CRANFIELD UNIVERSITY

NIKOLAOS MADENAS

INTEGRATING PRODUCT LIFECYCLE MANAGEMENT SYSTEMS WITH MAINTENANCE INFORMATION ACROSS THE SUPPLY CHAIN FOR ROOT CAUSE ANALYSIS

SCHOOL OF APPLIED SCIENCES

PhD Thesis
Academic Year: 2011 - 2014

Supervisors: Ashutosh Tiwari/Peter Ball
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This thesis is submitted in partial fulfilment of the requirements for
the degree of PhD

ABSTRACT

Purpose: The purpose of this research is to develop a system architecture for integrating PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise cross supply chain data in a single environment. By integrating product-data from PLM systems with warranty claims, vehicle diagnostics and technical publications, engineers were able to improve the root cause analysis and close the information gaps.

Methodology: The methodology was divided in four phases and combined multiple data collection approaches and methods depending on each objective. Data collection was achieved through a combination of semi-structured interviews with experts from the automotive sector, by studying the internal documentation and by testing the systems used. The system architecture was modelled using UML diagrams.

Findings: The literature review in the area of information flow in the supply chain and the area of root cause analysis provides an overview of the current state of research and reveals research gaps. In addition, the industry survey conducted, highlighted supply chain issues related to information flow and the use of Product Lifecycle Management (PLM) systems. Prior to developing the system architecture, current state process maps were captured to identify challenges and areas of improvement. The main finding of this research is a novel system architecture for integrating PLM systems with maintenance information across the supply chain to support root cause analysis. This research shows the potential of PLM systems within the maintenance procedures by demonstrating through the integration of PLM systems with warranty information, vehicle diagnostics and technical publications, that both PD engineers and warranty engineers were benefited. The automotive experts who validated the system architecture recognised that the proposed solution provides a standardised approach for root cause analysis across departments and suppliers. To evaluate the applicability of the architecture in a different industry sector, the proposed solution was also tested using a case study from the defence sector.

Originality/Value: This research addressed the research gaps by demonstrating that: i) A system architecture can be developed to integrate PLM systems with maintenance information to allow the utilisation of knowledge and data across the product lifecycle; ii) Network can be treated as a virtual warehouse where maintenance data are integrated and shared within the supply chain; iii) Product data can be utilised in conjunction with maintenance information to support warranty and product development engineers; iv) Disparate pieces of data can be integrated where later data mining techniques could potentially be applied.

Acknowledgements

I would like to thank the following people:

List of Publications

Madenas, N., Tiwari, A., Turner, C.J., Peachey, S., (2013), "Requirements Analysis for Decision-Support System Design: Evidence from the automotive industry", *Proceedings of the 11th International Conference on Manufacturing Research (ICMR2013)*, Cranfield University, 19-20 September 2013

Madenas, N., Tiwari, A., Turner, C. J., Peachey, S., Broome, S. (2014), "Integrating PLM Systems with maintenance information for root cause analysis", *Proceedings of the 8th International Conference on Modelling in Industrial Maintenance and Reliability (MIMAR)*, St Catherine's College, Oxford, 10-12 July 2014.

Madenas, N and Davies, A. (2014), "Integrating PLM systems with maintenance information across the supply chain", Proceedings of *the 12th International Conference on Manufacturing Research (ICMR2014)*, Southampton Solent University, 9-11 September 2014.

Madenas, N., Tiwari, A., Turner, C.J., Woodward, J., (2014), "Information Flow in Supply Chain Management: A Review Across the Product Lifecycle". *CIRP Journal of manufacturing science and technolog*y, vol. 7, pp. 335-346.

Madenas, N., Tiwari, A., Turner, C.J., Peachey S., (2014), "An analysis of supply chain issues relating to information flow during product development", *Journal of Manufacturing Technology Management* (Accepted – Under revision)

