-198.

Ahmad, R., Yuqing, F., Chaudhry, I. and Hamidullah (2005) 'Collaborative Product Development in Extended Enterprise', *9th International Multitopic Conference, IEEE INMIC 2005*, 1-6.

Alavi, M., Kayworth, T. R. and Leinder, D. (2006) 'An Empirical Examination of Organizational Culture on Knowledge Management Practices', *Journal of Management Information Systems*, 22(3), 191-224.

Amann, K. (2005) 'Product Data Management - The Foundation of PLM', [online], available: http://www.plmbok.com/cimdata_pdm.pdf [accessed 17/12/14].

An, X., Deng, H., Chao, L. and Bai, W. (2014) 'Knowledge Management in Supporting Collaborative Innovation Community Capacity Building', *Journal of Knowledge Management*, 18(3), 574-590, ISSN:1367-3270, DOI:10.1108/JKM-10-2013-0413.

Andriole, S. J. (2010) 'Business Impact of Web 2.0 Technologies', *Communications of the ACM*, 53(12), 67-79, DOI:10.1145/1859204.1859225.

Barnett, T. J. (2006) 'Knowledge Management Solutions and Selection Tool for Engineering Organisations', *PhD Thesis, Loughborough University, UK* [online], available: https://dspace.lboro.ac.uk/2134/7950 [accessed 19 Dec 2014].

Barnett, T. J., Harding, J. A. and Nurse, A. (2009) 'Design and Development of a Classification System for Knowledge Management Tools and Methods', *Proc. IMechE, Part B: Engineering Manufacture*, 224(2009), 981-993, DOI:10.1243/09544054JEM1582.

Basaruddin, S., Haron, H. and Noordin, S. A. (2013) 'Taxonomy Approach for Organizing Knowledge in Academic Institutions', *Journal of Organizational Knowledge Management*, 2013 (2013), 1-13, DOI:10.5171/2013.241646.

Baughey, K. (2011a) 'Functional and Logical Structures: A Systems Engineering Approach', *SAE International*, (2011-01-0517), DOI:104271/2011-01-0517.

Baughey, K. (2011b) 'Improving Program Management through Web Enabled PLM for All', *SAE International*, (2011-01-0520), DOI:10.4271/2011-01-0520.

Baxter, D. (2007) 'A Process-Based Approach to Engineering Design Knowledge Re-Use', *PhD Thesis, School of Applied Sciences,Cranfield University, UK* [Doctorate online], available: https://core.ac.uk/download/pdf/138452.pdf [accessed 22 Dec 2014].

Blessing, L. T. M. and Chakrabarti, A. (2009) *DRM, a Design Research Methodology*, Springer, DOI: 10.1007/978-1-84882-587-1, ISBN: 978-1-84882-586-4.

Blischke, W. R. and Murthy, D. N. P. (2000) *Reliability Modelling, Prediction, and Optimisation*, Wiley and Sons, ISBN:978-0-471-18450-8.

Bradfield, D. and Gao, J. X. (2007) 'Development of a Tool to Support the Dissemination of Information about Knowledge in Multilingual Product Development Teams', in *4th International Conference on Product Lifecycle Management*, Stezzano, Italy, 22 Dec 2014, Inderscience Enterprises, Available: http://gala.gre.ac.uk/id/eprint/2927 [accessed 22 Dec 2014].

Bradfield, D. and Gao, J. X. (2008) 'A Methodology to Facilitate Knowledge Sharing in the New Product Development Process', *International Journal of Production Research*, 45(7), 1489-1504, DOI:10.1080/00207540600942227.

Bradfield, D. J. (2007) 'A Prototype Method and Tool to Facilitate Knowledge Sharing in the New Product Development Process', *PhD Thesis, School of Applied Sciences, Cranfield University,UK* [Doctorate online], available: https://core.ac.uk/download/pdf/139840.pdf [accessed 22 Dec 2014].

Browning, T. R., Fricke, E. and Negele, H. (2006) 'Key Concepts in Modelling Product Development Processes', *Systems Engineering*, 9(2), 104-128.

Burney, A. (2008) *Inductive and Deductive Research Approach*, Pakistan: University of Karachi, [Online Lecture Presentation] Available: http://www.drburney.net, [accessed 15 Feb 2017]

Campean, I. F., Henshall, E. and Rutter, B. (2013) 'Systems Engineering Excellence Through Design: An Integrated Approach Based on Failure Mode Avoidance', *SAE International*, (2013-01-0595), 6(3), DOI:10.427/2013-01-0595.

Carter, C. (2005) 'Preparing for the Exodus - Knowledge Management White Paper', [Online] www.changeexcellence.com/white_papers/km_white_paper.pdf [accessed 10-May-2014].

CEN (2004a) *European Guide to good Practice in Knowledge Management - Part 1: Knowledge Management Framework*, Management Centre: Rue de Stassart, 36B-1050 Brussels ftp://cenftp1.cenorm.be/PUBLIC/CWAs/e-Europe/KM/CWA14924-01-2004-Mar.pdf [accessed 10-May-2014].

CEN (2004b) *European Guide to good Practice in Knowledge Management - Part 2: Organizational Culture*, Management Centre: Rue de Strassart, 36 B-1050 Brussels: ftp://cenftp1.cenorm.be/PUBLIC/CWAs/e-Europe/KM/CWA14924-02-2004-Mar.pdf [accessed 10-May-2014].

CEN (2004c) *European Guide to good Practice in Knowledge Management: Part 3: SME Implementation*, Management Centre: Rue de Stassart, 36B-1050 Brussels: ftp://cenftp1.cenorm.be/PUBLIC/CWAs/e-Europe/KM/CWA14924-03-2004-Mar.pdf [accessed 10-May-2014].

Chang, A., Hatcher, C. and Kim, J. (2012) 'Temporal boundary objects in Megaprojects: Mapping the System with the Integrated Master Schedule', *International Journal of Project Management*, 31(2013), 323-332.

Clark, K. B. and Fujimoto, T. (1991) *Product Development Performance; Strategy, Organization and Management in the World Auto Industry*, Boston, Massachusetts: Harvard Business School Press, ISBN: 0-87584-245-3.

Clausing, D. P. (2004) 'Operating Window: An Engineering Measure for Robustness', *Technometrics*, 46(1), 25–29.

Cooper, R. (2008) 'The Stage-Gate Idea-to-Launch Process Update, What's New and NexGen Systems', *Journal of Product Innovation Management*, 25(3), 213-232.

Creswell, J. W. (1994) *Research Design - Qualitative and Quantitative Approaches*, Thousand Oaks, California: Sage Publications, ISBN: 0-8039-5255-4.

Creswell, J. W. (1998) *Qualitative Inquiry and Research Design - Choosing Among the Five Traditions*, Thousand Oaks, California: Sage Publications, ISBN: 0-7619-0144-2.

Creswell, J. W. (2003) *Research Design - Qualitative, Quantitative, and Mixed Methods Approaches*, Thousand Oaks, California: Sage Publications, ISBN: 0-7619-2442-6.

Cross, M. S. and Sivaloganathan, S. (2007) 'Specialist Knowledge Identification, Classification and Usage in Company Specific New Product Development Processes', *Proc. IMechE*, (221) Part B: J. Engineering Manufacture, 1285-1298, DOI:10.1243/09544054JEM580.

Cusumano, M. A. and Takeshi, A. (1991) 'Supplier Relations and Management: A Survey of Japanese, Japanese-Transplant, and U.S. Auto plants', [online], available: https://dspace.mit.edu/bitstream/handle/1721.1/2339/SWP-3256-23328932.pdf [accessed 15-Feb-2017].

da Silva, S. L. and Rozenfeld, H. (2007) 'Model for Mapping Knowledge Management in Product Development: A Case Study at a Truck and Bus Manufacturer', *International Journal of Automotive Technology and Management*, 7(2), 216-234.

Danilovic, M. and Browning, T. R. (2006) 'Managing Complex Product Development Projects with Design Structure Matrices and Domain Mapping Matrices', *International Journal of Product Management*, 25(2007), 300-314.

Davis, F. D. (1989) 'Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology', *MIS Quarterly*, 13(3), 319-339.

Davis, T. (2004) 'Science, Engineering and Statistics', [online], available: https://www.researchgate.net/publication/275274375_Science_engineering_and_Statistics [accessed 05-Jan-2017].

Demidova, E., Fankhauser, P., Zhou, X. and Nejdl, W. (2010) '*DivQ*: Diversification for Keyword Search over Structured DatabasesDivQ: Diversification for Keyword Search over Structured Databases', in SIGIR, ed., *The 33rd international ACM SIGIR conference on Research and development in information retrieval*, Geneva, Switzerland.

DoD (2005) 'Integrated Masterplan and Integrated Master Schedule Preparation and Use Guide', *Department of Defense, USA* [online], available: http://www.acq.osd.mil/se/docs/IMP_IMS_Guide_v9.pdf [accessed 16-Feb-2017].

Doz, Y. L. and Hamel, G. (1998) *Alliance Advantage. The Art of Creating Value through Partnering*, Boston, Massachusetts, USA, ISBN: 0-87584-616-5 , Harvard Business School Press.

Drucker, P. (1988) "The Coming of the New Organization", *Harvard Business Review*, 66(1), 45-53.

du Plessis, M. (2005) 'Drivers for Knowledge Management in the Corporate Environment', *Int. J. of Information Management*, 25(2005), 193-202, DOI:10.1016/J.IJINFOMGT.200412.001.

du Plessis, M. (2007) 'The Role of Knowledge Management in Innovation', *Journal of Knowledge Management*, 11(4), 20-29.

Durst, S. and Edvardsson, I. R. (2012) 'Knowledge Management in SME's: A Literature Review', *Journal of Knowledge Management*, 16(6), 879-903.

EMC (2006) *A guide to Evaluating Enterprise Content Management Software* [online], available: http://www.aiim.org.uk/publications/ecm_at_work/pdfs/ecm_evaluation_guide.pdf [accessed 19-Dec-2014].

Eppinger, S. and Salminen, V. (2001) 'Patterns of Product Development Interactions', *International Conference on Engineering Design* [online], available: dspace.mit.edu/bitstream/handle/1721.1/4036/IMS1015.pdf?sequence=2 [accessed 16-Feb-2017].

Erbiyik, H. and Saru, M. (2015) 'Six Sigma Implementation in Supply Chain: An Application for an Automotive Subsidiary Industry in Bursa in Turkey.', *Procedia - Social and Behavioural Sciences*, 195(2556-2565).

Erdogan, A. and Canatan, H. (2015) 'Literature Search Consisting of the Areas of Six Sigma's Usage', *Procedia - Social and Behavioural Sciences*, 195(2015), 695-704.

Euler-Hermes (2014) 'The Global Automotive Market', [online], available: http://www.eulerhermes.com/mediacenter/Lists/mediacenter-documents/Economic-Outlook-The-global-Automotive-market-Sept14.pdf. [accessed 12/06/2016].

Evans, R., Gao, J., Woodhead, S., Martin, N. and Simmonds, C. (2012) 'An investigation into Collaboration and Knowledge Management during Product Development in the Aerospace and Defence Industry', in *10th International Conference on Manufacturing Research (ICMR)*, Aston Business School, Birmingham, UK, ISBN: 9781905866601.

Evans, R. D. (2013) 'A Semantic Web-Based Interactive Groupware to Facilitate Collaboration in Dispersed Product Development Teams', *PhD Thesis, Faculty of Engineering and Science, University of Greenwich, UK.*

Filieri, R. and Alguezaui, S. (2012) 'Extending the Enterprise for Improved Innovation', *Journal of Business Strategy*, 33(3), 40-47.

Fluid-Surveys (2015) 'Calculating the Right Survey Sample Size', [online], available: http://fluidsurveys.com/university/calculating-right-survey-sample-size/ [accessed 5th May 2015].

Ford (2004) 'Failure Modes and Effects Analysis; FMEA Handbook', *Version 4.1, Ford Motor Company* [Handbook online], available: cfile205.uf.daum.net/attach/170321414F3C726E2EFA29 [accessed 14-Feb-2017].

Ford (2015) 'Ford Sustainability Report', [online], available: http://corporate.ford.com/microsites/sustainability-report-2015-16/doc/sr15.pdf [accessed 29-Dec-16].

Ford (2016) 'Ford Targets Fully Autonomous Vehicle for Ride Sharing in 2021', [online], available: https://media.ford.com/content/fordmedia/fna/us/en/news/2016/08/16/ford-targets-fully-autonomous-vehicle-for-ride-sharing-in-2021.html [accessed 29-Oct-2016].

Fowler, D. (2008) 'Implementing Enterprise Content Management Using Microsoft Sharepoint', *School of Applied Information Management, University of Oregon, Portland, Oregon, USA* [MSc Dissertation online], available: ce.uoregon.edu/aim/Write08/Fowler2008.pdf [accessed 14-Feb-2017].

Fritzsche, R. (2006) 'Using Parameter-Diagrams in Automotive Engineering; Application Criteria, Guidelines and Best Practice', *ATZ*, 108(2006), 17-21, DOI:10.1007/BF03224834.

Gantz, J. and Reinsel, D. (2010) 'The Digital Universe Decade - Are You Ready?', [online], available: http://www.emc.com/collateral/analyst-reports/idc-digital-universe-are-you-ready.pdf [accessed Feb 2015].

Gausemeier, J., Gaukstern, T. and Tschirner, C. (2013) 'Systems Engineering Management Based on Discipline-Spanning System Model', in Paredis, C. J. J., Bishop, C. and Bodner, D., eds., *Conference on Systems Engineering Research (CSER '13)*, GIT Atlanta, GA, USA, Procedia Computer Science, 16(2013), 303-312, DOI:10.1016/J.PROCS.2013.01.032.

Glaser, B. and Strauss, A. (1967) 'The Discovery of Grounded Theory', [Book online], available: www.sxf.uevora.pt/wp-content/uploads/2013/03/Glaser_1967.pdf [accessed 14-Feb-2017].

Global-Graphics (2014) 'Knowledge Management', [online], available: http://www.globalgraphics.com/technology/knowledge-management/ [accessed 19-Dec-2016].

Gonzalez, R. V. D. and Martins, M. F. (2014) 'Mapping the Organizational Factors that Support Knowledge Management in the Brazilian Automotive Industry', *Journal of Knowledge Management*, 18(1), 152-176.

Grant, R. M. (1996) 'Toward a Knowledge-Based Theory of the Firm', *Strategic Management Journal*, 17, 109-122.

Grundstein, M. (2005) 'MGKME: A Model for Global Knowledge Management within the Enterprise', [online], available: http://michel.grundstein.pagesperso-orange.fr/News/grundstein%20KGCM07D.pdf [accessed 14/07/15], 1-10.

Hasan, S. M. (2013) 'A Collaborative Framework for Feasibility Analysis in Automotive Product Development with Global Supply Chain', *PhD Thesis, Faculty of Engineering and Science, University of Greenwich, UK*.

Hazlett, S. A., McAdam, R. and Gallagher, S. (2005) 'Theory Building in Knowledge Management: In Search of Paradigms', *Journal of Management Inquiry*, 14(1), 31-42.

Heisig, P. (2009) 'Harmonization of Knowledge Management - Comparing 160 KM Frameworks Around the Globe', *Journal of Knowledge Management*, 13(4), 04-31, ISSN:1367-3270, DOI:10.1108/13673270910971798.

Henshall, E. and Campean, F. (2009) 'Implementing Failure Mode Avoidance', *SAE International, ISSN 0148-7191*, (2009-01-0990), DOI:10.4271/2009-01-0990.

Henshall, E., Campean, I. F. and Rutter, B. (2014) 'A Systems Approach to the Development and Use of FMEA in Complex Automotive Applications', *SAE Int. J. Mat. Manf.*, 7(2): 280-290, DOI:2014-01-0740.

Henshall, E., Rutter, B. and Souch, D. (2015) 'Extending the Role of Interface Analysis within a Systems Engineering Approach to the Design of Robust and Reliable Automotive Product', *SAE Int. J. Mat. Manf.*, 8(2): 322-335, DOI:2015-01-0456.

Heyes, A. M. (1998) 'Automotive Component Failures', *Engineering Failure Analysis*, 5(2), 129-141.

Honda, A. (2011) 'Designing and Design Reviewing for Preventing Quality Problems in Automotive Parts', *SAE International*, 2011-01-0081.

INCOSE (2011) 'Systems Engineering Handbook - A Guide for System Lifecycle Processes and Activities v.3.2.2', *INCOSE-TP-2003-002-03-2.2* [Handbook online], available: http://disi.unal.edu.co/dacursci/sistemasycomputacion/docs/SystemsEng/SEHandbookv3_2006.pdf [accessed 14-Feb-2017].

Irani, Z., Sharif, A. M. and Love, P. E. D. (2009) 'Mapping Knowledge Management and Organizational Learning in Support of Organizational Memory', *Int. J. Production Economics*, 122 (2009), 200-215, DOI:10.1016/J.IJPE.2009.05.020.

ISO (2009) 'ISO/TS 16949:2008 (Technical Specification) - Quality Management Systems', *Particular requirements for the application of ISO 9001:2008 for automotive production and relevant service part organisations* [ISO Standard online], available: https://www.iso.org/standard/52844.html [accessed 14-Feb-2017].

ISO (2011) 'ISO 26262-1: Road vehicles - Functional safety', [ISO Standard online], available: https://www.iso.org/standard/43464.html [accessed 14-Feb-2017].

ISO (2015) 'ISO 9001: Quality Management Systems - Requirements', [ISO Standard online], available: https://www.iso.org/standard/62085.html [accessed 14-Feb-2017].

ISO/IEC (2008) 'ISO/IEC 15288:2008 Systems Engineering - System Life Cycle Processes', [ISO Standard online], available: https://www.iso.org/standard/63711.html [accessed 14-Feb-2017].

Jabareen, Y. (2009) 'Building a Conceptual Framework: Philosophy, Definitions and Procedure', *International Journal of Qualitative Methods*, 8(4), 49-62.

Jennex, M. E. and Addo, T. B. A. (2005) 'Issues in Knowledge Management Strategy', *Information Resource Management Conference, Idea Group Publishing* [Conference Paper online], available: http://www.irma-international.org/viewtitle/32656/ [accessed 14-Feb-2017].

Johnsen, T. E. (2009) 'Supplier Involvement in New Product Development and Innovation: Taking Stock and Looking to the Future', *Journal of Purchasing and Supply Management*, 15(2009), 187-197.

Karlsson, C., Johansson, B. and Norman, T. (2011) 'Innovation, Technology and Knowledge', *CESIS Electronic Working Paper Series* [online], available: http://www.cesis.se [accessed Feb 2015].

Knowledge-Management-Online (2014) *'What is Knowledge Management?'* [online], available: http://www.knowledge-management-online.com/what-is-Knowledge-Management.html [accessed 10-May-2014].

Lakshman, C. (2007) 'Organisational Knowledge Leadership: A Grounded Theory Approach', *Leadership and Organisational Development Journal*, 28(1), 51-75, DOI:10.1108/01437730710718245.

Liviero, F. and Kaminski, P. C. (2009) 'Managing Transnational Product Development Teams', *Product: Management & Development*, 7(1), 3-15.