Table of Contents

List of Figures

List of Tables

List of Abbreviations

API: Application Programming Interface

APQP: Advanced Product Quality Planning

CAD: Computer Aided Design

ERP: Enterprise Resource Planning

FMEA: Failure Mode and Effect Analysis

MRO: Maintenance and Repair Overhaul

NTF: No Trouble Found

OEM: Original Equipment Manufacturer

OSA-CBM: Open Systems Architecture for Condition-Based Maintenance

PD: Product Development

PDM: Product Data Management

PLM: Product Lifecycle Management

POC: Proof of concept

PSW: Part Submission Warranty

SCM: Supply Chain Management

SOAP: Simple Object Access Protocol

SOA: Service-oriented architecture

SysML: Systems Modelling Language

UI: User Interface

UML: Unified Modelling Language

VIN: Vehicle Identification Number

XML: Extensible Markup Languag

Introduction

This chapter provides an introduction to this research project. Firstly, this chapter introduces the concepts of "information flow in the supply chain" and "root cause analysis" as a background to this research. Definitions for the key terms used are also presented in this section. Secondly, this chapter presents the wider "VE-DRIVE" project that this research was part of. Furthermore, the research motivation, the problem statement and the research scope are defined. Finally, a thesis structure is also presented to provide the reader with a general overview.
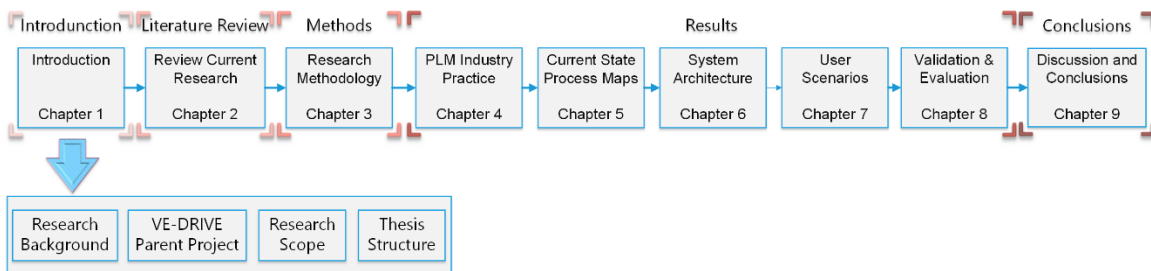
1.1. Research Background

This section introduces the concepts of "information flow in the supply chain" and "root cause analysis" and provides definitions for the key terms used throughout this thesis. These two concepts are considered fundamental to the activities undertaken in this research project. Moreover, this section covers the initial investigation and the challenges identified prior to conducting a detailed literature review.

1.1.1. *Information Flow in the Supply Chain*

This thesis is part of the wider literature in the area of information flow in the supply chain. The literature of information flow in the supply chain covers studies that

propose a range of research outcomes such as proof of concept studies, modelling techniques, framework and system architecture developments. This thesis examines how cross supply chain data can be used to support processes where supply chain collaboration is required, in this instance the root cause analysis process, and proposes a system architecture to aid this process. A detailed examination of the literature is provided in chapter 2.

During the last decade, Supply Chain Management (SCM) has changed significantly due to globalisation and the pace of technological innovation. Competitive pressures have forced companies to increase supply chain collaboration throughout the whole product lifecycle. To improve their ability to integrate processes, businesses are also facing the challenge of shorter product lifecycles, globally dispersed design teams, a constant increase in outsourcing and the market demand for mass customisation. This has forced companies to create demand-driven and flexible supply chains in order to satisfy customers' expectations. Key business processes are integrated through the supply chain while strategic knowledge and issues are shared in order to achieve mutual benefits (Lin et al., 2002).

The integration of supply chain systems has recently been under discussion in both information management and SCM literature. Through these publications a number of definitions have been used to define SCM. Although the definitions provided by Lambert et al. (1998) and Mentzer et al. (2001) are most commonly referred to; in this thesis the definition from Swaminathan and Tayur (2003) will be used, as it is more appropriate for the specific aspect of SCM that this research focuses on. Swaminathan and Tayur (2003) define *SCM* as "the efficient management of the end-to-end process, which starts with the design of the product or service and ends when it has been consumed and discarded by the consumer". *Information sharing* within a supply chain is defined as "the integration of information systems, decision systems, and business processes used to conduct information searches, manage business operations, monitor business details and perform other business activities" (Hsu et al., 2008).

SCM has become dependent on information flow as it can be characterised as the enabler of collaboration and improvement (Power and Bahri, 2005; Pereira, 2009; Vickery et al., 2003). Significant improvements can be achieved by integrating the information flow within the supply chain. OEMs can concentrate on the core activities of the product while using suppliers' additional resources, capabilities and skills to build lower cost and better quality products (Lindquist et al., 2008; Fliess and Becker,

2006). Often, suppliers have the capability, the knowledge and the expertise to develop better and more mature products. Bowersox and Calantone (1998) state that even though collaboration in the supply chain is not new; information advantages have only recently allowed companies to exchange more accurate and low-cost information. Information technology is only one element of the supply chain equation but it can be characterised as the enabler for improvements in global operations.

The evolution of technology and the internet have allowed the development of web-based systems that can lead to improved collaboration within the supply chain. Within the manufacturing industry, digital systems are used daily to design, develop, produce, deliver and support products for global markets. However, the wide range of systems used, such as Computer Aided Design (CAD), Product Data Management (PDM), Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), have created the landscape of "Isolated Islands of Information" where information is locked in different repositories, making it difficult to share. Although some of these systems allow data exchange in a dynamic and direct way, organisations still need to work closely with suppliers to improve the decision making process and the entire supply chain performance (Fiala, 2005; Rungtusanatham et al., 2003). An area that has received significant attention during the last decade is that of PLM systems mainly due to the potential they offer for improving supply chain collaboration. CIMdata (2002) define *PLM* as "a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems, and information". Although the benefits that can be obtained when using a PLM system are significant, SMEs cannot easily integrate PLM systems (Duigou et al., 2011). In addition multinational suppliers, required to work with multiple OEMs, are facing similar challenges as integrating multiple PLM systems is considered inevitable. As PLM systems require considerable investment of time and resources, suppliers are now facing the challenge of being able to integrate their systems and share information with various OEMs.

One of the main reasons that many researchers have highlighted the importance of information flow in the supply chain is the continual increase in its complexity. Operating in this new complex environment, collaboration is no longer a theoretical concept but a widely adopted supply chain practice (Wiengarten et al., 2010).

1.1.2. *Root Cause Analysis*

Root cause analysis is defined as "the establishing of logically complete, evidence-based, tightly coupled chains of factors from the least acceptable consequences to the deepest significant underlying causes" (Latino et al., 2011). Root cause analysis within the automotive sector has become more complex due to the number of participants involved, the volume and the structure of information required, and the high number of interrelated functions that are impacted both upstream and downstream in the value chain. In addition, in the last couple of decades, there is a constant growth of electronic systems in vehicles which increased their complexity and restricted the dealer's ability to diagnose and resolve a problem (Chougule et al., 2011).

During the warranty period, identifying the root cause of a particular in-service product failure and developing knowledge such as trends and patterns between product failures and warranty claim attributes is key in achieving warranty cost reduction (Buddhakulsomsiri et al., 2006). As suppliers are often responsible for supplying not only individual parts, but in many cases complete sub-systems, they need to work closely with OEMs to analyse claims and understand interactions among all the systems involved. *Fault* is defined as "an unpermitted deviation of at least one characteristic property or parameter of the system from the acceptable, usual or standard condition" while *failure* is defined as "a permanent interruption of a system's ability to perform a required function" (Nke, 2013).

In the last few decades, vehicle manufacturers have developed diagnostic sensors which are embedded in vehicles and are used to quickly detect component or systematic failures (Rajpathak, 2013). Vehicle sensors not only constantly monitor the operation of critical systems but also provide great insights for warranty and PD engineers. Gulledge et al. (2010) state that proactive equipment maintenance is based on real-time data extracted from embedded sensors and external tests that are extracted from the equipment. The area of maintenance is currently more related to the aerospace sector as the profitability of the aerospace industry relies, not on the sale of the aircraft but from maintaining the product for a longer period of time (Lee et al., 2008). Similarly, recent examples from the automotive industry showed that critical vehicle failures can have an adverse effect on company's profitability and brand reputation. Although vehicle manufacturers were traditionally focusing on introducing new vehicles in the market as early as possible, they are now concerned about the increased warranty costs which can have an impact on both customers'

satisfaction and brand reputation. This observation can be enhanced by Bates et al. (2006) study which questions if one of the side effects of faster lead times is the increased number of vehicle faults. Bates et al. (2006) examines patterns and trends in motor vehicle safety recalls using a UK dataset between 1992 and 2002 and provide ideas that may explain these patterns. Mannar et al. (2006) state that although studies in the area of warranty analysis extract important information related to lifetime and failure rates, they do not demonstrate how these data could feed back to manufacturing or design in order to identify interactions between design changes and warranty failures. The use of maintenance information such as vehicle diagnostics from the sensors, warranty claims and technical publications in relation to design data from the PLM systems could potentially offer significant benefits. This research examines the integration of PLM systems with cross supply chain maintenance information to support root cause analysis.

1.2. **"VE-DRIVE" - Parent Project of the Research**

This research was part of a wider research project under the name VE-DRIVE (Virtual Enterprise-Digital Resource Integration Visualisation and Exploitation). VE-DRIVE was a £1.28m, 2-year collaborative research and development project, co-funded by the Technology Strategy Board and the project partners, started on December 2011 and completed on January 2013. The project consisted of four project partners from across market sectors and supply chain positions with Jaguar Land Rover (JLR) acting as the lead, BAE Systems, Theorem Solutions and Holovis International and with project management support provided by Axillium Research.

The aim of the project was to: "generate technology and expertise to connect digital technologies across supply chains and deliver the key innovation of directly linking digital product development approaches to the consumer in new digital and immersive environments. By applying a new generation of connected, digital environments to product life cycle, this project aimed to add value directly at all stages through direct user interaction with virtual information, content and services in digital 'showrooms' and wider 'virtual' environments."