Louw, R. and Mtsweni, J. (2013) 'Guiding principles for adopting and promoting the use of Enterprise 2.0 collaboration technologies within the enterprise environment', [MSc Thesis online], available: http://uir.unisa.ac.za/bitstream/handle/10500/14319/dissertation_louw_rl.pdf [accessed 14-Feb-2017], DOI: 978-1-4799-3067-8/13

Lytras, M. D. and Pouloudi, A. (2006) 'Towards the Development of a Novel Taxonomy of Knowledge Management Systems from a Learning Perspective: An Integrated Approach to Learning and Knowledge Infrastructures', *Journal of Knowledge Management*, 10(6), 64-80.

MaaS_Alliance (2015) 'The MaaS Alliance - Building an open market in seamless, demand-based travel', [online], available: http://maas-alliance.eu/ [accessed 29-Dec-2016].

Maier, R. (2007) *Knowledge Management Systems: Information and Communication Technologies for Knowledge Management*, 3rd ed., Springer, ISBN: 978-3-540-71407-1.

Marxen, L. and Albers, A. (2012) 'Supporting Validation in the Development of Design Methods', *International Design Conference - Design 2012, Dubrovnik - Croatia. 1009 - 1018.* [Conference Proceedings online], available: https://www.designsociety.org/publication/32069/supporting_validation_in_the_development_of_design_methods [accessed 14-Feb-2017].

McKendrick, J. (2011) 'The Post-Relational Reality Sets In: 2011 Survey on Unstructured Data', *Information Today Inc.* [Report online], available: http://www.ciosummits.com/media/pdf/solution_spotlight/marklogic_2011-survey.pdf [accessed 28-Nov-2014].

McKinsey (2015) 'The Road to 2020 and Beyond: What's Driving the Global Automotive Industry?', [Report online], available: http://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-road-to-2020-and-beyond-whats-driving-the-global- [accessed 14-Feb-2017].

McMurran, R. (2014) 'Design for Robustness of Complex Automotive Electronic Systems', *Phd Thesis, School of Engineering, University of Warwick, UK.* [Doctorate online], available: http://wrap.warwick.ac.uk/65186/ [accessed 16-Feb-2017].

Menzies, T., Althoff, K.-D., Kalfoglu, Y. and Motta, E. (2000) 'Issues with Meta-Knowledge', *International Journal of Software Engineering and Knowledge Engineering*, 10(4), 549-555.

Ming, X., Yan, J., Wang, X., Li, S., Lu, W., Peng, Q. and Ma, Y. (2008) 'Collaborative Process Planning and Manufacturing in Product Lifecycle Management', *Computers in Industry*, 59, 154-166.

Monczka, R. M., Handfield, R. B., Scannell, T. V., Ragatz, G. L. and Frayer, D. J. (2000) *New Product Development - Strategies for Supplier Integration*, Milwaukee, Wisconsin, USA: ASQ, ISBN:0873894685.

Morgan, J. M. and Liker, J. K. (2006) *The Toyota Product Development System; Integrating People, Process, and Technology*, New York: Productivity Press, ISBN:1563272822.

Motoring-Research (2016) 'UK's Most Dependable Cars 2016', [online], available: https://www.motoringresearch.com/advice/buying-selling/j-d-power-reveals-dependable-cars-2016 [accessed 07-Dec-2016].

Murman, E. M. (2002) *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative*, Palgrave MacMillan, ISBN:0333976975.

Murphy, J. (2009) 'The US Automotive Product Pipeline; Car Wars 2010 - 2013', [Report online], available: www.autonews.com/assets/PDF/CA66116716.PDF [accessed 17-Feb-2017].

Nonaka, I. and Takeuchi, H. (1995) *The Knowledge-Creating Company*, Oxford University: Oxford Press, ISBN:0195092694.

Odogwu, A. H. A. (2002) 'World-class Project Management', *Phd Thesis, School of Management and School of Engineering, University of Bradford, UK.* [Doctorate online], available: http://catalogue.brad.ac.uk/record=b1013950 [accessed 17-Feb-2017].

OECD (2015) 'Frascati Manual - Proposed Standard Practice for Surveys on Research and Experimental Development', *Organisation for Economic Co-operation and Development, ISBN 978-92-64-19903-9.* [Book online], available: http://oe.cd/frascati [accessed 17-Feb-2017].

Oh, J. and Rhee, S.-K. (2010) 'Influences of Supplier Capabilities and Collaboration in New Car Development on Competitive Advantage of Carmakers', *J. of Management Decision*, 48(5), 756-774.

Oppat, K. (2008) 'Disseminative Capabilities - The Impact of Sender Capabilities on Knowledge Transfer Success; A Case of Collaborative Development in the Auto Industry', *PhD Thesis, University of St. Gallen, France.* [Doctorate online], available: https://link.springer.com/book/10.1007%2F978-3-8349-8116-5 [accessed 17-Feb-2017].

Oppenheim, B. W. (2011) *Lean for Systems Engineering with Lean Enablers for Systems Engineering*, INCOSE-PMI-MIT LAI, ISBN:1118063988.

Pahl, G., Beitz, W., Feldhausen, J. and Grote, K. H. (2007) *Engineering Design: A Systematic Approach*, Springer, ISBN:1846283183.

Paroutis, S. and Saleh, A. A. (2009) 'Determinants of Knowledge Sharing Using Web 2.0 Technologies', *Journal of Knowledge Management*, 13(4), 52-63, ISSN:1367-3270, DOI:10.1108/13673270910971824.

Pawlowski, J. and Bick, M. (2012) 'The Global Knowledge Management Framework: Towards a Theory for Knowledge Management in Globally Distributed Settings', *The Electronic Journal of Knowledge Management*, 10(1), 92-108.

Pero, M., Abdelkafi, N., Sianesi, A. and Blecker, T. (2010) 'A Framework for the Alignment of New Product Development and Supply Chains', *Supply Chain Management: An International Journal*, 15(2), 115-128.

Petersen, K. J., Handfield, R. B. and Ragatz, G. L. (2005) 'Supplier integration into new product development: coordinating product, process and supply chain design', *Journal of Operations Management*, 23(3–4), 371-388.

Pirkkalainen, H. and Pawlowski, J. (2013) 'Global Social Knowledge Management: From Barriers to the Selection of Tools', *The Electronic Journal of Knowledge Management*, 11(1), 03-17.

Pitt, M. and MacVaugh, J. (2008) 'Knowledge Management for New Product Development', *Journal of Knowledge Management*, 12(4), 101-116, ISSN:1376-3270, DOI: 10.1108/13673270810884282.

Power, J. D. (2016) '2016 Dependability Ratings and Awards', [online], available: http://www.jdpower.com/cars/awards/Vehicle-Dependability-Study-(VDS)-by-Category/843ENG [accessed 07-Dec-16].

Pryce-Jones, J. (2013) 'Gen Y workers represent a 'ticking time-bomb of potential cost and disruption' to employers', [Magazine Article online], available: http://www.hrmagazine.co.uk/article-details/gen-y-workers-represent-a-ticking-time-bomb-of-potential-cost-and-disruption-to-employers [accessed 17-Feb-2017].

Pugna, A., Negrea, R. and Miclea, S. (2016) 'Using Six Sigma Methodology to Improve the Assembly Process in an Automotive Company', *Procedia - Social and Behavioural Sciences*, 221(2016), 308-316.

Pyster, A., Olwell, D., Hutchison, N., Enck, S., Anthony, J., Henry, D. and Squires, A. (2017) 'Guide to Systems Engineering Body of Knowledge (SEBoK) version 1.8.', [Edited Book online], available: sebokwiki.org/wiki/Download_SEBoK_PDF [accessed 17-Feb-2017].

Quality-One. 'EIght Disciplines of Problem Solving (8D)', [online], available: http://quality-one.com/8d/ [accessed 28-Feb-2017].

Ragatz, G. L., Handfield, R. B. and Scannell, T. V. (1997) 'Success Factors for Integrating Suppliers into New Product Development', *Journal of Product and Innovation Management*, 14(3), 190-202.

Ramesh, B. and Tiwana, A. (1999) 'Supporting Collaborative Process Knowledge Management in New Product Development Teams', *Decision Support Systems*, 27(1999), 213-235.

Robson, C. (2002) *Real World Research: A Resource for Social Scientists and Practitioner Researchers*, 2nd Edition ed., Blackwell Publishing, ASIN: B00I63V9B2.

Rosell, D. T. and Lakemond, N. (2012) 'Collaborative Innovation with Suppliers - A Conceptual Model for Characterizing Supplier Contributions to NPD', *International Journal of Technology Intelligence and Planning*, 8(2), 197-214.

Rozenfeld, H. (2006) 'Gestao do Desenvolvimento de Produtos - Uma Referencia Para a Melhoria do Processo', [Presentation online], available: www.producao.ufrgs.br/.../080331_Workshop_Rozenfeld.pdf [accessed 17-Feb-2017].

Rusu, O., Halcu, I., Grigoriu, O., Sandulescu, V., Marinescu, M. and Marinescu, V. (2013) 'Converting Unstructured and Semi Structured Data into Knowledge', *11th Roedunet International Conference (RoEduNet), Iasi, Romania*.

Sahno, J. and Shevtenko, E. (2014) 'Quality Improvement Methodologies for Continuous Improvement of Production Processes and Product Quality and their Evolution', *9th International DAAAM Conference on Industrial Engineering,* Estonia 2014, [Conference Proceedings online], available: https://pdfs.semanticscholar.org/e96b/6b7d86b3869e64521a4dbe324f861e02af26.pdf [accessed 28-Feb-2017].

Saunders, M., Lewis, P. and Thornhill, A. (2002) *Research Methods for Business Students*, 3rd ed., FT Prentice Hall, ISBN:0273716867.

Saxena, A., Davis, T. P. and Jones, J. A. (2015) 'A Failure Mode Avoidance Approach to Reliability', 2015 Annual Reliability and Maintainability Symposium, *IEEE*, (978-1-4799-6703-2/15), DOI:10.1109/RAMS.2015.7105062.

Schaeffer, A., Kamargianni, M., Matyas, M. and Li, W. (2015) *Feasibility Study for 'Mobility as a Service' concept in London (TfL)*, London: UCL Energy Institutehttps://www.bartlett.ucl.ac.uk/energy/docs/fs-maas-compress-final [accessed 29/12/2016].

Schwandt, T. A. (1994) 'Constructivist, interpretivist approaches to human inquiry', *Handbook of Qualitative Research* [Book online], available: https://www.researchgate.net/profile/Thomas_Schwandt/publication/232477264_Constructivist_Interpretivist_Approaches_to_Human_Inquiry/links/557048d908aeab777228bfef/Constructivist-Interpretivist-Approaches-to-Human-Inquiry.pdf [accessed 17-Feb-2017].

Sharon, A. and Dori, D. (2014) 'A Project -Product Model-based Approach to Planning Work Breakdown Structures of Complex Systems Projects', *IEEE Systems Journal* [Journal Paper online], available: http://ieeexplore.ieee.org/document/6748857/ [accessed 17-Feb-2017].

Soderquist, K. E. D. (1997) 'Inside the Tier Model: Product Development Organization and Strategies in Automotive Expert Supplier Firms', *PhD Thesis, Henley Management College, Brunel University, UK.* [Doctor of Business Administration online], available: http://www.academia.edu/31131686/Inside_the_tier_model_product_development_organization_and_strategies_in_automotive_supplier_firms [accessed 17-Feb-2017].

Stonehouse, G., Hamill, J., Campbell, D. and Purdie, T. (2001) *Global and Transnational Business - Strategy and Management*, John Wiley and Sons Ltd., ISBN:0470851260.

Svensson, D. and Malmqvist, J. (2000) 'Strategies for Product Structure Management in Manufacturing Firms', in ASME, ed., *Proceedings of the 2000 ASME Design Engineering Technical Conferences*, Baltimore, Maryland, USA.

Tavakolikhou, M. (2013) 'A Knowledge Sharing Framework to Support Rapid Prototyping in Collaborative Automotive Supply Chain', *PhD Thesis. Faculty of Engineering and Science, University of Greenwich, UK.* [Doctorate online], available: http://gala.gre.ac.uk/id/eprint/10213 [accessed 14-Feb-2017].

Tumer, I. Y., Stone, D. G. and Bell, D. G. (2003) 'Requirements for a Failure Mode Taxonomy for Use in Conceptual Design', *ICED '03, the 14th International Conference on Engineering Design* [Conference Proceedings online], available: https://www.designsociety.org/publication/24135/requirements_for_a_failure_mode_taxonomy_for_use_in_conceptual_design [accessed 17-Feb-2017].

Uder, S. J., Stone, R. B. and Tumer, I. Y. (2003) 'Failure Analysis in Sub System Design for Space Missions', *Design Theory and Methodology, ASME Design Engineering Technical Conferences,* [Conference online], available: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1651492 [accessed 17-Feb-2017].

van Echtelt, F. E. A., Wynstra, F., van Weele, A. J. and Duysters, G. (2008) 'Managing Supplier Involvement in New Product Development: A Multiple Case Study', *The Journal of Product Innovation Management*, 25, 180 - 201.

van-Echtelt, F. (2004) 'New Product Development: Shifting Suppliers into Gear', *PhD Thesis, Technische Universiteit Eindhoven, Netherlands.* [Doctorate online], available: https://pure.tue.nl/ws/files/2293783/200410455.pdf [accessed 17-Feb-2017].

Wasti, S. N. and Liker, J. K. (1999) 'Collaborating with suppliers in product development: a US and Japan comparative study', *Engineering Management, IEEE Transactions on*, 46(4), 444-460.

Wynstra, F., van Weele, A. and Weggemann, M. (2001) 'Managing supplier involvement in product development: Three critical issues', *European Management Journal*, 19(2), 157-167.

Wynstra, F., von Corswant, F. and Wetzels, M. (2010) 'In Chains? An Emperical Study of Antecedents of Supplier Product Development Activity in the Automotive Industry', *Journal of Product Innovation Management*, 27(5), 625 - 639.

Yahia, N. B., Bellamine, N. and Ghezala, H. B. (2010) *On the Convergence of Collaboration and Knowledge Management* [Paper] available: https://arxiv.org/ftp/arxiv/papers/1202/1202.6104.pdf [accessed 17-Feb-2017]

Yin, R. K. (2013) *Case Study Research - Design and Methods (Applied Social Research Methods)*, 5th ed., Sage Publications Ltd., ISBN:1452242569.

Zahay, D., Griffin, A. and Fredericks, E. (2004) 'Sources, Uses and Forms of Data in the New Product Development Process', *Industrial Marketing Management*, 33(2004), 657-666, DOI:10.1016J.INDMARMAN.2003.10.002.

Zedtwitz, M. v., Gassmann, O. and Boutellier, R. (2004) 'Organizing Global R&D: Challenges and Dilemmas', *Journal of International Management*, 10(2004), 21-49.

Zhang, P. (2011) 'Requirement Driven Knowledge Management System Design to Support Automotive Product Development', *PhD Thesis, Dept of Engineering and Science, University of Greenwich, UK.* [Doctorate online], available: http://gala.gre.ac.uk/7661/ [accessed 17-Feb-2017].

Zhang, Q., Caillaud, E., Deniaud, I. and Baron, C. (2012) 'Modelling Innovative Design Using Systems Engineering', in *9th International Conference of Modeling, Optimization and Simulation - MOSIM '12*, Bordeaux, France, 68-78.

APPENDICES

Appendix A - Methodologies Advanced in Selected Prior Research

The below table provides and overview of the methodologies employed in prior PhD theses relevant to this research.

Author	Purpose	Approach	Strategy	Methods	Data collection	Research Domain
Soderquist (1997)	Exploratory, Descriptive	Inductive	Case study /Industrial Investigation (Multiple)	Qualitative	Interviews, Observation and Document Review	Auto Supplier PD Strategies and Organisation
van-Echtelt (2004)	Exploratory	Inductive	Multiple Case Study / Cross Case Analysis	Qualitative and Quantitative	Interview and Survey Questionnaire	Supplier Collaboration in PD
Barnett (2006)	Exploratory, Explanatory	Inductive	Grounded Theory	Qualitative and Quantitative	Review of literature and existing tool solutions	Method for KM Tool selection
Baxter (2007)	Exploratory	Inductive	Case study /Industrial Investigation (Single)	Qualitative	Interviews, observation and Document review	Design Knowledge Re-use in vacuum pump PD
Bradfield (2007)	Exploratory	Inductive	Case study /Industrial Investigation (Single)	Qualitative	Interviews, observation and Document review	Barriers to Knowledge Sharing in Domestic Heating PD
Oppat (2008)	Exploratory, Explanatory	Inductive	Multiple Case study //Industrial Investigation	Qualitative	Interviews and Document Review	Knowledge Transfer success in collaborative Auto PD
Zhang (2011)	Descriptive, Exploratory	Inductive	Case study /Industrial Investigation (Single)	Qualitative Quantitative	Interviews, observation, Document review	Requirements driven KM for Auto PD
Hasan (2013)	Exploratory	Inductive	Case study /Industrial Investigation (Single)	Qualitative	Interviews, Observation, Document Review	Feasibility Analysis in Auto PD
Tavakolikh ou (2013)	Exploratory	Inductive	Case study /Industrial Investigation (Single)	Qualitative & Quantitative	Interviews, observation and Document review	KM for Rapid Prototype in Auto PD
Evans (2013)	Exploratory	Inductive	Case study / Survey / /Industrial Investigation (Single)	Qualitative & Quantitative	Interviews, observation and Document review	Semantic Web 2.0 for collaboration in Aerospace and defence Industry

Table 30. Summary of Methodologies Advanced in Selected Prior Research

Appendix B - Ford Sustainability: Prioritisation of Innovation Drivers

Ford Motor Company critical factors towards sustaining a viable long term global business.