1.2.1. *"VE-DRIVE" and This Research*

The author of this thesis supported the wider project by conducting the background investigation as well as designing the system architecture. Therefore the background investigation, the research gap identification, the requirements elicitation and modelling as well as the design of the system architecture for the automotive use case was part of the researcher's main responsibilities. The outcome of this thesis

was used by the two software development partners to develop a Proof Of Concept (POC) system that was used to test the functionality of the architecture and demonstrate the benefits achieved. Theorem Solutions was responsible for developing the data aggregator and the user interface for a desktop application, while Holovis International was responsible for developing the user interface for a high-end immersive environment (CAVE and Powerwall). BAE Systems conducted requirements elicitation and analysis within their own organisation as well as supported the development of the system architecture with a view to extend the architecture further by including ontological representations for data selection and developing a user interface for portable devices.

Although this research was conducted with the sponsor's support, the outcome of this thesis was based on semi-structured interviews with multiple automotive companies and therefore it does not represent processes, challenges or opportunities coming from a specific OEM manufacturer. A detailed data collection approach is presented in section 3.2. In addition, the proposed solution was validated using semi-structured interviews with experts from a vehicle manufacturer and a tier-1 automotive supplier, ensuring that the outcome of this research is applicable to the wider automotive sector.

1.3. Research Motivation

In large and complex automotive supply chains, suppliers are often responsible for supplying not only individual parts but in many cases complete sub-systems. Therefore, in order to improve product quality, companies need to extend their area of analysis and decision making to include not only their internal business units but also their supply chain (Baihaqi and Beaumont, 2006). Recent advances in IT have enabled companies to improve supply chain collaboration and share more accurate information. However the vast amount of systems used to design, develop, produce, deliver and support products for global markets has created a major barrier in information sharing. Recent investments on PLM systems demonstrate how important is for manufacturers to improve supply chain collaboration as well as store data in a central location. It is worth pointing out that during the recent years there has been a significant investment on PLM systems, making PLM a $33.4 billion industry in 2012 (McLeod, 2013) compared to $16 billion in 2004 (Tang and Qian, 2008). Although PLM systems offer a centralised location for maintaining and managing product data, their focus is still fragmented within the product development phase of the product lifecycle (Lee et al., 2008). The integration of maintenance

information such as vehicle diagnostics, warranty claims and technical publications with PLM systems will allow information and knowledge to be reused both by PD engineers and by warranty engineers. As information sharing is the enabler for improving the decision making process and the entire supply chain performance, it is important not only to determine the level of access for suppliers but also determine how processes are integrated and what information should be made available to suppliers.

In the automotive sector, it is estimated that warranty costs represent 2.5-3.0% of the OEMs revenue (Sairamesh et al., 2004; Sureka et al., 2008). The latest figures show that 586 recalls were responsible for more than 16 million vehicles being recalled in the US alone in 2012 (National Highway Traffic Safety Administration (NHTSA), 2012). Root cause analysis and decision making rely heavily on providing all the involved stakeholders with timely access to the right amount of information. Manufacturers invest a significant amount of time and resources in order to develop the infrastructure required to capture, monitor, evaluate or in some cases predict warranty problems. Root cause analysis is usually supported by terabytes of data captured within multiple software applications, usually developed to support proprietary methods of working. Manufacturers need to provide engineers with the appropriate amount of information required for root cause analysis in order to understand the system interactions, internally and externally, as well as the environment conditions that the system was operating. Although it can be argued that one of the main challenges that currently engineers encounter is the ability to utilise too much information, the interpretation of those data and their transformation into knowledge could potentially lead to significant cost reductions in warranty as well as improvements in customer satisfaction and product quality.

The intention of this research is to create a shared working environment that removes as much technological burden from suppliers as possible since currently supplers are obliged to meet the OEM's requirements. This research will provide engineers with a shared working environment that helps OEMs and suppliers to take advantage of all the required information in a timely manner in order to improve root cause analysis and close the information gaps.

1.4. Problem Statement

Founded on the research motivation outlined in section 1.3, the problem statement is formulated based on some of the key challenges:

- ***Complexity of root cause analysis for maintenance***: Root cause analysis within the automotive sector has become more complex due to the number of participants involved, the volume and the structure of information required, and the high number of interrelated functions that are impacted both upstream and downstream in the value chain. In most cases, it is very difficult to differentiate between an actual part defect and a system related failure. In addition, the constant growth of electronic systems in vehicles have increased the complexity of the product and made root cause analysis even more challenging. MacDonnell and Clegg (2007) highlight the lack of automation in managing maintenance supply chains as until recently organisations have developed multiple internal systems to manage different types of maintenance information and as a result they now face the need to develop transaction standards and integrate those systems.