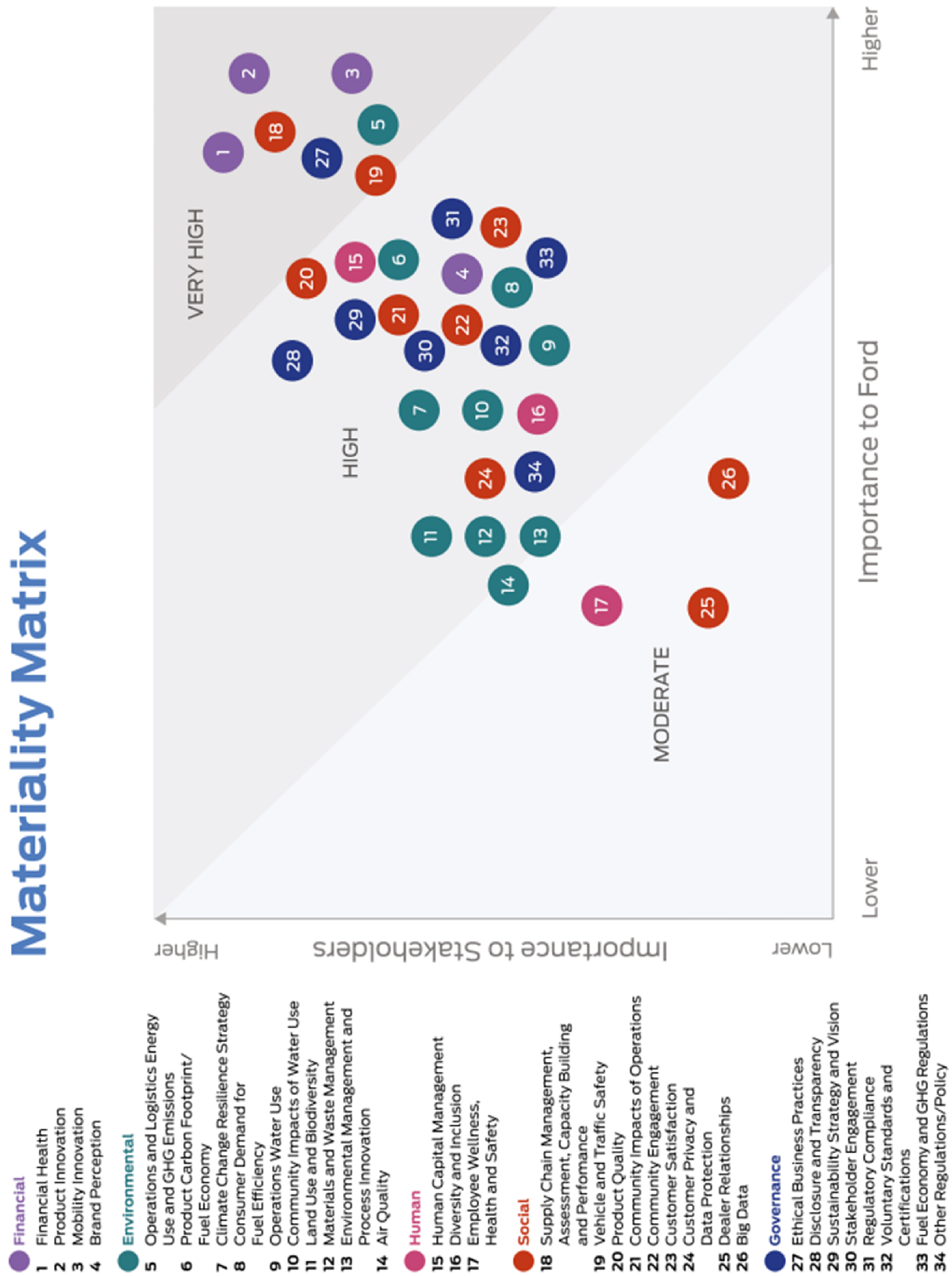


Figure 71. Ford Motor Company - Materiality Matrix (Ford 2015)

Appendix C - Semi Structured Interview Outline: Internal OEM teams

The following table represents the outline questions used to guide the semi structured interviews conducted with *employees of Ford Motor Company* as discussed in stage 3 of the exploratory industrial investigation (section 4.6)

Semi Structured Interview Outline: Internal OEM teams
Profile and Overview of the *OEM PD Commodity Engineering team*
- What are the major products / group of commodity technologies managed by your dept./team?
- Who are the Major Suppliers that you deal with, in each region, for each of the major platforms? (GCBP profile)
- What is the OEM PD team organisational structure - Locations of Global PD offices / regional sites, Core / Application teams etc. (Incl. history of team restructuring as part of globalization)
- Number of concurrent programs being managed at any point in time
The Effect of Globalisation of the Automotive Industry
- What have been the most noticeable changes caused by globalisation of the auto industry over the last 5 – 10 years?
- What are the great challenges and frustrations that have been encountered as a result? What have been the key impacts on conducting day-to-day business?
- What do you believe are the major risks and consequences to the business?
Knowledge created during the Product Development Process
• What general complications that have arisen in the management of global programs, in terms of;
a) Communication (volume of emails/ frequency of meetings/audio and conference calls etc.)
b) Exchange of information to enable robust on time decisions to support the PD deliverables at each gateway/milestone?
- How and where do you generally store <u>informal</u> PD technical and program files?
- What types of structure do you use for your PD archival records management?
- How and where do you generally store <u>formal</u> PD technical and program files?
- How do you typically share files created during the PD Process?
- Do you believe there is sufficiently adequate knowledge management?
- If KM is inadequate, what are the greatest impacts on the business?
- How might any inadequacies be addressed?
- Which formal corporate Content Management Systems do you regularly use and what is your perception of each towards knowledge Management?

Table 31. Semi-Structured Interview Outline Questionnaire – OEM PD

Appendix D - Semi Structured Interview Outline: External Suppliers

The following table represents the outline questions used to guide the semi structured interviews conducted with *Suppliers of Ford Motor Company* as discussed in stage 3 of the exploratory industrial investigation (section 4.6)

Semi Structured Interview Outline: External Suppliers
Profile and Overview of the Supplier Operations
- Major products produced (Group of Technologies)
- Global Facilities for Manufacturing – Regions / Countries (Incl. history of restructuring)
- Manufacturing Volumes, Turnover and Employees
- Major Customers (Other than Ford)
- Global sites for PD and Manufacturing
- Supplier PD team organisational structure and interface to OEM customers (Incl. history of restructuring as part of globalisation)
The effect of Globalisation of the Automotive Supplier Industry
- What effect has globalisation had on complications of day-to-day business?
- Noticeable changes experienced over the last 5 – 10 years?
- What do you believe are the major risks and consequences to the business?
Knowledge created during the Product Development Process
- Does your company have a single PD Process that is rigorously applied globally throughout all operations?
- How is the PD Process cascaded internally to all divisions in terms of training for all appropriate employees?
- How is the PD Process administered in terms of day to day management of inputs/outputs and tracking of program deliverables?
- How and where do you store informal PD technical and program files?
- What types of structure do you use for your PD archival records management?
- How and where do you generally store formal PD technical and program files?
- How do you typically share files created during the PD Process?
- Do you believe there is sufficiently adequate knowledge management?
- If KM is inadequate, what are the greatest impacts on the business?
- How might any inadequacies be addressed?
- What ICT infrastructure and/or software packages are used to support information exchange and data transfer with Ford as your customer?

Table 32. Semi-Structured Interview Outline Questionnaire – Supplier PD

Appendix E - Review of PD Engineering Document Archives

The following screenshots detail various PD engineer archival records (section 4.7.1).

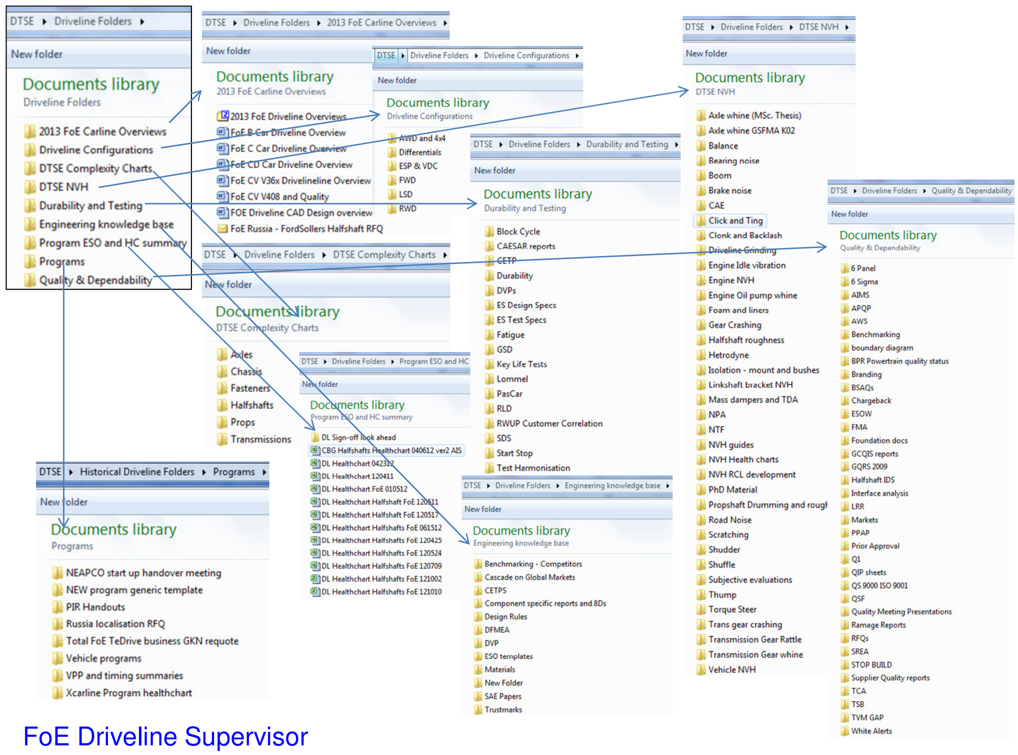


Figure 72. FoE Driveline Supervisor – Annotated Document Library

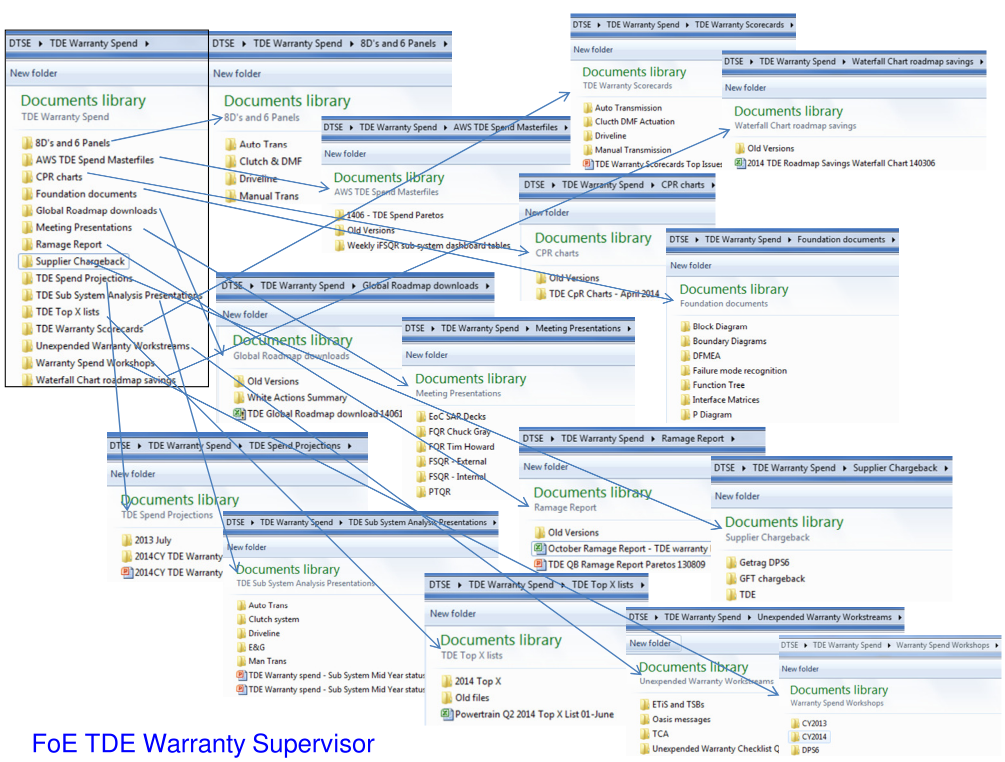


Figure 73. FoE TDE Warranty Supervisor - Document Library

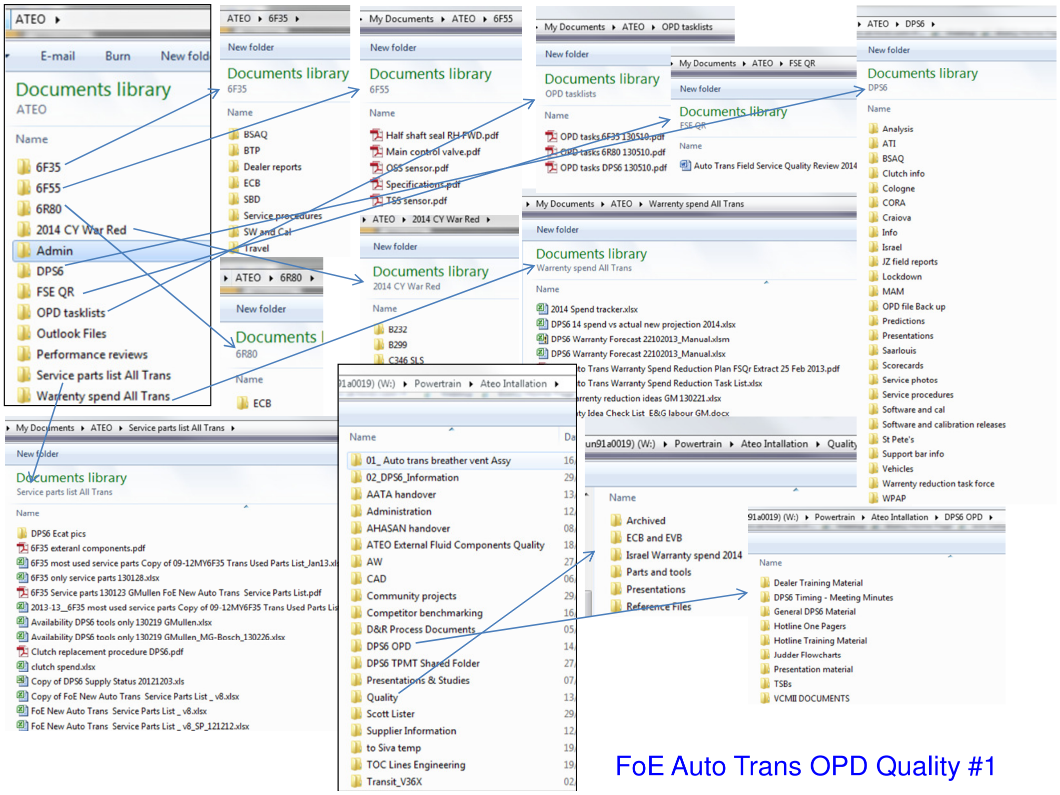


Figure 74. FoE Auto Trans OPD Engineer (1) – Annotated Document Library

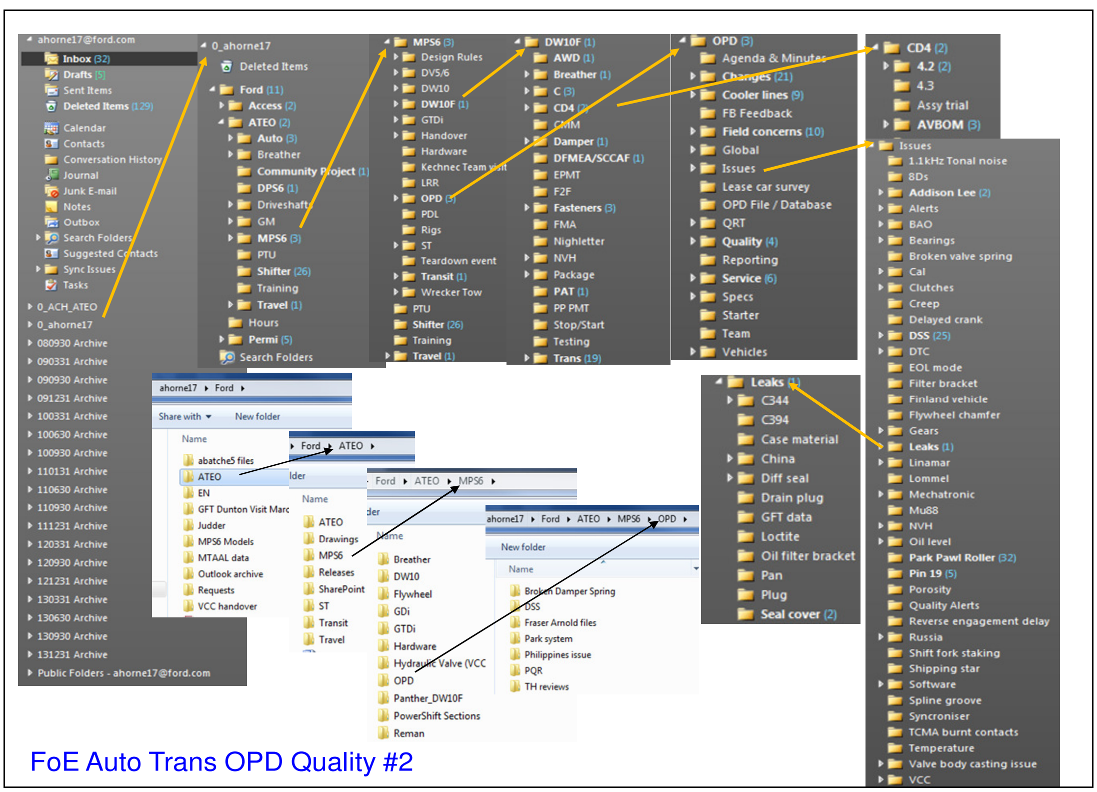


Figure 75. FoE Auto Trans OPD Engineer (2) – Annotated Document Library

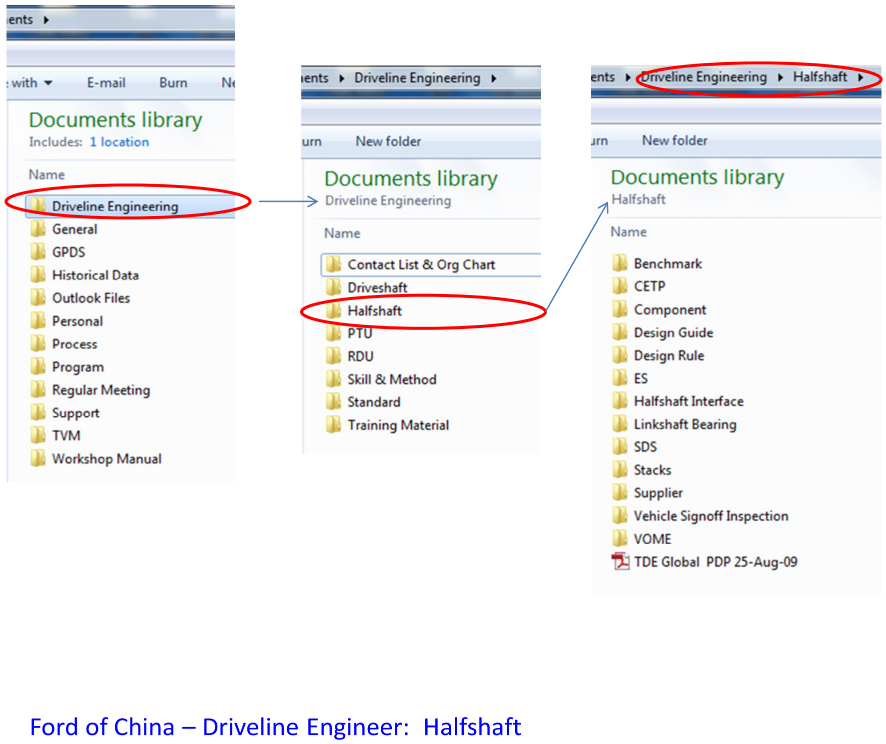


Figure 76. Ford of China Driveline Engineer (1) – Annotated Document Library

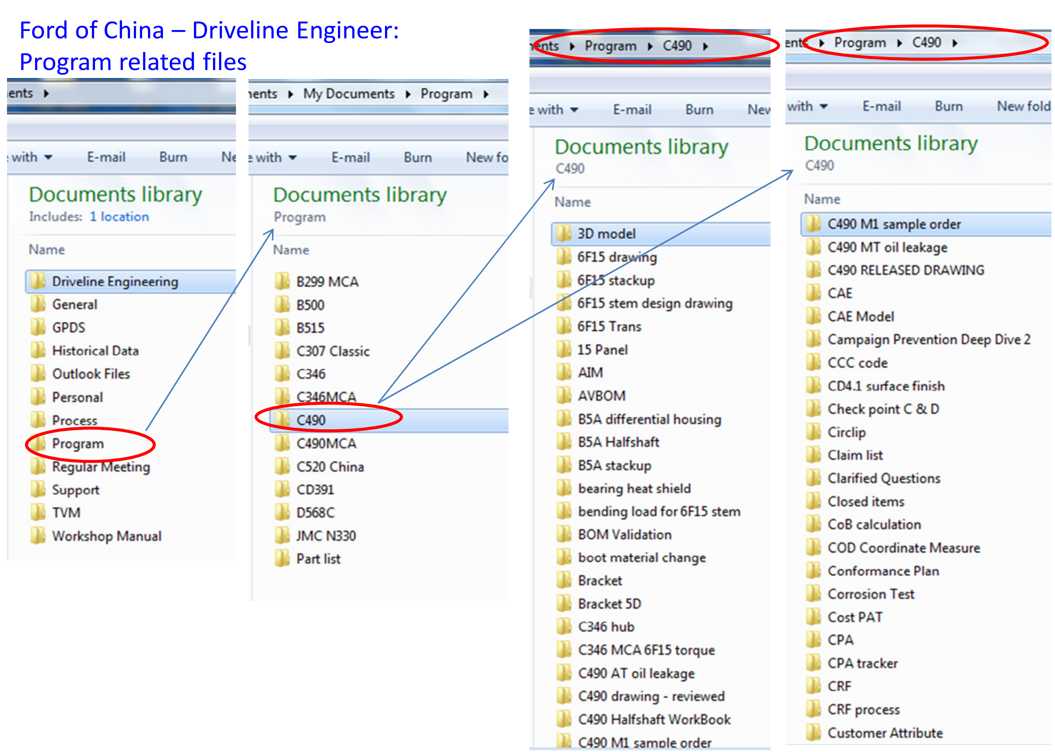


Figure 77. Ford of China Driveline Engineer (2) – Annotated Document Library

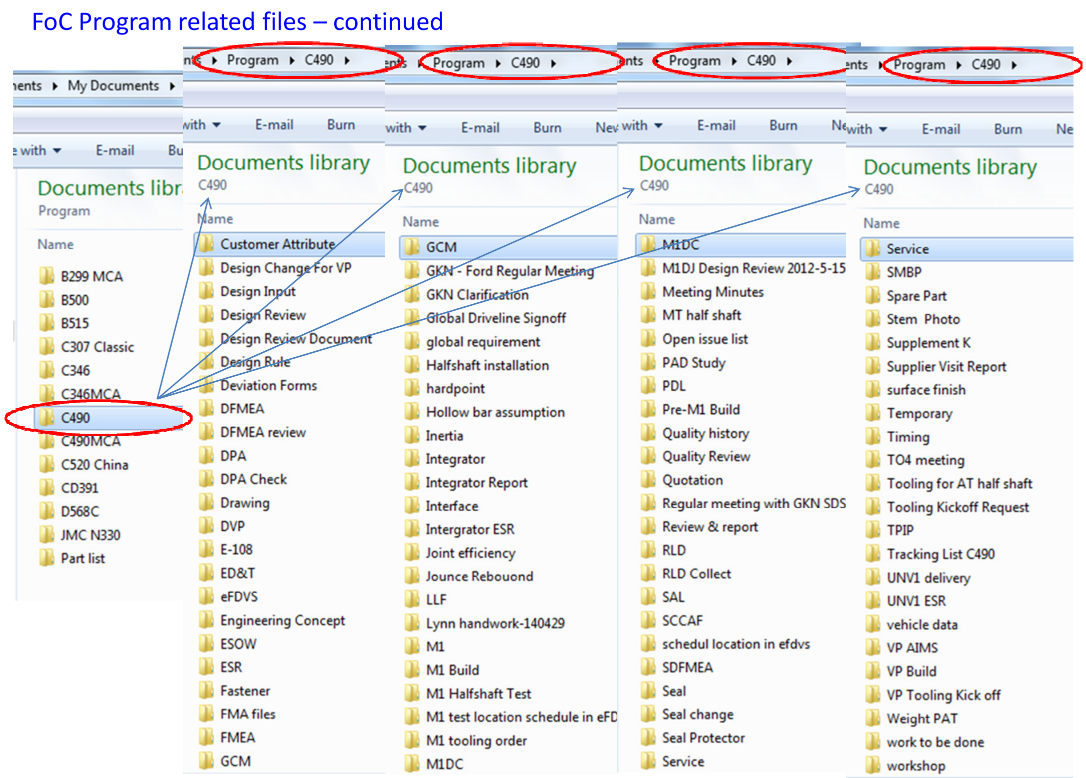


Figure 78. Ford of China Driveline Engineer (3) – Annotated Document Library

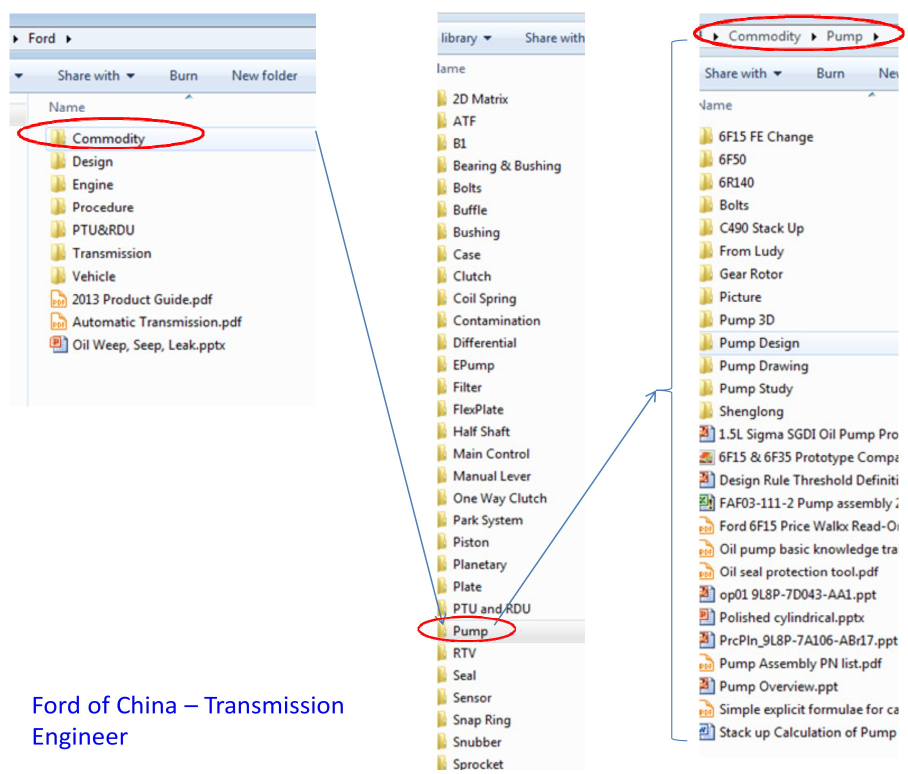


Figure 79. Ford of China Driveline Engineer (4) – Annotated Document Library

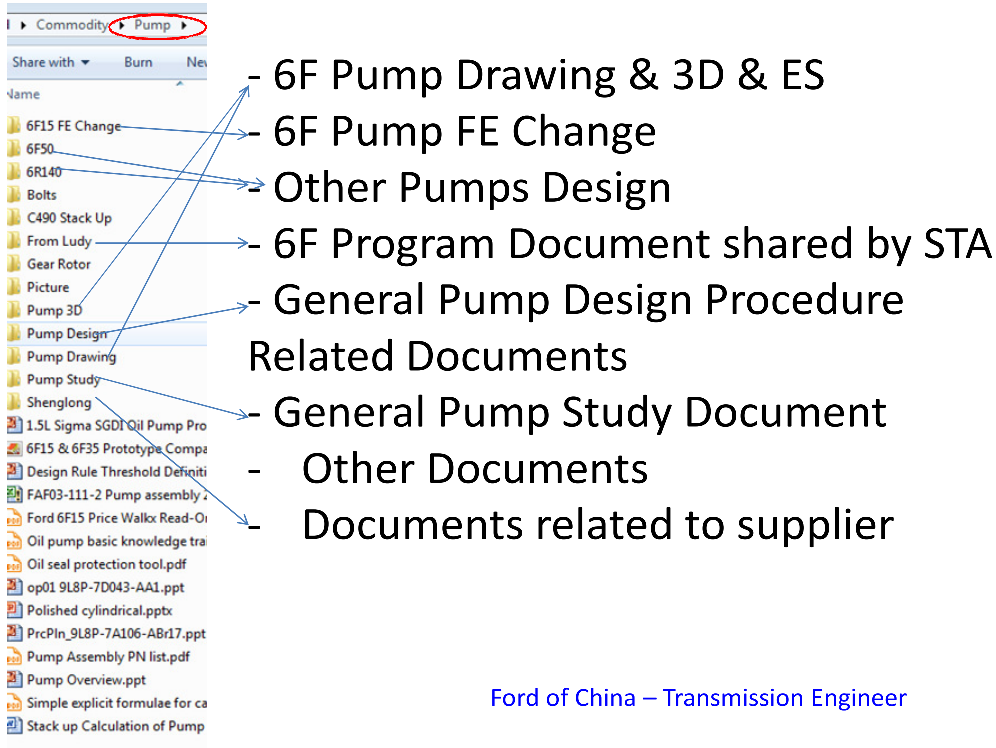


Figure 80. Ford of China Trans Engineer (1) – Annotated Document Library

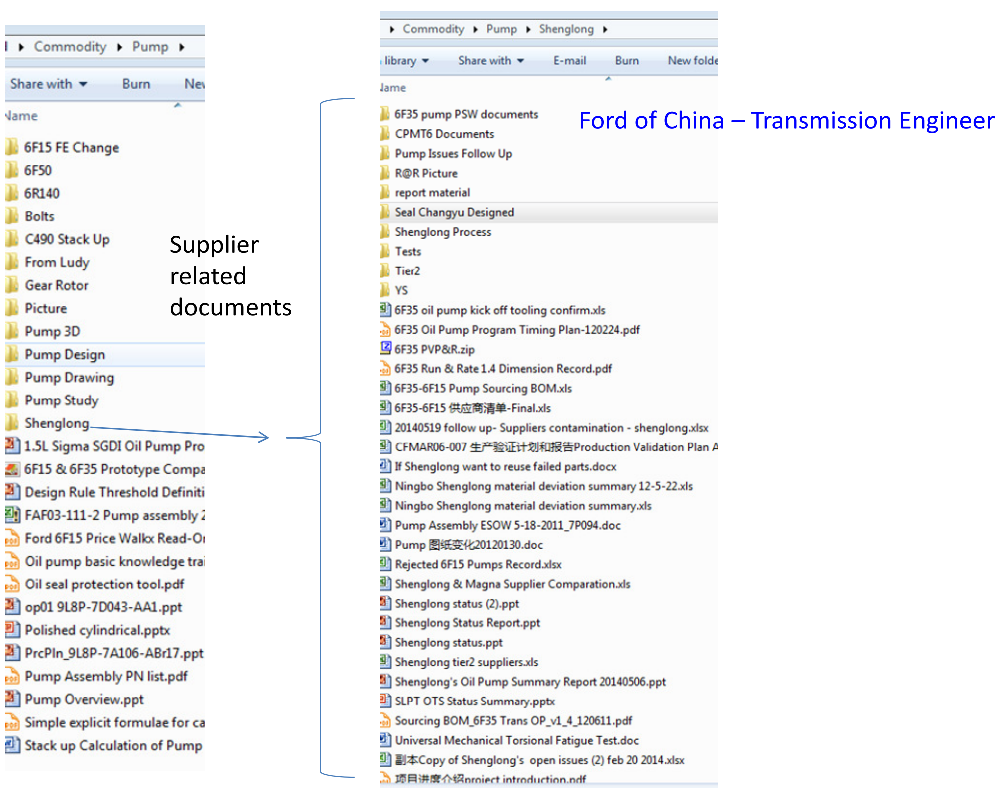


Figure 81. Ford of China Trans Engineer (2) – Annotated Document Library

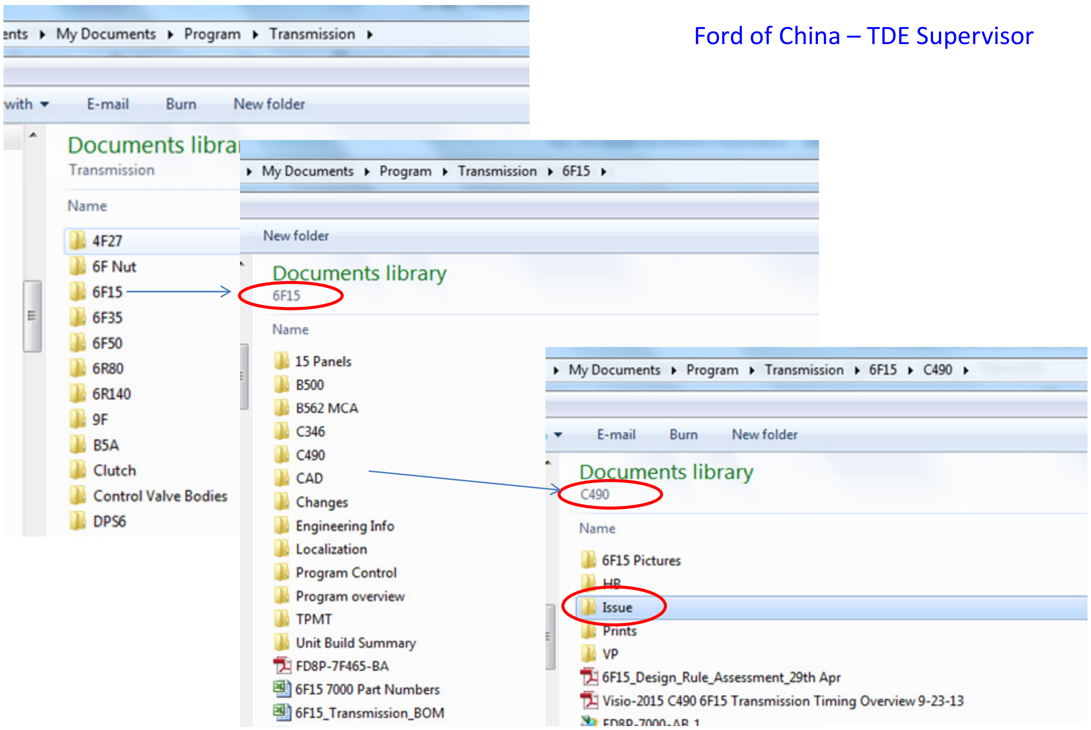


Figure 82. Ford of China TDE Supervisor (1) – Annotated Document Library

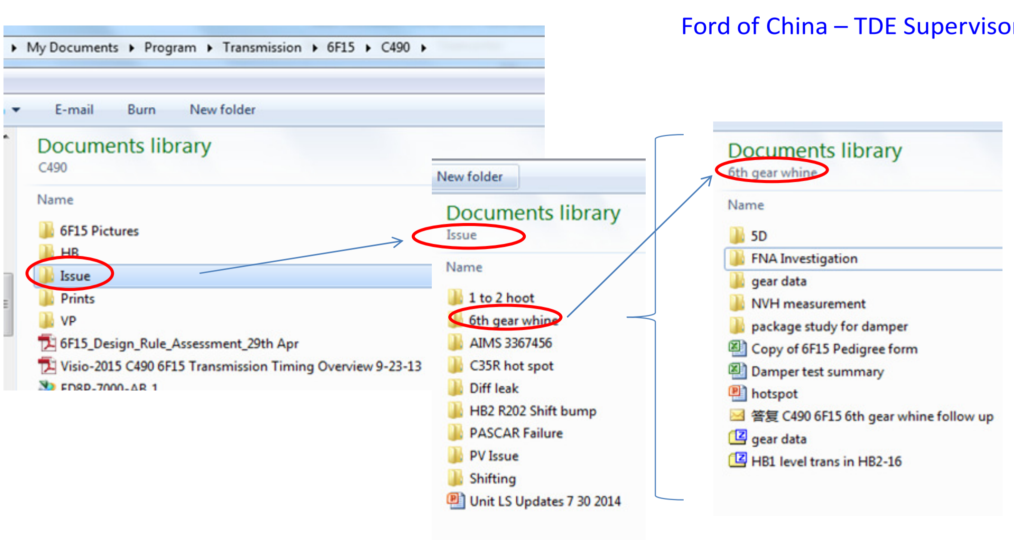