- ***Multiple systems and process-disconnections:*** Root cause analysis needs to be data driven in order to interpret a "problem perception" into a real tangible and measurable cause. Therefore information needs to be easily accessible from OEM and supplier engineers. The vast amount of systems used within the automotive sector, including enterprise systems such as PLM and ERP systems, make the integration among suppliers and OEMs challenging. In most companies, integration is done in an ad-hoc manner which restricts the ability to extend the integration to new operations. Each one of the software applications is designed to work with its own database and as these systems are purchased from multiple vendors they are designed using different database management systems.

- ***Multi-format information:*** In most organisations, information such as warranty claims, vehicle diagnostics, technical service bulletins and CAD models are distributed among heterogeneous databases and multi-vendor systems. Therefore information are saved in multiple formats which makes integration even more challenging.

- ***System infrastructure***: While suppliers aim to meet the needs of OEMs in terms of product, their methods of working are individual and restricted by their own level of technological adoption. Most of the systems offer little or no integration capabilities which makes information sharing difficult. In addition, as suppliers are required to meet the OEM's requirements in terms of systems used there is an additional cost that suppliers are forced to cover in order to build the OEM's infrastructure.

Based on the challenges explained, this research will integrate the right level of information required to support root cause analysis by allowing engineers to visualise cross supply chain data in a single environment. By integrating PLM systems with maintenance information, it is expected that engineers will be able to improve the root cause analysis and close the information gaps.

1.5. Research Scope

This research is concerned with improving the information flow in the supply chain during the maintenance phase of the product lifecycle within the automotive sector, and its focus is on developing a system architecture for integrating cross supply chain data to support engineers with root cause analysis. Therefore the areas of information sharing related to root cause analysis and supply chain collaboration comprised the high level scope of this research. The scope became more specific and included the integration of PLM systems with maintenance information, as stated in the tile of this thesis, once the literature review was completed and research gaps were identified. Although the system architecture was developed to support the automotive sector, an evaluation case study from the defence sector was selected in order to test the applicability of the architecture in a different industry sector.

The outcome of this research provides the "design blueprints" for developing a software application that allows engineers to integrate PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise cross supply chain data in a single environment. Moreover the outcome of this research provides insights on the data required, the decision points and the processes followed by automotive engineers during root cause analysis.

1.6. Thesis Structure

This thesis is divided in the following nine chapters. Figure 1-1 shows a diagrammatic approach of the thesis structure.

Chapter 1 presents a high-level research background by introducing the areas of information flow in the supply chain and root cause analysis. In addition this chapter describes the research motivation, the problem statement, the scope and outlines the structure of this thesis.

Chapter 2 presents the detailed and structured literature review in the area of information flow across the supply chain mainly during maintenance and warranty procedures. In addition a comprehensive review of system architectures proposed in the literature to improve information sharing across the supply chain is also provided.

The outcome of this chapter is the identification of the research gap that will determine the aim and objectives of this research.

Chapter 3 presents the aim an objectives, the chapter explains how this research was carried out and demonstrates the research methods used. Furthermore, the overall research methodology, the data collection approach and the methods applied for each objective are described in this chapter.

Chapter 4 purpose is to identify, measure and prioritise the perceived importance of supply chain issues related to information flow and the use of PLM systems within the automotive industry. This analysis provides a good understanding on how PLM systems are currently utilised which will feed into the development of the proposed system architecture.

Chapter 5 presents two business process maps that describe the flow of maintenance information, including tasks and information systems used and highlights significant challenges and critical operating issues that will drive the development of the proposed system architecture.

Chapter 6 purpose is to analyse and model the requirements captured as well as demonstrate, through the use of three different architectural views (use case, static, dynamic), the interactions among the end users and the proposed system, the structure and the dependencies between the different elements of the proposed system, and the sequences of tasks that occur within the proposed system over time.

Chapter 7 describes three user scenarios and explains how the proposed system architecture could be used to deliver the use cases. Three scenarios were captured, one for each key use case.

Chapter 8 is two-fold: The first part validates the outcome of the proposed system architecture through experts' opinion. The second part of this chapter covers the evaluation of the system architecture in a different industry sector. A use case was used to evaluate the applicability of the proposed system architecture within the defence sector.

Chapter 9 concludes the thesis with a discussion on the key outcomes of the research, the contribution to knowledge and the research limitations. In addition, this chapter provides directions for further research.
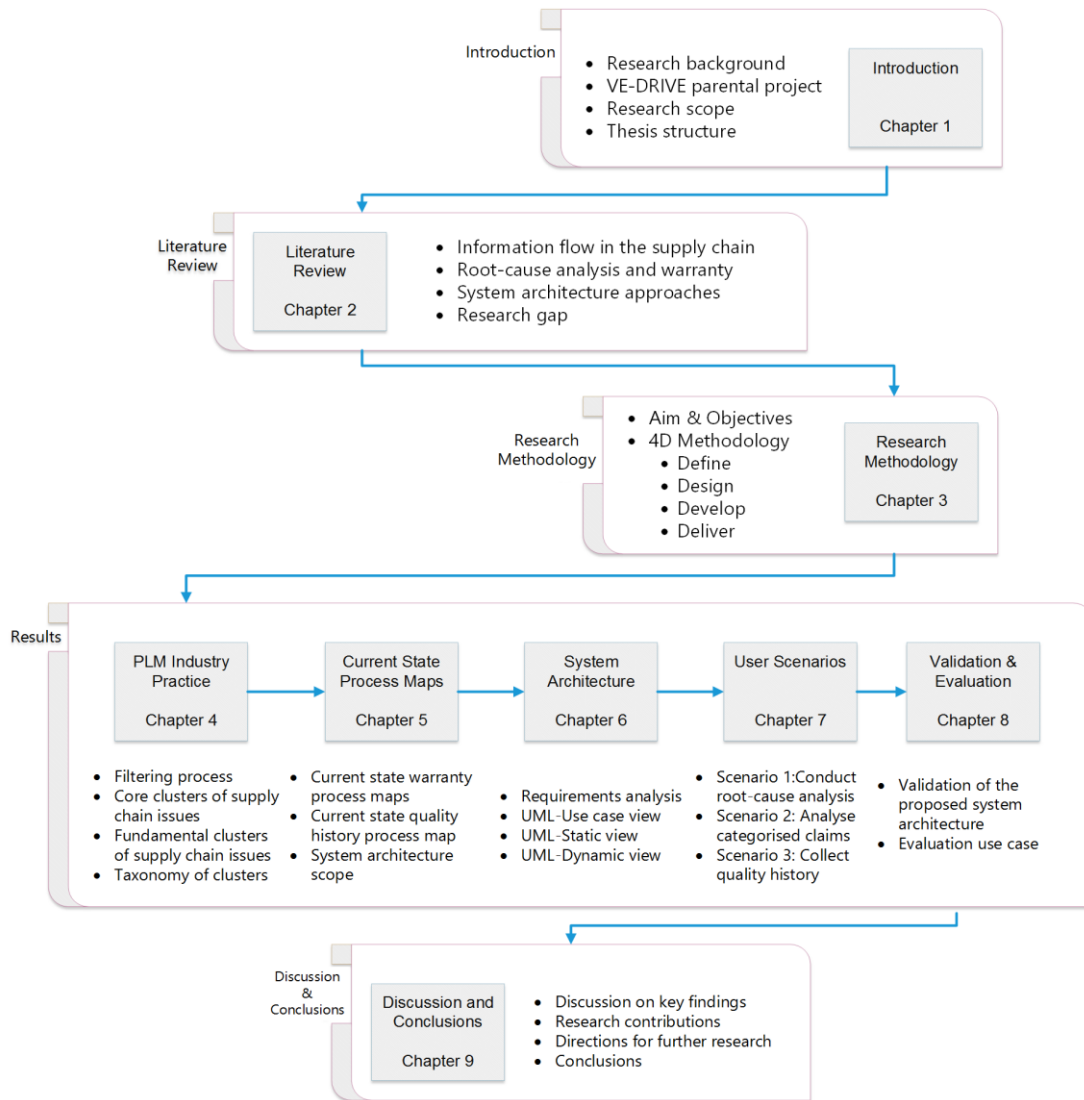
Figure 1-1 Thesis Structure

Literature Review

This chapter presents a structured literature review in the area of information flow across the supply chain mainly during maintenance and warranty procedures. In addition a comprehensive review of system architectures proposed in the literature to improve information sharing across the supply chain is also provided. This chapter is divided in five core sections. Section 2.1 provides an overview of the chapter with an explanation of how the different sections are linked. Section 2.2 presents a holistic literature review to capture background information in the area of information flow across the supply chain while 2.3 focuses solely on the area of root cause analysis and warranty procedures. Section 2.4 provides a review of articles related to system architecture development in order to capture best practices and methodologies used. Finally section 2.5 presents the research gap that this research aims to address.
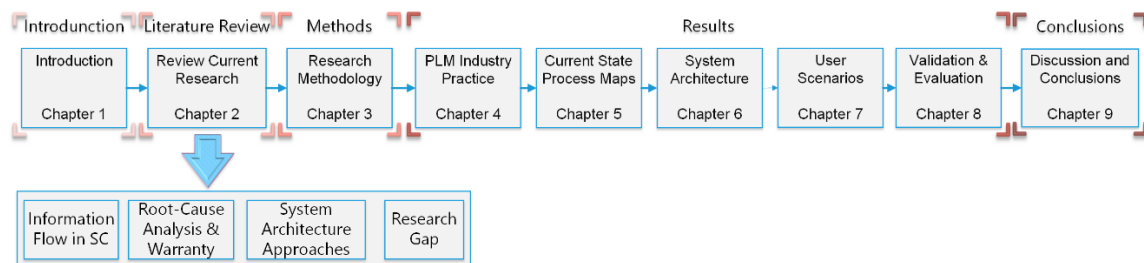
2.1. Introduction