Figure 83. Ford of China TDE Supervisor (2) – Annotated Document Library

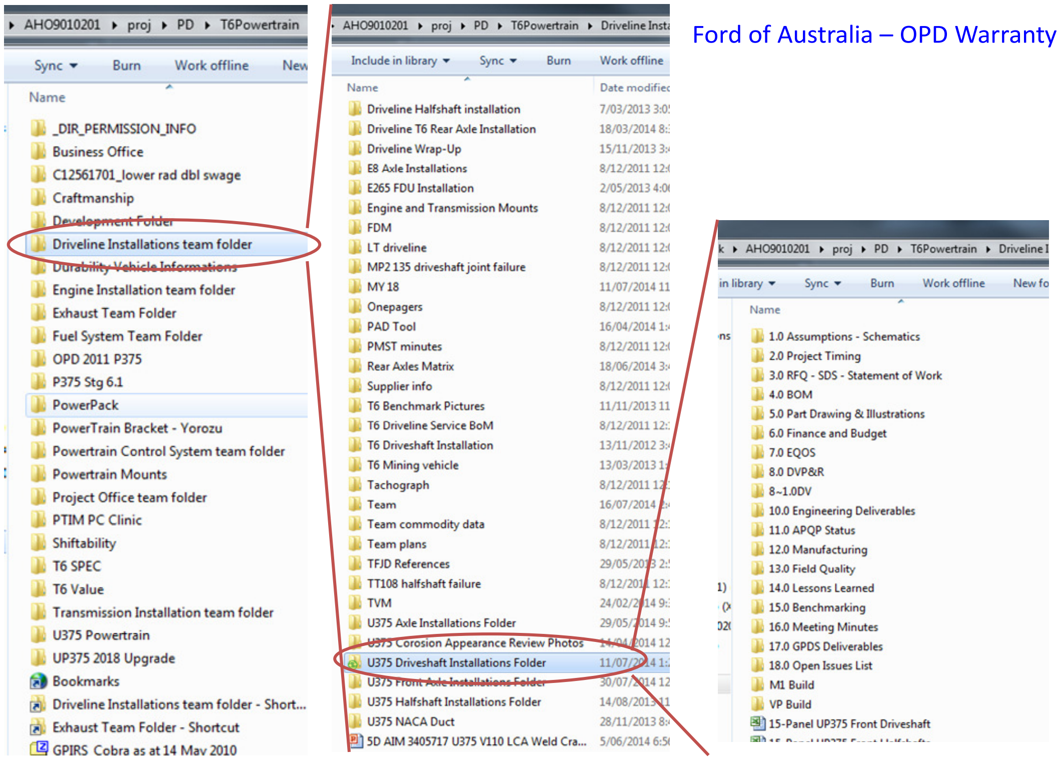


Figure 84. Ford of Australia OPD Engineer (1) – Annotated Document Library

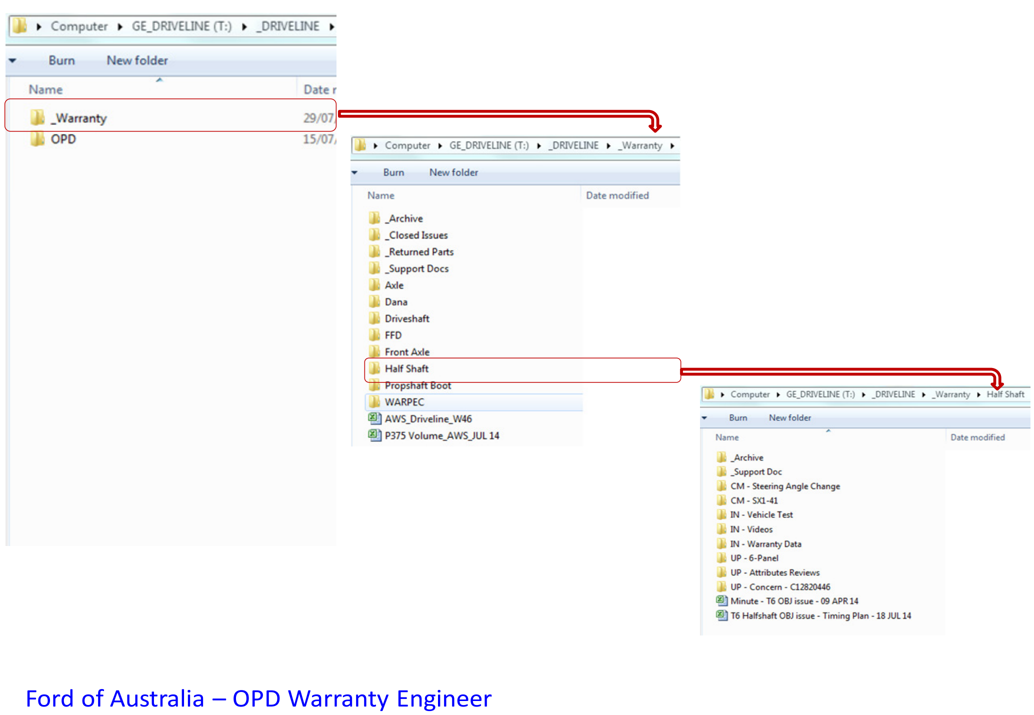


Figure 85. Ford of Australia OPD Engineer (2) – Annotated Document Library

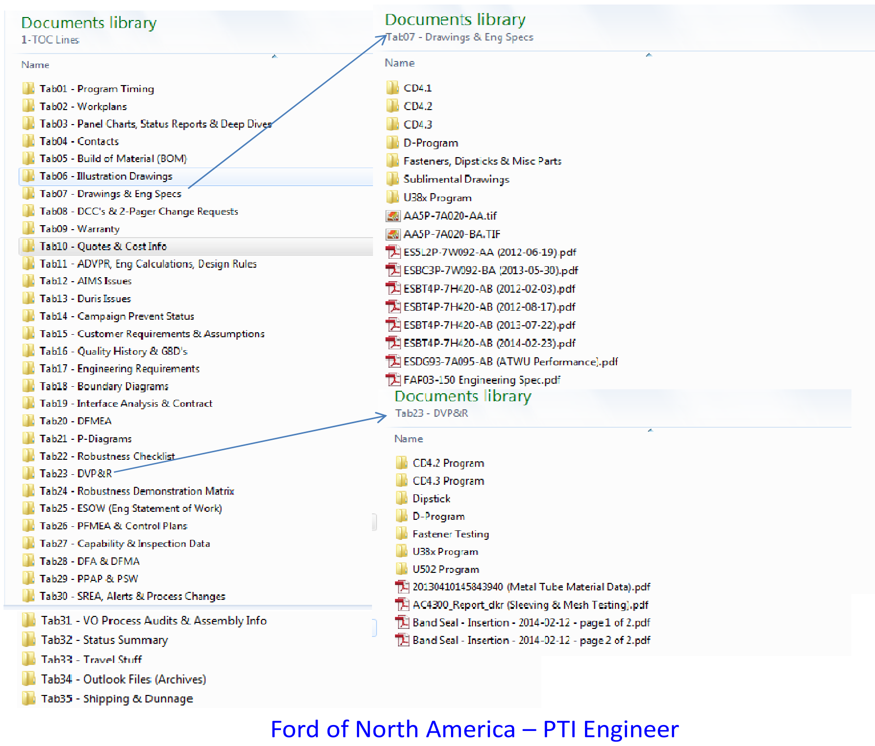


Figure 86. Ford North America PTI Engineer – Annotated Document Library

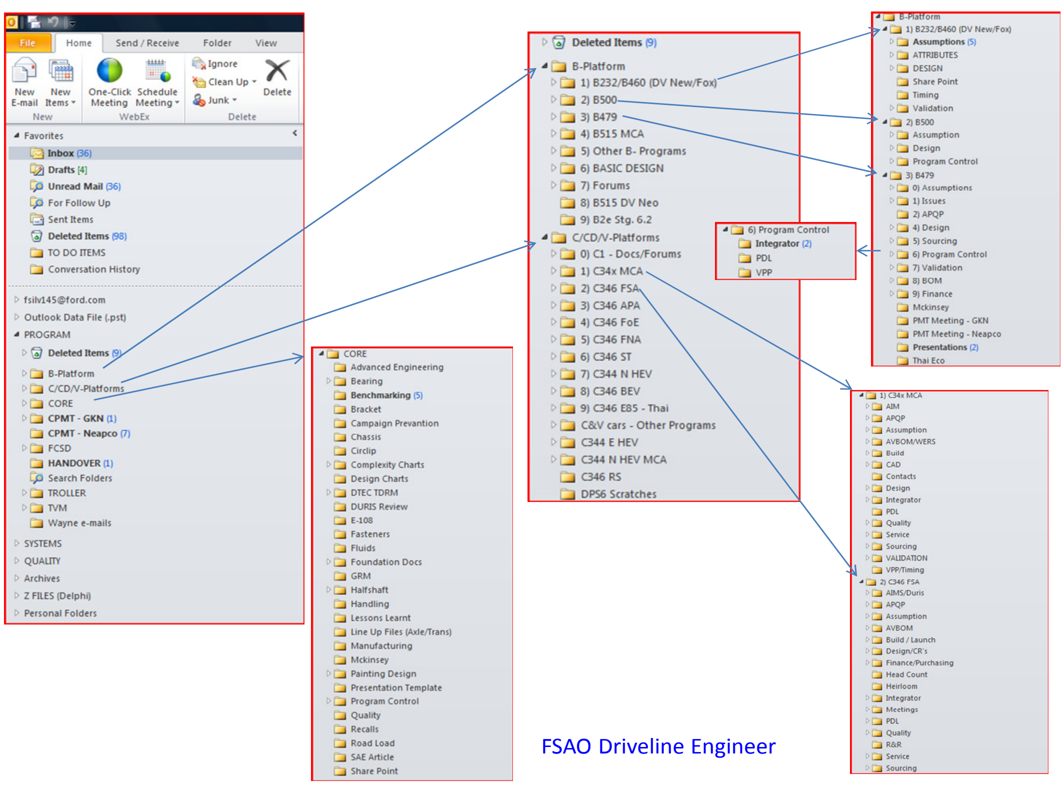


Figure 87. Ford of S.America Driveline Engr (1) – Annotated Document Library

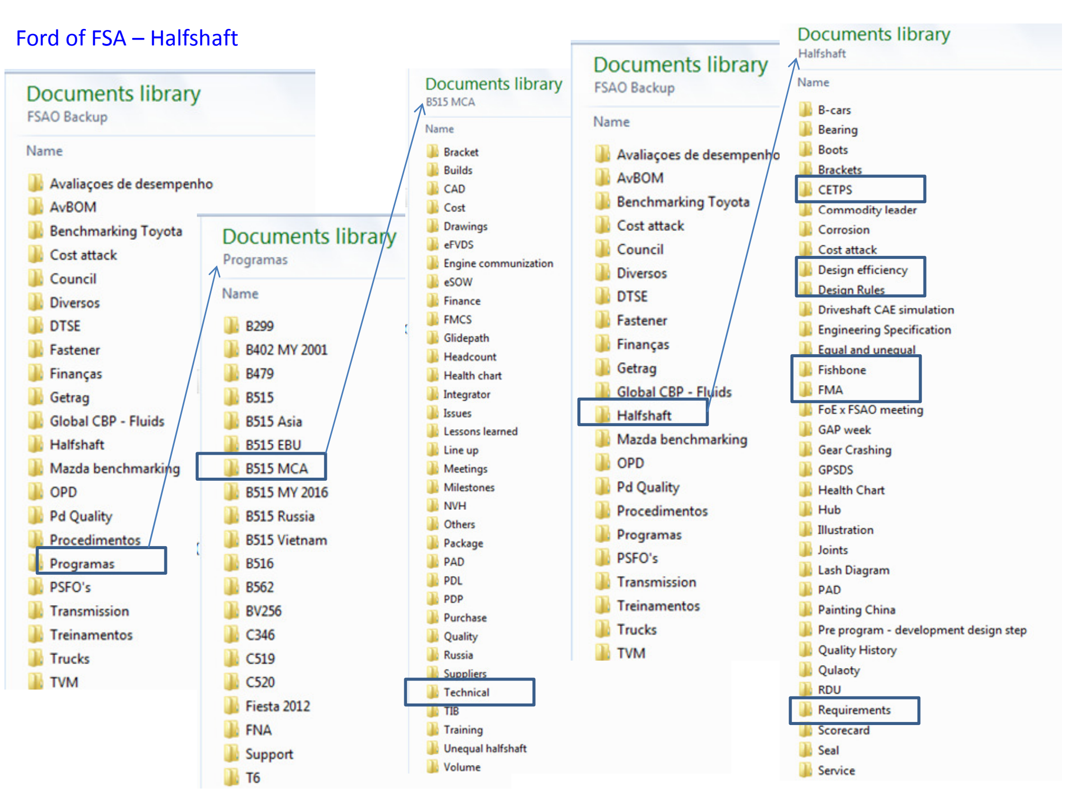


Figure 88. Ford of S.America Driveline Engr (2) – Annotated Document Library

Appendix F - Review of Internal Corporate CMS's

This appendix contains multiple screenshots of the different in-house CMS's as discussed in stage 4 of the exploratory industrial investigation (section 4.7.2).

APDM – Analytical Powertrain Data Manager

REDACTED DUE TO CONFIDENTIALITY

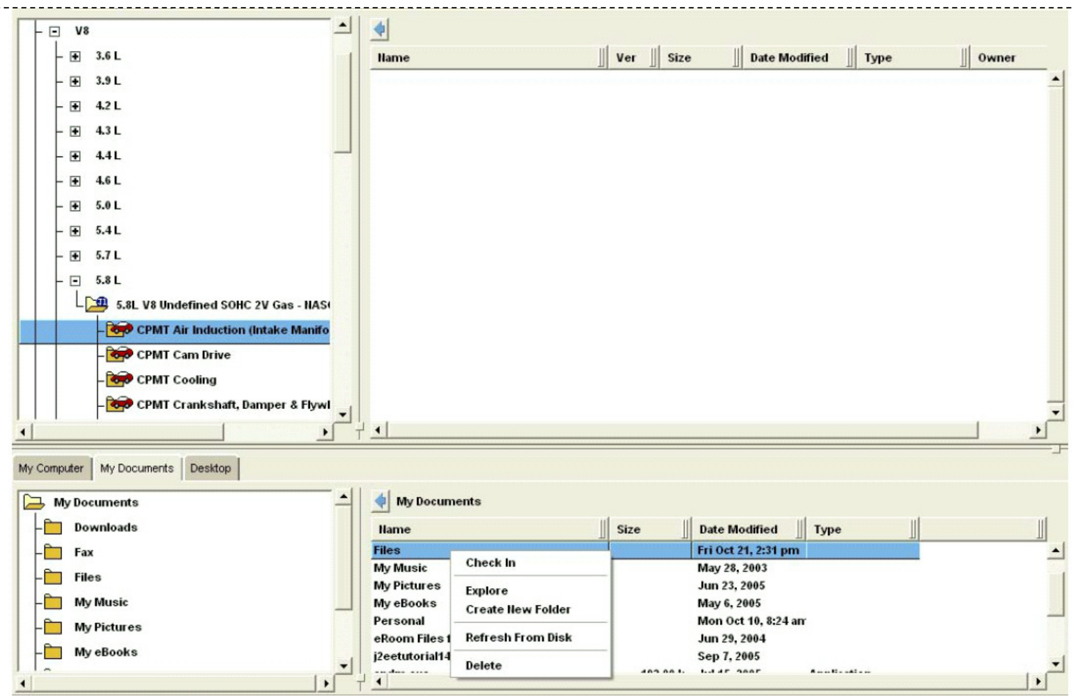
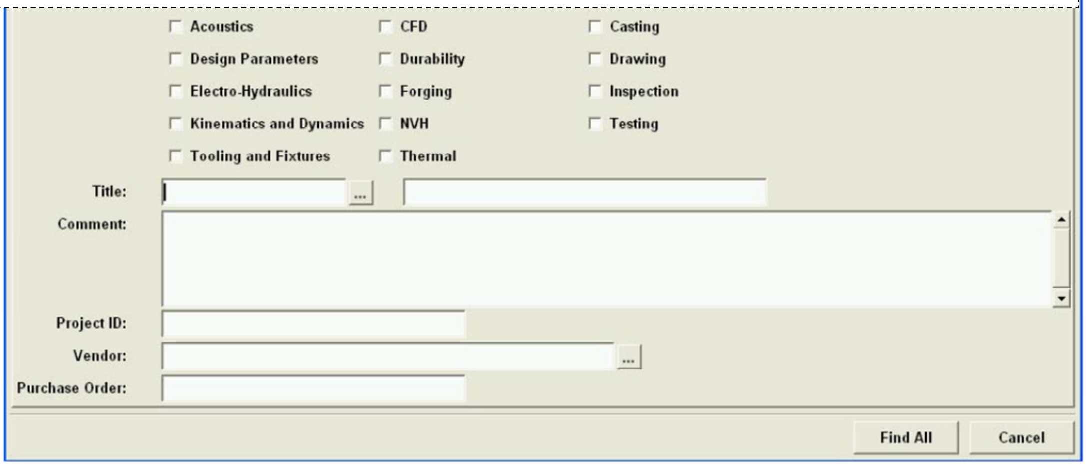


Figure 89. APDM – Analytical Powertrain Data Manager

REDACTED DUE TO CONFIDENTIALITY



REDACTED DUE TO CONFIDENTIALITY

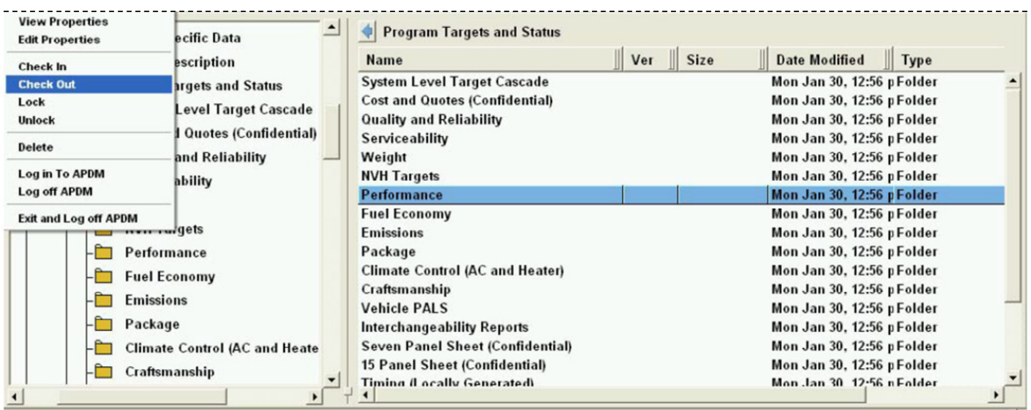
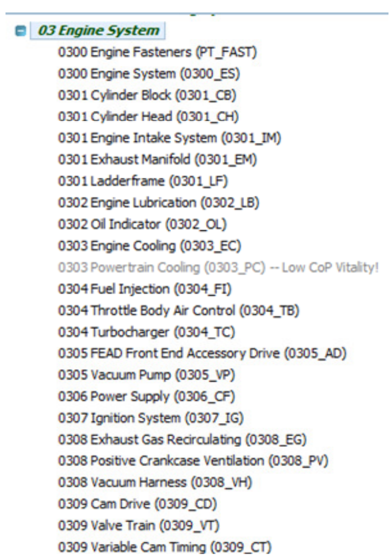
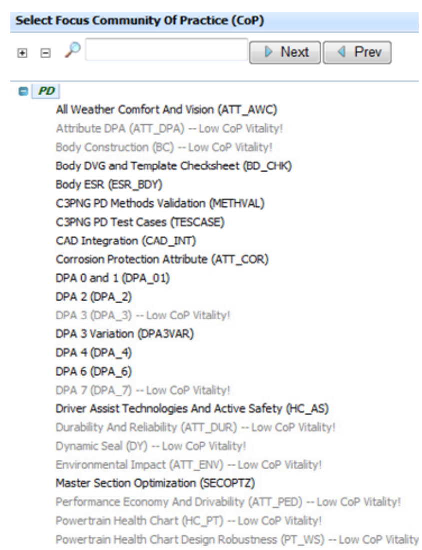