The introduction in chapter 1 outlined the scope of this research project and demonstrated the importance of researching this area further. Within this chapter, a structured approach was followed in order to review the existing literature and identify research opportunities. Figure 2-1 shows the different areas of literature reviewed.
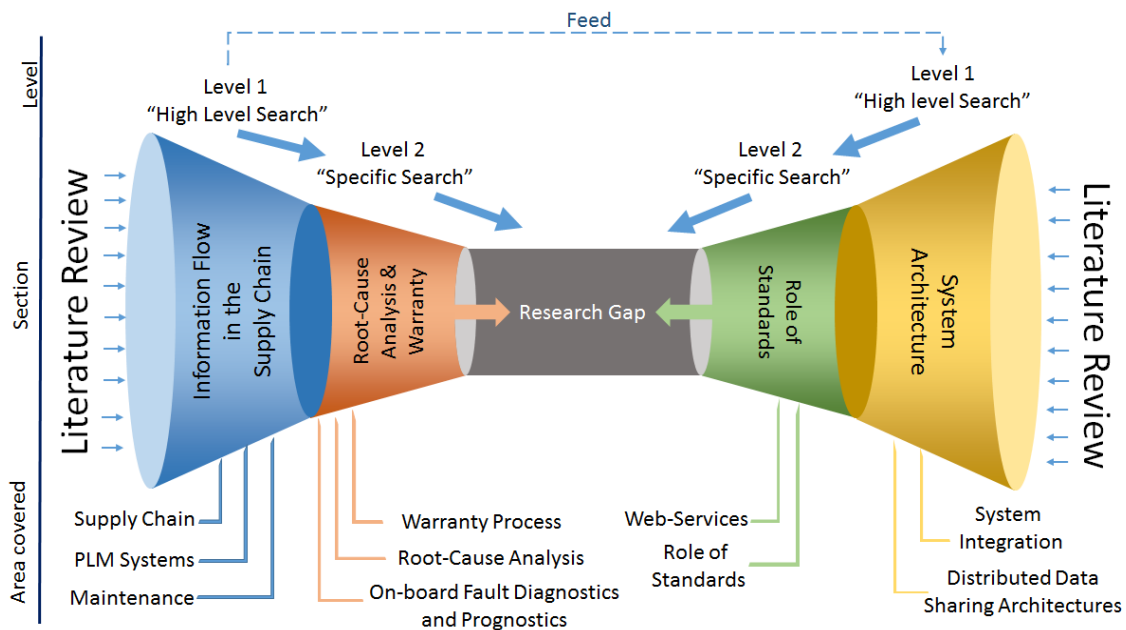
Figure 2-1 Literature Review Overview

Section 2.2 provides a literature review in the area of information flow within the supply chain. Although the aim of this research is to integrate PLM systems with cross supply chain maintenance information to support root cause analysis; the literature review in section 2.2 covers the product lifecycle scope including product development and manufacturing. By conducting a wider review, the author was able to analyse the literature in each phase of the product lifecycle and through cross-phase examinations, which provided a better understanding of the current research gaps as well as methodologies, best practices and research trends. A classification framework is proposed and clusters the articles based on the product lifecycle phase: (i) PLM, (ii) PD, (iii) Manufacturing, (iv) Logistics & Maintenance and the type of each article: (a) review (b) proof of concept (c) modelling & frameworks (d) system architecture. The outcome of this section provides a strong input on defining the research gap and is linked with three areas of the research aim: (i) PLM systems, (ii) maintenance information and (iii) supply chain. Section 2.3 focuses solely on the root cause analysis literature and reviews multiple areas such as on-board failure diagnostics and prognostics, FMEA and warranty analysis including data mining techniques. This part is linked with the root cause analysis area of the research aim.

The purpose of this section is to capture previous work done in the area of warranty root cause analysis in order to ensure that the research scope was covered and no meaningful publications have been missed. As the purpose of this research is to propose a system architecture, section 2.4 focuses exclusively in the area of "system architecture" from the classification framework proposed. The outcome of this review justifies the selection of several architectural decisions such as the use of XML-based data sharing architectures and the JT and XML file formats. Finally section 2.5 discusses the research opportunities identified and presents the research gap that this thesis will address.