Figure 90. APDM – Analytical Powertrain Data Manager – continued

E2KS – Enterprise Engineering Knowledge System

REDACTED DUE TO CONFIDENTIALITY



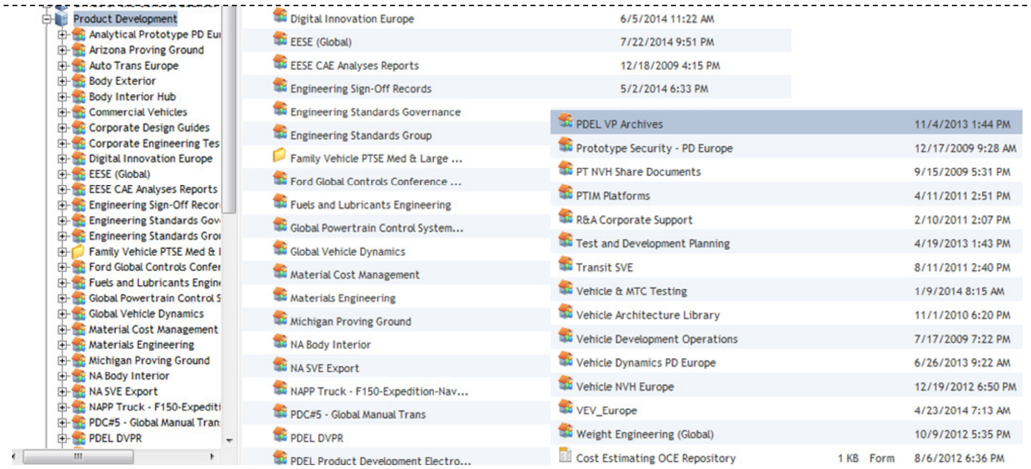


REDACTED DUE TO CONFIDENTIALITY

Figure 91. E2KS – Enterprise Engineering Knowledge System

EDMS – Engineering Data Management System

REDACTED DUE TO CONFIDENTIALITY



REDACTED DUE TO CONFIDENTIALITY

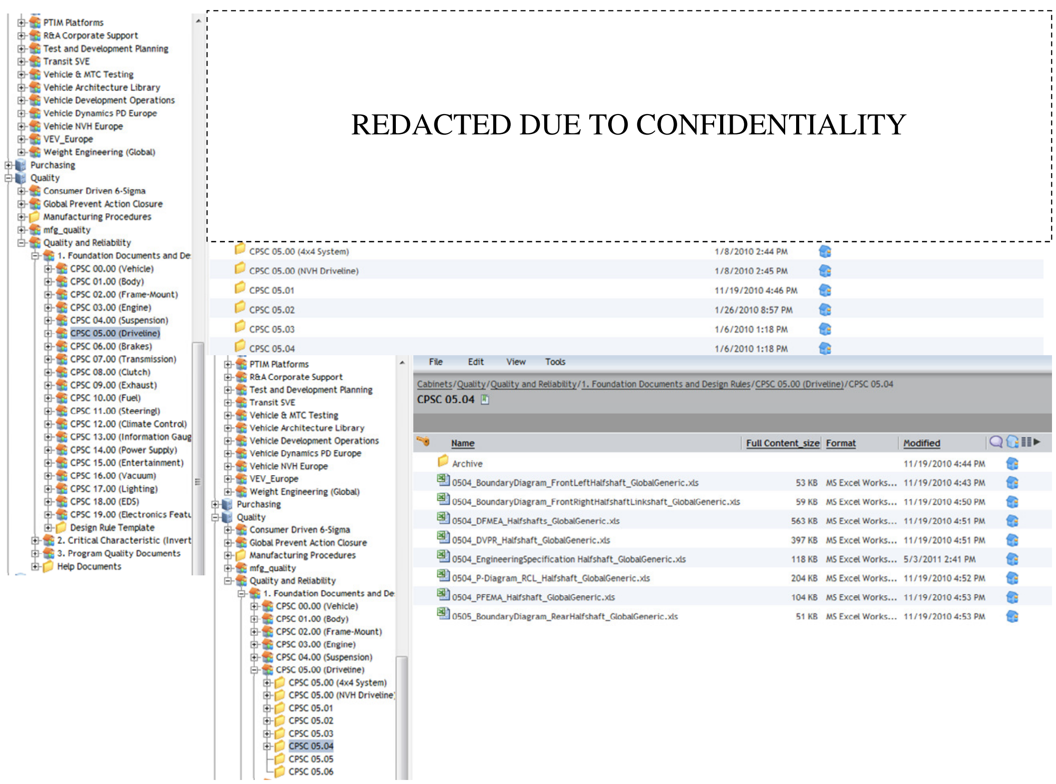


Figure 92. EDMS – Engineering Data Management System

REDACTED DUE TO CONFIDENTIALITY

REDACTED DUE TO CONFIDENTIALITY

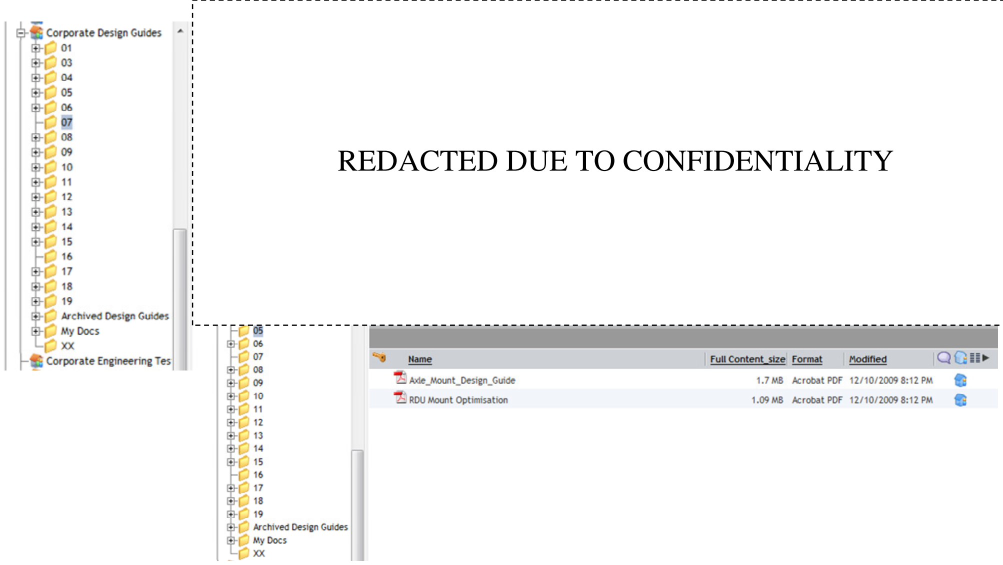


Figure 93. EDMS – Engineering Data Management System – continued

LFMA – Lean Failure Mode Avoidance

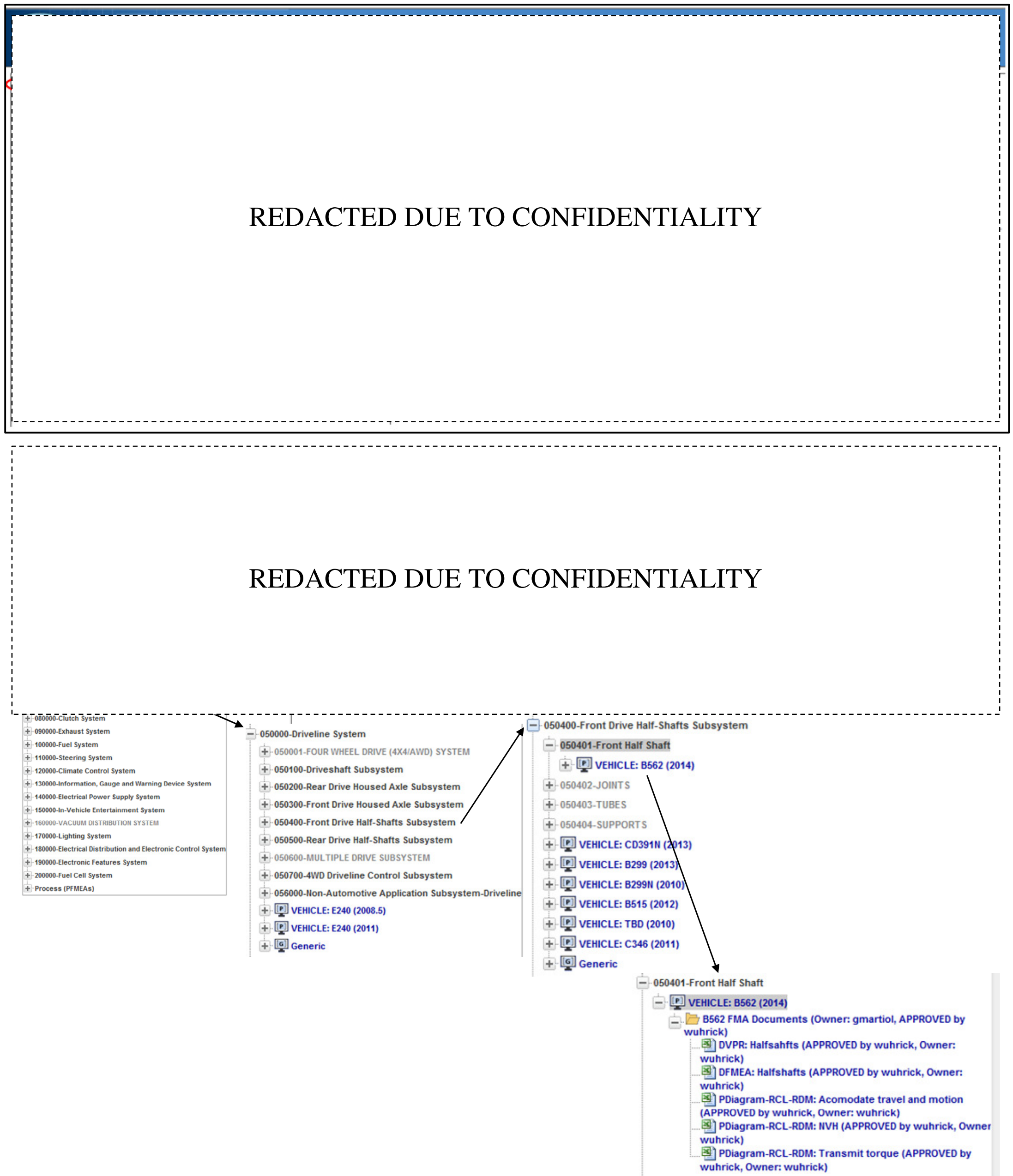
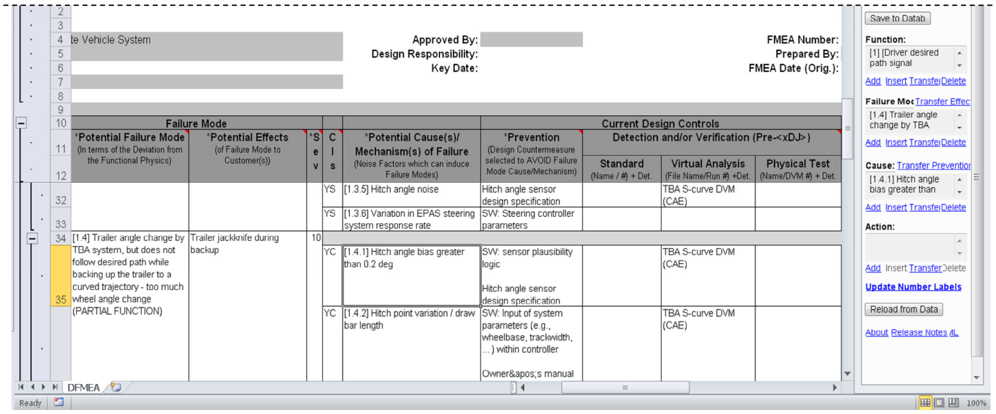


Figure 94. LFMA – Lean Failure Mode Avoidance

REDACTED DUE TO CONFIDENTIALITY



te Vehicle System

Approved By:
Design Responsibility:
Key Date:

FMEA Number:
Prepared By:
FMEA Date (Orig.):

Failure Mode				Current Design Controls				
*Potential Failure Mode (In terms of the Deviation from the Functional Physics)	*Potential Effects (of Failure Mode to Customer(s))	*Sev	Cls	*Potential Cause(s)/ Mechanism(s) of Failure (Noise Factors which can induce Failure Modes)	*Prevention (Design Countermeasure selected to AVOID Failure Mode Cause/Mechanism)	Detection and/or Verification (Pre-<xDJ>) Standard (Name / #) + Det.	Virtual Analysis (File Name/Run #) +Det.	Physical Test (Name/DVM #) + Det.
			YS	[1.3.5] Hitch angle noise	Hitch angle sensor design specification		TBA S-curve DVM (CAE)	
			YS	[1.3.6] Variation in EPAS steering system response rate	SW: Steering controller parameters			
[1.4] Trailer angle change by TBA system, but does not follow desired path while backing up the trailer to a curved trajectory - too much wheel angle change (PARTIAL FUNCTION)	Trailer jackknife during backup	10						
			YC	[1.4.1] Hitch angle bias greater than 0.2 deg	SW: sensor plausibility logic Hitch angle sensor design specification		TBA S-curve DVM (CAE)	
			YC	[1.4.2] Hitch point variation / draw bar length	SW: Input of system parameters (e.g., wheelbase, trackwidth, ...) within controller Owner's manual		TBA S-curve DVM (CAE)	

REDACTED DUE TO CONFIDENTIALITY

Figure 95. LFMA – Lean Failure Mode Avoidance – continued

PeBOD – Powertrain e-Bill of Design

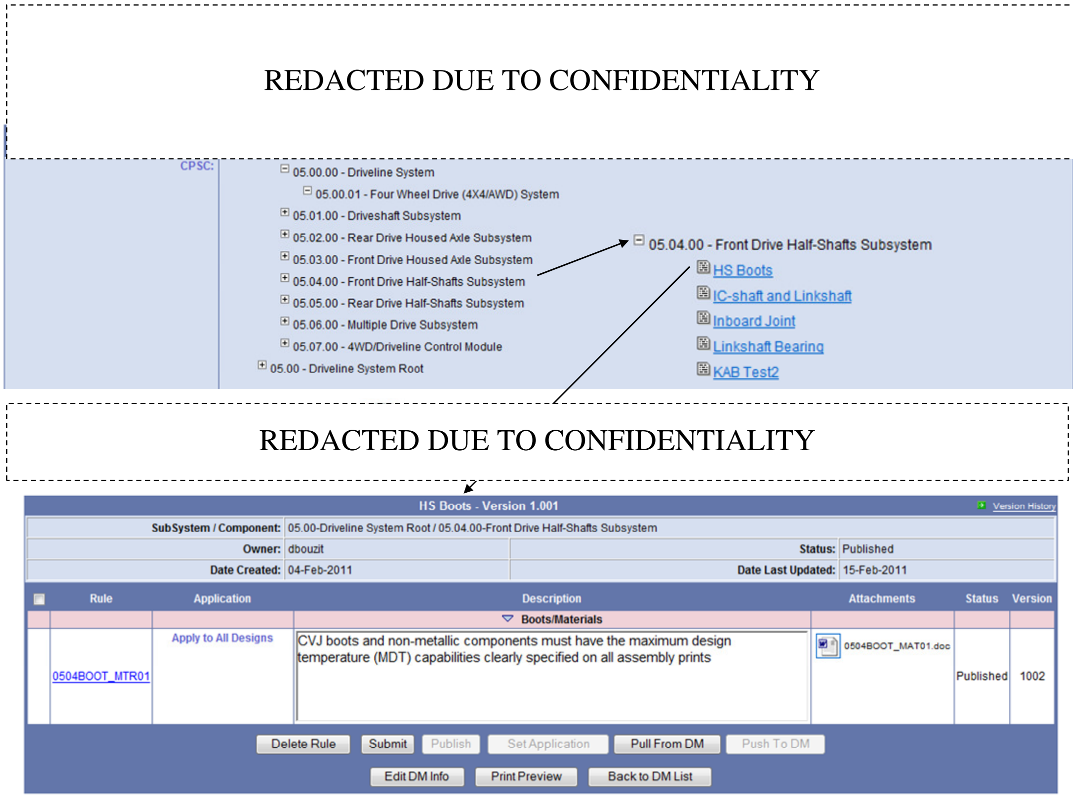
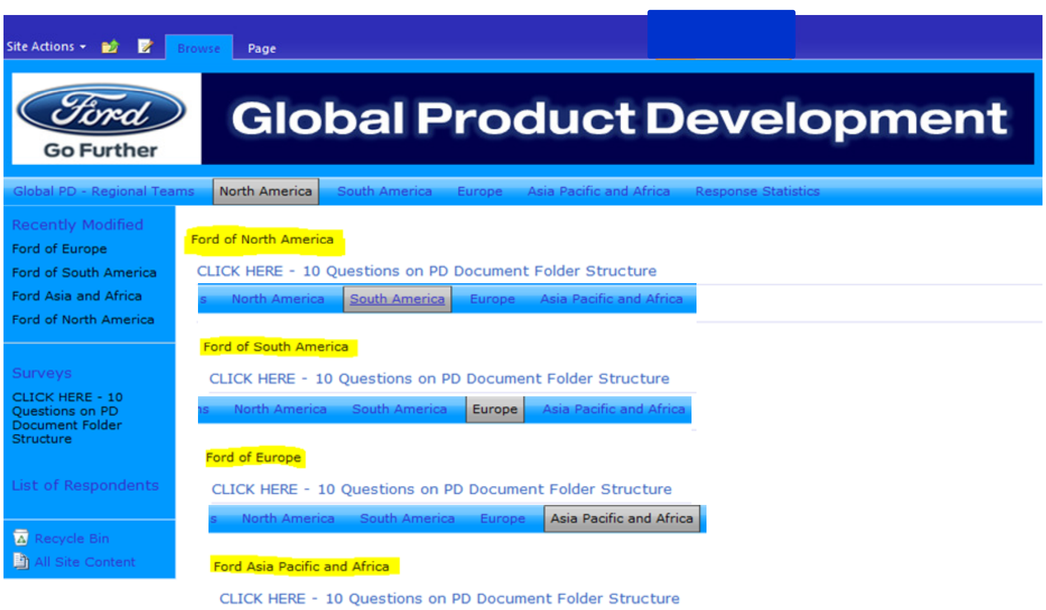


Figure 96. PeBOD – Powertrain e-Bill of Design – Screenshots

Appendix G - Global Product Development Survey

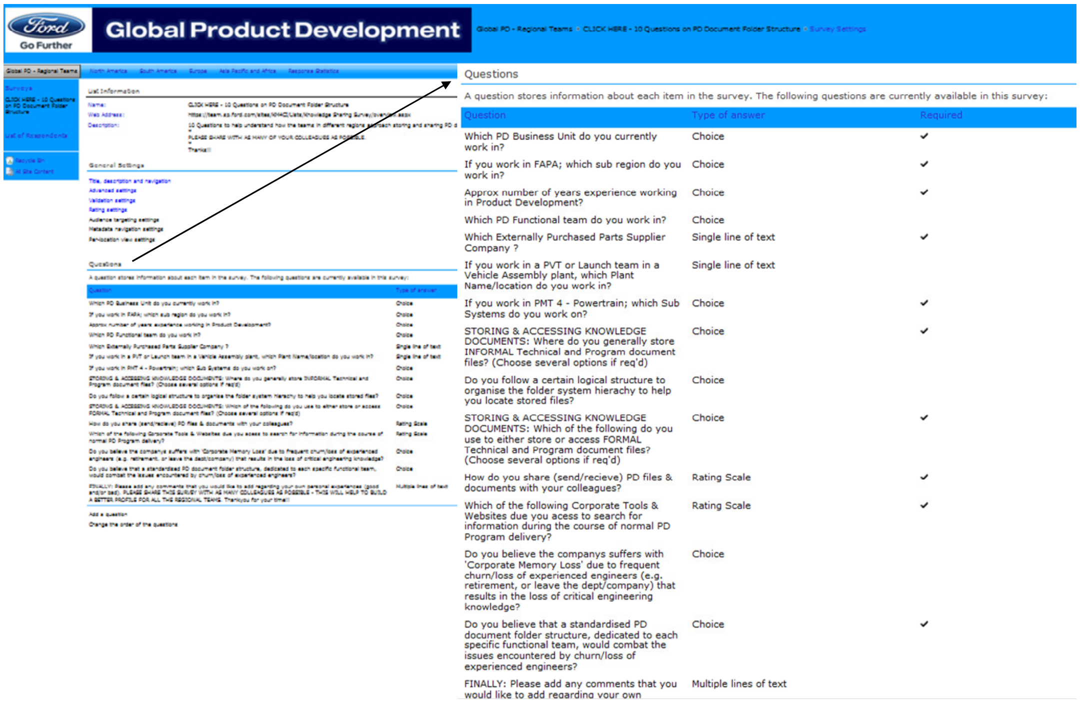
Screenshots of the multinational PD survey website pages.