2.2. Information Flow in the Supply chain

Over the last two decades, many industries, including the automotive industry has undergone a major transformation. Nowadays, due to market change and the increased inclusion of electronic parts in vehicles, the automotive industry is producing different and more complex products while facing the challenge of maintaining their flexibility by delivering more content to consumers at reduced prices (Swiecki and Gerth, 2008). Moreover the increased product development pace in the automotive sector means that an increased number of new products will be introduced within a year, making the reduction of time-to market even more significant (Waurzyniak, 2006). Therefore, the industry is currently operating in a completely different landscape. This has led the automotive manufacturers to re-evaluate their operating models in order to meet customer expectations and face the upcoming challenges. In this complex, global environment knowledge resides in each part of the value chain as companies rely on technologies and services provided from partnerships with other organisations (Hu et al., 2010). Literature suggests that a number of benefits can achieved through supply chain collaboration (Wiengarten et al. 2010), such as sharing risks, reducing costs and time to market. This collaboration, however, brings many challenges and risks which can only be justified by the increased benefits that can potentially be achieved. A failure of delivering consistent information to every supply chain participant might result in design iterations and waste time and resources for every member of the value chain.

Whenever OEMs share their information and knowledge with suppliers, they allow their knowledge assets to become public and as a result risk their competitive edge (Kyu Kim et al., 2011). Therefore, the level of integration into OEMs' processes and the depth of collaboration need to be defined. The level of information sharing is defined by (Li et al., 2006) as the extent to which critical and proprietary information

is communicated to one's supply chain partner. Several researchers have focused on clustering the different types of relationships between suppliers. A classification of suppliers is key for OEM and Tier 1 companies as it will drive the type of connection required for each cluster of suppliers as well as reduce the number of suppliers required to become directly connected. Multiple types of categorisation have been proposed in the literature and can be used as a starting point for clustering suppliers and as a result reduce the cost in managing multiple types of relationships (Dyer et al., 1998; Lambert and Cooper, 2000; Petersen et al., 2005; Fliess and Becker, 2006; Tang and Qian, 2008; Uusipaavalniemi and Juga, 2009).

Much of the research in this field over the last decade has focused on specific phases of the product lifecycle. It is critical at this point to summarise the work that has been completed over the last decade in each phase of the product-lifecycle. The review of Power (2005) focuses on SCM integration and implementation from a strategic perspective. Although Power follows a holistic approach, most of the examples and the use cases demonstrated focus on the manufacturing phase. Similarly, Pereira (2009) reviews the current issues and trends in the IT-enabled SCM strategy using examples from manufacturing and logistics case studies. Burgess et al. (2006) provides a very structured review on SCM. Burgess et al. (2006) highlight that SCM is relatively a "young" field with exponential growth in interest from researchers. Arshinder et al. (2008) provide a literature review with an emphasis on SC coordination. A framework is provided to support further research. The work of Marra et al. (2012) explores IT enabled SCM from a knowledge management perspective. This review highlights the importance of measuring the impact of knowledge management in supply chain performance by directly relating IT adoption to the firm's growth. Helo and Szekely (2005) examine the benefits of SCM that can be achieved through logistics information systems. This review paper demonstrates a software classification which includes applications that improve the information sharing in the manufacturing and service phase. Huang et al. (2003) discusses the impact of information sharing in supply chain dynamics. This paper proposes a framework for categorising literature and research publications based on three key elements: supply chain structure, level of decision, and the production information model. Discussing mainly the information flow in the manufacturing phase and how suppliers exchange information such as capacity variances data, order data and lead times, this comprehensive review paper is a very good example of literature classification as it clearly shows the different types of information shared among the supply chain members as well as various modelling approaches used by

researchers. Buyukzkan and Arsenyan (2012) is the only review identified in this study that investigates the area of collaborative product development and provides future direction to support information flow during product development.

2.2.1. *Methodology for the Analysis of Literature in the Area of "Information Flow in Supply Chain"*

This section examines publications between 2000 and 2012 that study the subject area of information flow in SCM. It is important to highlight that studies that examine either the information flow internally in organisations or the general literature of SCM are not included in this literature review. In addition, studies that discuss the subject area from high level without referring to a specific phase of the product lifecycle are also considered out of scope. Figure 2-2 shows the selection and evaluation process that was taken in order to cover the whole product lifecycle.

Once the scope of the literature was defined, the selection process involved searching in the SCOPUS online database for peer-reviewed journal articles. From the SCOPUS database using two combinations of keywords, "supply chain" AND "information flow" and "supply chain" AND "information sharing", 1400 articles were identified. Through a filtering process the