- Dedicated MS Sharepoint site was established to allow full participation from all regions
- 'World' map – inserted as a web part Image map, with links to dedicated pages for each region

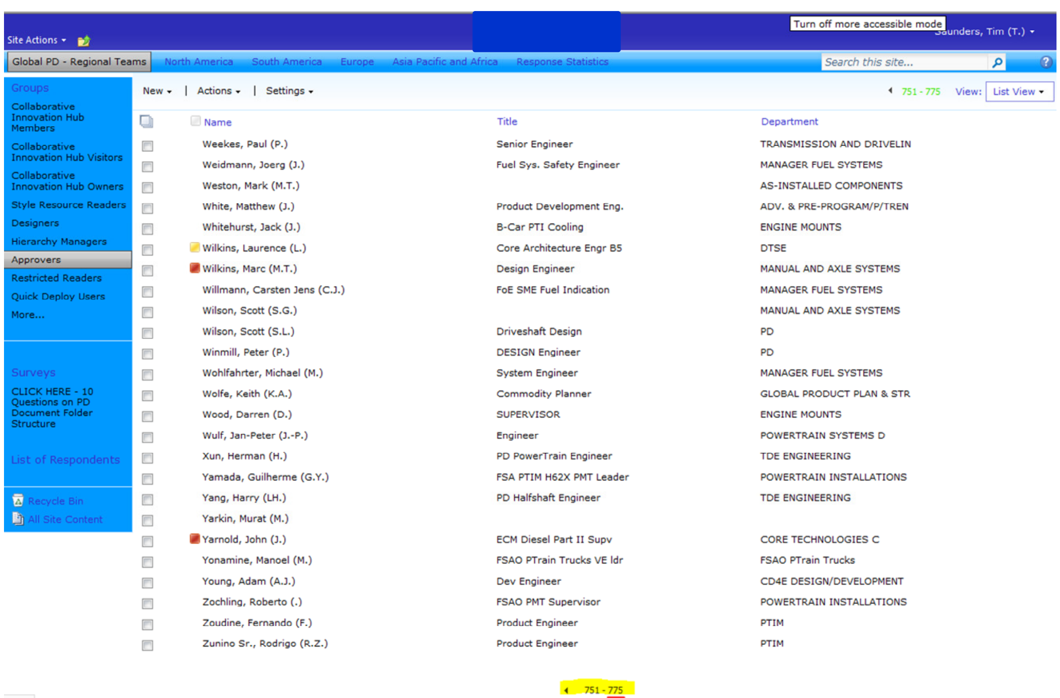


- 'World' map – inserted as a web part Image map, with links to dedicated pages for each region
- Dedicated pages were set up inside the site for each global region – to generate a sense of inclusion
- Single common survey was integrated within the sharepoint site and linked to each regional page

Figure 97. Global PD Survey - ICT Site Layout



- Questionnaire constructed inside the MS sharepoint environment
- Mix of initial Profile questions, followed by main questions on KM practices and behaviours



- Targeted emails sent to individuals and distribution lists from within the MS Sharepoint environment
- As of 11/08/14 a total of +1000 engineers had been invited to participate in the survey

Figure 98. Global PD Survey ICT Site Questions

Appendix H - Written Responses to Global PD Survey

The following statements are the raw entries provided by the multinational PD survey in response to the final survey question (section 4.8.2).

1 Storing and then relocating documents is a nightmare. Folder structures that evolve over time become eclectic and disorganised. A fundamental 'Core' folder structure system would provide a useful guide for all new graduate (and experienced) engineers to start with a logical organisation.

2 - No formal process for backing up .pst files; corporate inbox can only hold 200 MB (~1-2 weeks) of emails, laptop hard drives not reliable enough to store backups beyond that time. Compare to my personal (free) email account which holds more than 7 GB of email (and is easily searchable). - Particularly within APA region, a unified format would be useful - we work as regional teams but W: drive access is country-based, making simple storage and sharing of documents (e.g. Team of 4 working documents) difficult.

3 A better document of the files for the program / technical info will help to reduce the loss of the engineering knowledge. But the engineering knowledge is more than the documents. Globally I think the critical thing is to have a solid global functional team -- so it will not impact the business that much when someone leave the one regional team. We have developed many engineers from zero for couple of systems by working together with global functional team. But in the region, it's more important to have a standardised PD document folder structure.

4 Lots of websites don't open access for China engineers, we have problem when seek for info internal Ford.

5 1/ Generally large delta between Contract and Perm Staff due diligence. Contract staff should not be given critical engineering positions without mentorship and control of data archiving / due process. Inheriting an ex-contract staff workload almost always [9/10] means 6 to 12 months rebuilding the knowledge base / supplier relationship, which creates stress

and directly impacts the Program / employee affected. Certain Critical /Core Knowledge Positions should never be allocated to Contract Staff. 2/ Much more thought and consideration to conservation of engineering knowledge and skills base must be applied by senior management prior to a restructuring. My perception is that engineering skills have NO VALUE in this organisation from middle management and above. Most of this knowledge has now, sadly, migrated into the supplier base, which significantly weakens FORD's negotiating position and hinders problem resolution. This also leads to costly and time consuming repetition of failure modes across Programs/Cycle Plans as any lessons learned / experience gained has been dissipated.

6 There are situations when access to folders takes a really long time or it's not clear who the authority to grant access is. SharePoint® is better in this regard.

7 I started to make a standard program folder tree to use in our team but not finished yet. A standard folder tree may help to reach the required documents.

8 Management and system churn creates contradiction and lack of transference of data from one system to the next.

9 Thanks for considering the opinion. I work in PD - Programs and don't belong to any functional team. In B562i program, we are comfortable with W drive and Program SP site. But note, I work from PA milestone only. Note: I selected PTI in PMT4 question, as system is mandating that.

10 Every Engineer should properly document each issue and it should be kept in easily accessible state: issue Team involved: Attach communication Part affected Root cause : Any related concern / alert / finance approval / other documents like comparison data / bench mark data etc. latest communication Pending action or next if closed : closed status and the improvement

11 PD Team should have a standard folder structure across globe. All Design calculations data transfer should be stored component wise that will be great thing while transferring the work to some other team.

12 Good thing to have a global common SharePoint® function wise. There should be an error proofed system that makes sure that all required documents are saved in the SharePoint®. As there are many SharePoint® sites available now which are not maintained properly.

13 Emails will stored just locally. No copying of .pst files to personal network drive designated (Size limitation). If the computer crashes the email is lost.

14 I think the above survey had answered your questions. Nevertheless, we have so many sites that one engg may not be familiar with all the sites.

15 URLs are often too long for application retrieval (folders within folders within folders etc.), uncontrolled and without structure, logic or discipline. It is essential that archived data is held in Archive folders within the folder holding the current document. There is also an acute lack of discipline when expressing dates. Often you will see the same date expressed as 01.07.14 or 07.01.14 or 1-7-2014 etc. When storing files they should be date-marked as 140701 (YYMMDD). When in text form, the Corporate Standard is 07-Jul-14 (not 7th July etc.).

16 As well as churn of people there is an even greater churn of process, which knocks the wind out of people's sails.

17 Ford desperately needs commonality and standards for network/document layout and structure. Everyone does it differently, so many places to find info and we all sign our AFR every year!

18 Especially for the handover process detailed and logical data storage is perfectly helpful to reduce the issue solving time

19 I would suggest having program specific PD document folder structure. It will help us to cascade the program specific issues/lessons learnt to Global PD team.

20 Capacity is an issue for shared document repositories. Applies to outlook, shared drives and SharePoint®. We need a process that deletes superseded documents whilst maintaining the need to understand the history.

21 Frequently, PD engineers are urged to "follow the process" or told "That's not part of the process!" The problem is: the "process" is so convoluted, so filled with jargon and acronyms, and so multi-layered that few people (it seems) really understand it with any assurance. This issue is compounded by the fact that there is no real "Powertrain 101" or "Driveline 101," etc.; instead, everyone has to learn "the process" by observation and osmosis. Confusion multiplies when it becomes apparent that the processes and agendas of FNA and FoE sometimes conflict during conjoined programs under development.

22 Good record retention structures, and access tools, are difficult to develop. Tools developed locally by small teams to address a specific purpose can fail when leveraged for larger needs. Many people I interact with do not seem to have acquired a sense of logical orderly flow and capture of information from corporate systems. Too often people seem to want to avoid corporate systems by saving copies to local drives, keeping excel files on work computer C: drive of test results, etc. Being unable to link to relevant data to understand the appropriate responses to changing business needs is very compromising to financial stability. Recently I was a key FNA team member in rolling Duris into AIM. We have very competent IT personnel whose task it is to manage and implement corporate data systems. These people should be relied on to deliver first class systems that are responsive to user requirements.

23 SharePoint® structure could use work, but the turnover of Senior Engineers seems low in TDE which prevents corporate memory lose at least within our department.

24 "Knowledge Transfer" should be taken seriously in this technology cutting edge era. We should have some establish plan For Those who: * Retire or Internal Transfer Employee: New appointee should get trained for few

months. Once appointee is confidence/up to the speed one can retire/transfer. *

In-house developed procedures /methods /protocols /software /standard template/macros/....etc.....should be shared with more than two people and stored safely. This will help our company to save the hard work/know how.

25 I took the Advanced SharePoint® site training. It is my hope to expand the use of SharePoint® from just a "storage site" for files.

26 Yes, we tend to re-learn the same things over and over again due to not only churn/loss of experienced engineers, but also the lack of sharing information between engineers. Better means to share information as this survey is addressing will be a big help

27 There are so many different websites to restore different documents, and some of them are not maintained anymore. I strongly advise to have one common website for PD technical documents. All formal documents must be updated online.

28 Maintaining a good filing method in Outlook is difficult due to excessive email usage.

29 Ford database system is like a jungle. There is an amazing amount of stuff, but all entangled together. Search for anything is always as random as throwing a fishing line. The organisation of the various database sets is free-for-all process, it does not look that there is any structured management or adherence to any given / logical rules. Some leadership in this area is needed to implement some discipline to make the wealth of data useful to Ford as well as secure.

30 Management of the capacity of W Drive has been an issue for me. Frequently there is not enough room on the drive to store new files / folders. Adding space alone is not the answer. Deletion of old & unwanted files would assist. Not sure how this could be implemented as a system and/or enforced however.

31 Through a GPDS program or an OPD/PVT change; lots of data have been studied and exchanged within the company. However there are a few of them are the key and would be required for future reference (such as change content, CAEs, DVP&Rs, PPAP docs, etc.), therefore having a global shared folder with defined folder hierarchy for the basic info would work. Milestone sign-off documents in Integrator and WERS online partially helps, however mostly depending on engineer/supervisor. There is a potential to improve.

32 Lessons learned from previous programs and Prevent Reoccurrence items are not well documented/actioned

33 If we had a search engine that worked well it would speed up finding information, at the moment Ford search is fairly useless.

34 I believe which the PD document folder structure could help us, it is a good idea just if does not down in the dark, in another words, the people really use it to show and training new employees. but I'm already tried to see sites like that be forgotten.

35 AVBOM system need friendly usage than the current and speed of system must be improved TCe/AVBOM frequently present misalignment

36 We should have pages to follow like a game. When you complete this page you go to next and it should be the same for all. Like a game for this new generation coming (PS3, XBOX). And you can add this to a competition and lock others if the last did not complete the task.

37 It should exist a unique knowledge base inside the Ford WEB structure were we could add the experiences during program design, lessons learned, divided by function. Also at the same base it would be useful concentrate links that we already use like: FACTS.ford.com RLIS.ford.com And all knowledge sites that already exist to be structured like a “Ford Virtual library”, a place where we could access and have all knowledge bases at the same place.

38 Unfortunately the company suffer a lot with 'Corporate Memory Loss'. In my team, we're used to storage all test information on EDMS, but the system in my opinion is not friendly when you need to find a specific files. Despite to that, there are several different sites, you need to request access for each one, one system don't work with another. I'm almost 9 years working for Ford and until now I have difficulties with the system.

39 Even if you create a folder structure we will depend on people to load it. Without any check or verification people will not load all files into the folders. My suggestion is to have especial "online software" that you must load your information / file to move on to the next step.

40 Ford has very good data management system since long ago. We no need to reinvent the wheel. In my opinion what we are missing here is, There are so many new joiners entering into FORD. But, In Ford there used to be Buddy system for system knowledge sharing for new joiners from the existing experienced Engineers. Nowadays, I think FORD not giving respect to experienced people. From the very first, New joiners are assigned major program task without practising FORD system. (This excludes HR orientation).

41 Need to enhance importance of storing data in shared drive.

42 May be a training on "formal and informal data management" could help.

43 It is would be better to follow structure which I have seen with B515 EU Program management Team

44 Need more storage spaces. This is a common issue

45 There is lot of data, converting this data to the required information within the typically available short time is the crux. In some case, the document has a procedure but the practice is more than what is written in the document is the 'tricks of the trade'.

46 It’s a good thing to get the feedback from employees

47 With the advent of so many SharePoint® sites, it’s extremely challenging to

keep track of all the SharePoint® sites that one has access to. Not sure whether it's possible to have a SharePoint® dashboard when we log-in showing the SharePoint® sites we have access to. Also an option to cluster a set of SharePoint® sites applicable to a function into single bundle so that new joiners can get access through single approval without missing any req'd ones.

48 DFMEA to easily retrieved based on base no

49 SharePoint® always provide a good possibility to share and don't lost the history of documents, but many engineers don't know how do the correct use of this tool

50 Thanks for opportunity. I would like add few more points here: I am fresher for this department. I am struggling to get or to know the resources (like DURIS, Integrator, etc.) that may useful for us in PD. It is better to share basic training material for how to use the resources more frequently and fluently Thanks.

51 The advice given by IT in inductions is too complex. The issue is not policed, held to account by line management on a day to day basis, its currently annual. The complexity of document hierarchy and locations gets in the way of day to day. Underlying issues of trust between colleagues, data context, document pitching, and security are all reasons why people "manage" documents in their own way. To not recognise this during "coaching" means it's unlikely that issuing new "guidelines" or "rules" is not going to change behaviour.

52 Documentation combined with induction training for new starters in the team and good handover procedure needs to be set-up to resolve the data loss issues due to churn/loss of experienced engineers. Educating all team members to put in practice to store the info accessible to team and familiarise themselves with the tools and resources available to find the right info when and where required will improve the efficiency.

53 I agree with the last question ONLY if the other systems were removed from use. IT will not work unless people are forced to use it

54 Main root cause for 'lost' memory is that there is no chance for a robust hand-over. In most cases, the one has already left before the next comes. This is caused by the very slow hiring process.

55 I have moved jobs many times and it is frustrating when you cannot find information from your predecessor that you know should exist. Once I was given an email folder to search for data which was a nightmare for trying to find information. I have also had good handovers when information has all been stored in one place in logical folders so it is easy to find and includes links when information is stored somewhere else.

56 I believe some people does not have information about all the tools provided by Ford.

57 No central area for test reports - relies on user CETPs used to be a lot better, now historic CETPs are impossible to find SDS, do these still exist, used to be significantly better organised through requirements.ford.com user unfriendly programs that require a lot clicks - drag and drop is available on eBay websites, should be here too.

58 Each team has a SharePoint® site(s) but they work in isolation from each other. It would be useful if I could start at a single SharePoint® site for the whole vehicle, and then drill down to the relevant team I'm interested in finding; this type of approach is already used in eCAT (i.e., Vehicle -> Powertrain -> Engine -> induction systems). This would make finding a contact name for other teams a lot easier.

59 Would expect PMT related SharePoint® with key information stored.

60 All the ford site information for newly joined employee is not available at one common site. How many access, how many sites, we have to refer to perform respective roles is not clear. May be one link page at ATford.com can be useful for the above request.

61 When I joined Ford a year ago replacing another engineer who resigned his job, I was left with a pile of files and folders completely disorganised. Lot of information was there, but not in an easily accessible manner.

62 Try to put program docs in integrator or EFDVS. Did use Dept. SharePoint® buy now not supposed to - replaced by EDMS??? use not clear.

63 You can never retain an engineer's experience using a tick box mentality. There is no substitute for experience, a good example of this are design rules which can be applied very poorly because they are not written correctly. The best way to retain corporate memory is for good HR planning where people are rewarded for staying in position.

64 Too much time is spent feeding the numerous 'processes.' When a 'new' process is introduced at least 2 old ones should be decommissioned.

65 I believe new engineering pick up the roles quickly, but the loss of information is a problem.

66 Pros: Benchmarking site is very useful in terms of design comparison and new technology. Cons: New documentation methodology need to be implemented for Localization projects. No specific documents available which explains the entire life of localization project.

67 Standard document storage would benefit, common requirements, deviations, and data storage in a structured way would aid info re-use and not repeat testing from step 1 or repeat mistakes etc.

68 Corporate data structure must be established to keep important data within company for a long time. Each function have to have solid / frozen structure.

69 People use to many private Excels, and everything should be able to be in SharePoint®, or the official Tools but people do not find the SharePoint® sites, as Key reasons: -Too complicated to find again back one SharePoint® -Each Region creates their different SharePoint® sites and lots of things still not global. -Each Supervisor/Manager, wants to have their Excels and there are double work from several departments, where one is looking for

information A, and the other looks for Information B. But at the End of the day, they are really tracking the same, with other formats. From my point of view we need someone to keep the overview of SharePoint®, but everyone creates so many pages as they want. And should not be allow to send Excels, so that slowly people get use to SharePoint®.

70 Suffer from different programme teams wanting same document stored in different locations, want master document location with linkage. Different vehicle teams sometime looking for different formats for the same engine. Better guidance for formats and when to store.

71 We go through many sites so we can make our job, why did we not have a only one site and system to query? How long time we need to train a new staff member? I don't understand why we have to use AVBOM if we have the WERS.

72 I suspect that most component teams suffer from an overload of data pushed out to the teams. It is not always easy to access and maintain systems that are not intuitive to use. AVBOM particularly bad press. Team SharePoint® recently activated, and is proving useful for retaining access to the data, but it needed a filing structure and a roadmap for program data. More useful than the W-Drive. but confidentiality needs to be managed closely.

73 There are no shared drives and no one knows any type of document storage system

74 We generally use APDM for storage + the various Ford general sites as part of our daily work i.e. access. You already know we should have a common standard across our business but we don't. Suspect you also know the answer to this survey. Valuable if we could get a common structure - good luck

75 I use a standardised PD document folder structure that was "recommended" to me by management 8 or 9 years ago. It is a great format and I have passed it along and recommended it to others as well. If you want an example, I can be contacted to provide it.

76 Need more time between retirements and training of replacements.

77 As a PD engineer, I expect to share our lessons more and more each other. Then we can work efficiently for our new program in Ford.

78 When I am on a trip, some work cannot be done by using other's computer.

79 Ford is a global company, need to collect the lesson learnt & experience & regional market condition from all Ford global plants, and store it in a global share drive or SharePoint®. It can help to hand down the experience and help to improve the design robustness. Thanks.

80 1. Format of the rank 1-5 questions is horrible. Cannot tell where one sentence starts and ends. 2. The last couple of questions give away the reason for the survey. In regards to knowledge loss, there are many experienced engineers within a group or department. Sadly, as a new employee looking to gain knowledge, these engineers do not readily give up the knowledge. Whether this is due to culture, fear of being passed over, or just general personality I do not know. But I can testify that in a group where almost half is new to Ford, most would rather approach the newbies rather than asked the experienced employees.

81 Hi Tim, I believe history files for engine team at FSA should be improved. Once I worked with FNA team, and they used to work with an e-DVP where all program tests was well managed and filed. It would be good to have the best in class file management process applied globally.

82 I think that a standardized PD document folder structure could help on a small scale, but over time would be ineffective. People seem to have a habit of only looking forward at the problems they can see coming, therefore making it difficult to look in old documents for assistance. The best solution seems to be talent acquisition and retention. Getting new hires into a position to succeed by having them work with/under more experienced people that already understand the systems, as well as the pitfalls that may be encountered.

83 I think the key thing is very early in the program to build yourself a structure tree of folders in both your email and storage location and use that. It should be easy enough for someone after you to get into and find things, but know doing that is tedious. The biggest issue I see is getting people to feel comfortable using a shared drive now with everyone being mobile. It makes it very difficult to trust being able to get to your files if you are not on the Ford network. One big suggestion we need to work on is a good way to provide an automatic backup of your local data to a server that is quicker than the methods currently being used.

84 We already have a dedicated document folder structure that works quite well. However, the facilitation of GIS standards and AFR compliance the way APDM does it would be greatly helpful.

85 Just by changing the structures would not force people to use them, thus when people leave and they did not update systems with their knowledge, it is still lost.

86 Lessons Learned from Program milestones should be documented and a sign-off prior to next mile stone should be done

87 We don't see a list that is OK to store PD information, and these places are not available for all the PD engineers.

88 This is an excellent project and will be of high value to the company. One of my biggest frustrations is difficulty in finding information when needed.

89 We need to follow a disciplined systems engineering design approach which records our failure modes and the mitigation against them

90 Changing tools and systems too frequently can put people off learning about tools that might otherwise help them in their work.

91 Finding documents such as FMEAs from old program is a good example of not storing data robustly.

92 Many people e-mail giant files rather than a link to a SharePoint® seizing in boxes. There should be a limit on e-mail size. SharePoint® / Web sites are fractured in location with missing or non-working links. Information is generally hard to find, the search function is not great. A standardised tree and SharePoint® links would be far more sensible. A web portal with search function to link to EDMS would be useful; I have never found it to be particularly intuitive or easy to navigate.

93 DVP&R share to local PD

94 Far too much variability in documents creation / individual doc structure & retention across individual engineers, sections, departments & functions. Everyone does what they want. No discipline.

95 My current role I work in TVM & note that the CRID 2 data base does not appear in the selection list

96 Data to be stored in shared drive as per project wise for future reference and considered as asset for the organisation.

Appendix I - SE KM Framework Case Study – Supporting Evidence

The following photos support the case study example used to validate the KM framework (section 6.3)

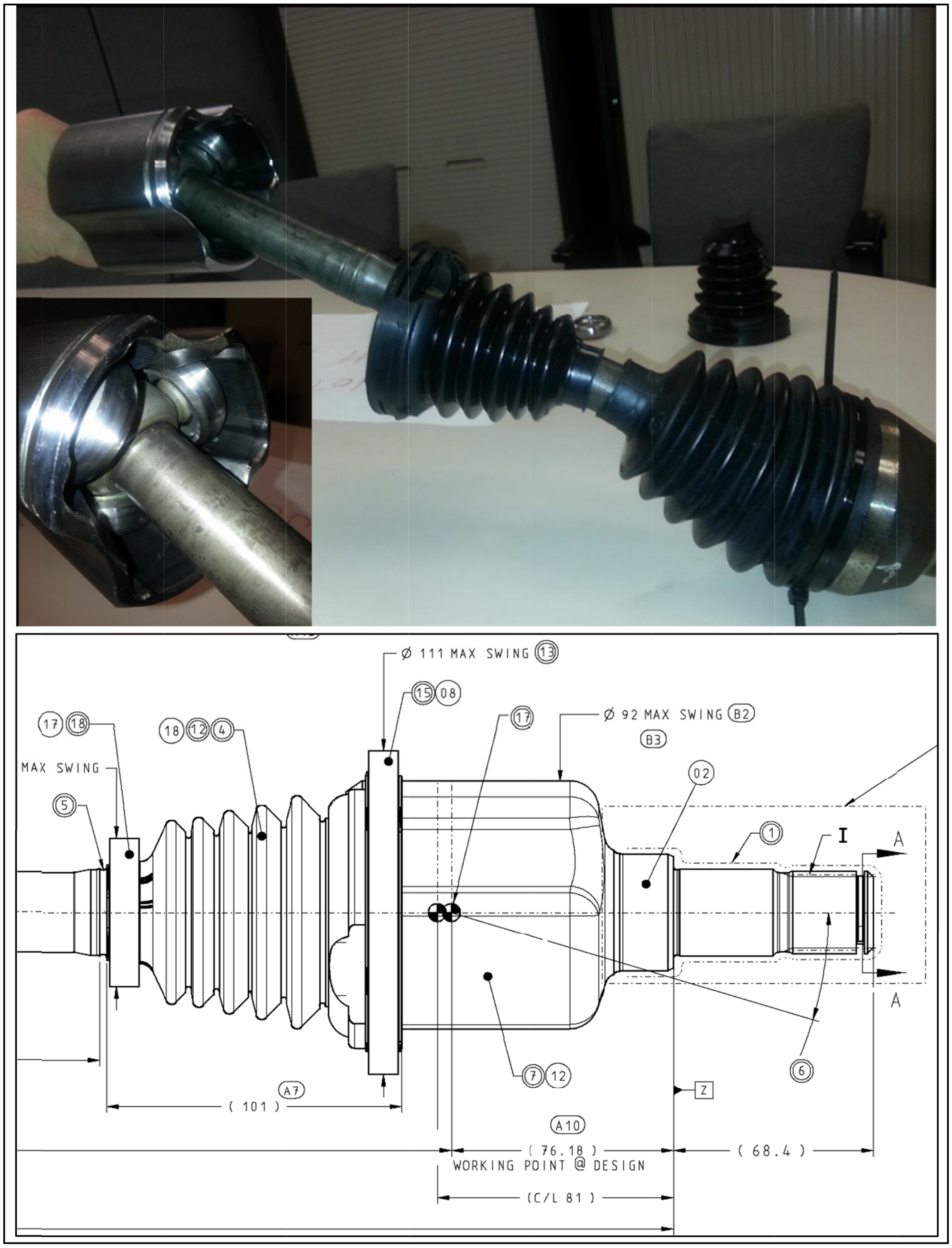


Figure 99. Framework Validation - Case Study: Driveshaft Inboard Joint

Figure 100. Framework Validation – Case study: Photos of Failed Component

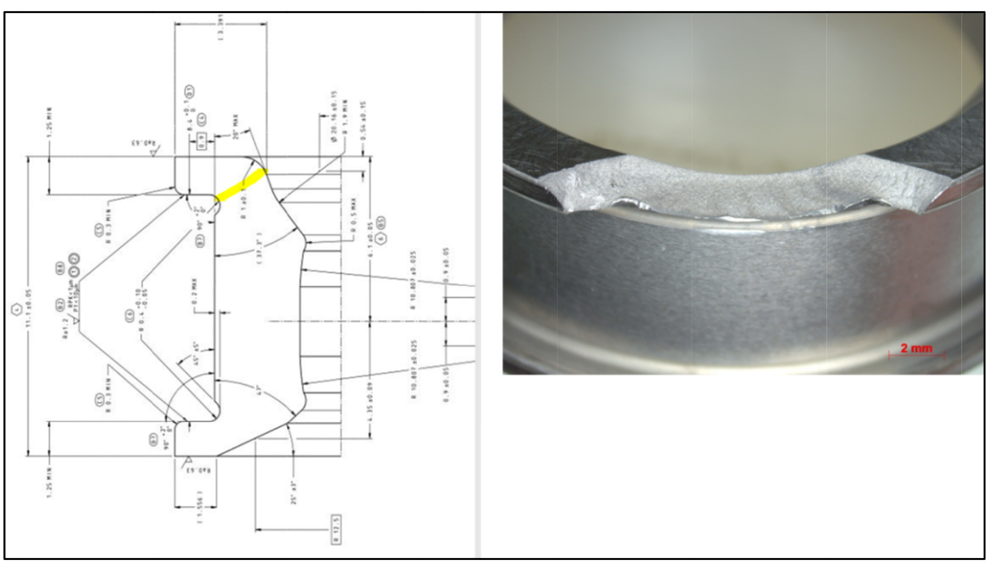


Figure 101. Framework Validation - Case Study: 2D Cross section of Inner Race

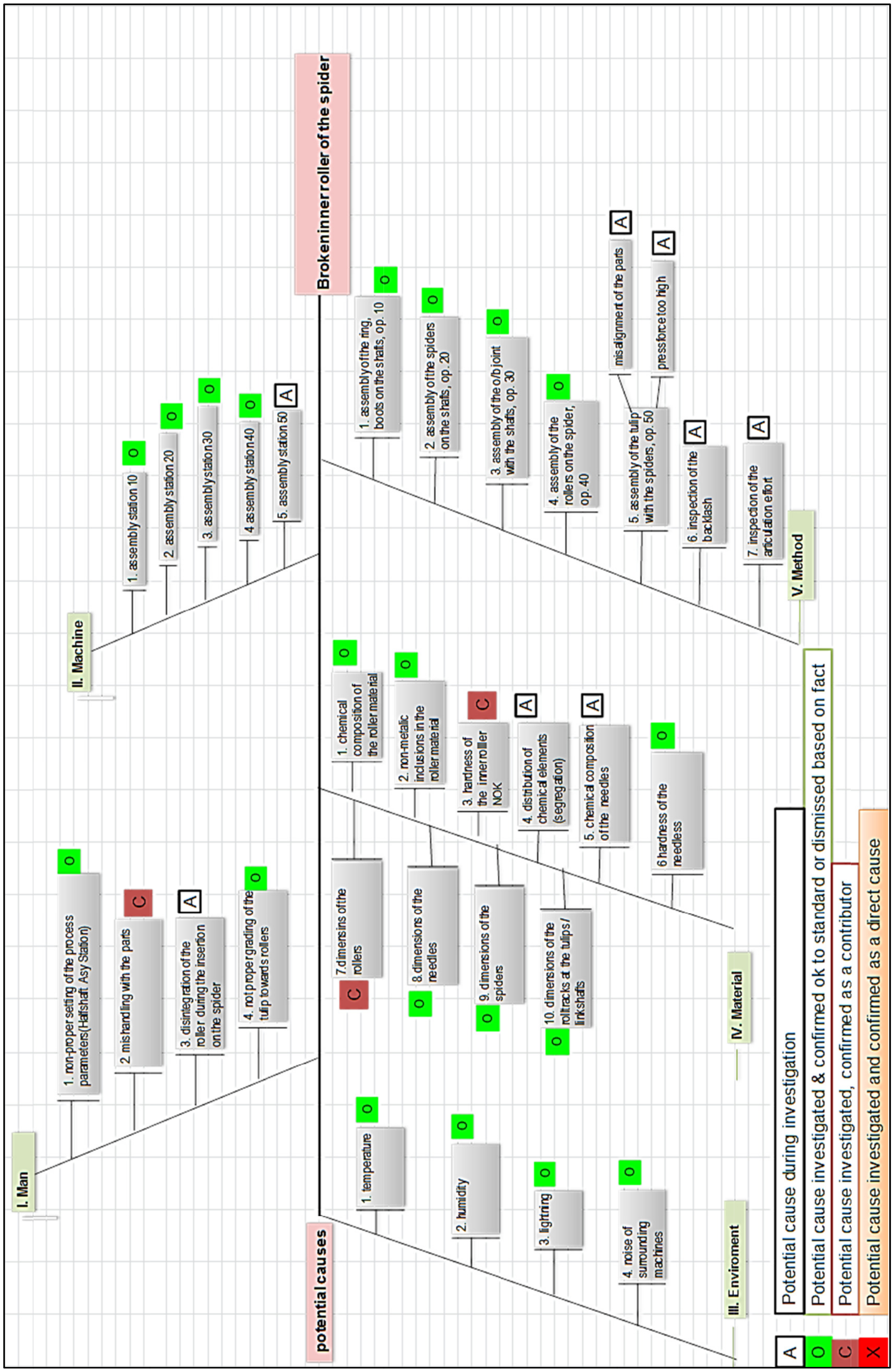
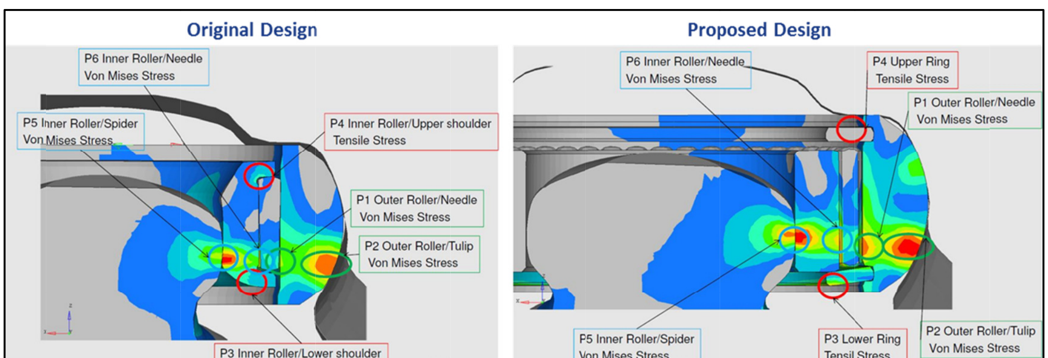


Figure 102. Framework Validation - Case Study 'Cause and Effect Diagram'

Figure 103. Framework Validation - Case Study: Vertical Axial Press Bench Test



Position				P1	P2	P3	P4	P5	P6
Design	Load	Angle	Displcacement	Element Stresses		Nodal stresses		Element Stresses	
				Von Mises Stress		First Principal		Von Mises Stress	
				Outer Roller		Inner Roller Soulder		Inner Roller	
				Inn	Out	Upper	Lower	Inn	Out
	[Nm]	[°]	[mm]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]
Reinf.03V01	1815	21.5	41.934	1382	2864	1582	1282	3019	1695
Integrated Roller V1				1538	2535	188	1533	1968	1507

Figure 104. Framework Validation - Case Study: CAE Analysis

Appendix J - Review of Commercial PLM Systems

The table below represents the brief overview of the key KM features built into the most popular commercially available PLM systems used within the automotive industry and supplier network (section 7.2)

Autodesk PLM 360	Siemens Teamcenter	Aras Innovator PLM	Dassault Systèmes 3DS PLM Solutions	PTC Windchill, PTC Creo, & PTC Arbortext
AUTODESK www.autodeskplm360.com	SIEMENS www.plm.automation.siemens.co	aras corp www.aras.com	DASSAULT SYSTEMES www.3ds.com	PTC www.ptc.com
Select Customers Porex, Electrical Components International, Zep Solar, Greenpoint	**Select Customers** Firewire Surfboards, Procter & Gamble, Astrium, BAE Systems	**Select Customers** CarestreamHealth, Xerox, Lear Corporation, Motorola, Freudenberg	**Select Customers** Jaguar, Minesto, Olympus, Boeing	**Select Customers** Axeon, Medco Equipment, Xerox Corp, InterComm
Key Features • Complete Product Lifecycle Management • Bill of materials (BOM) management • Engineering Change management • New product introduction (NPI) • Supplier collaboration • Quality management • Cost management • Integration with NetSuite ERP • Integration with Autodesk Vault and other PDM solutions • Integrated 3D product visualization • Dashboards and reporting • Highly customizable • Easy to use and configure • Accessible anytime, anywhere • Secure and Reliable • Fast to implement • Affordable for companies of any size	**Key Features** • Bill of materials mgmt • Community collaboration • Compliance mgmt • Content & document management • Engineering process management • Enterprise knowledge foundation • Formula, package, & brand management • Lifecycle visualization • Maintenance, repair & overhaul • Manufacturing process management • Mechatronics process management • Platform extensibility services • Portfolio, program & project mgmt • Reporting & analytics • Simulation process management • Supplier relationship management • Systems engineering & requirements mgmt	**Key Features** • Bill of materials mgmt • Multi-CAD PDM for CATIA, NX Creo, SolidWorks, Solid Edge, Inventor, AutoCAD, OrCAD, PADS, Altium, Alegro, DxDesigner and other CAD & EDA systems • Document mgmt • 3D PDF visualization with view & mark-up • Version control & release • Engineering change • CMII-certified best practices for configuration mgmt • AVL / AML • Project portfolio mgmt, program mgmt, NPDI • Requirements mgmt for systems engineering • Quality mgmt, risk mgmt, FMEA, APQP, PPAP • Extended enterprise collaboration • Microsoft Office Integration	**Key Features** • Complete line of Dassault Systèmes products includes: Catia, Solidworks, Geovia, Simulia, Enovia, Delmia, Exalead, Netvibes, 3DVIA, 3DSwYm, Draftsight • CATIA : the digital product experience • SOLIDWORKS : 3D design • GEOVIA : Virtual Planet • SIMULIA : Realistic Simulation • ENOVIA : Collaborative Innovation • DELMIA : Digital Manufacturing • EXALEAD : Information Intelligence • NETVIBES : Dashboard Intelligence • 3DVIA : 3D Communication • 3DSwYm : Social Innovation • Draftsight : Free CAD Software	**Key Features** • Windchill: • Product definition and collaboration capabilities • Repeatable, end-to-end process support and automation • Product deliverable management including MCAD, ECAD, service and documentation • Multiple cost estimation techniques • Reporting and analytics • Manage cost targets, multiple cost estimates, estimate confidence level per part • Creo: • Lightweight 3D CAD driven design process • User-friendly, collaboration-friendly • Scalable design software environment • Direct geometry creation and editing • Ownership, revision and state control • 3D to 2D associativity, part comparisons,&more

Table 33. Review of Commercial PLM Systems

Appendix K - Support Tool Evaluation – Interview Questionnaire

In the questions below the term 'tool' refers to the demonstrated Sharepoint® groupware.

Perceived Usefulness

Q1. Do you feel the tool would help improve knowledge capture and sharing between non collocated PD team members? Please explain:
Q2. Would the tool help you to find critical knowledge and information created by other engineers that you typically need to use as part of your role? Please explain:
Q3. Do you feel that co-locating all technology specific knowledge into separately partitioned sub sites is an appealing feature? Please explain:
Q4. Based on your limited observations do you believe that engineers would be willing to invest the time populate and maintain the tool? Please explain:
Q5. What do you see as being the main challenges and difficulties with encouraging the adoption of and use of the tool? Please explain:

Perceived Ease of Use

Q6. Does the structure and layout of the site, and sub sites, seem intuitive? Please explain:
Q7. Do you think any engineers will struggle to understand how to add new items into the correct areas and folder locations of the tool? Please explain:
Q8. Do you see there being any potential issues with managing the site structure and content? Please explain:
Q9. What do you see as being the main weaknesses and areas requiring improvement within the tool? Please explain:

Q10. Please provide any other comments: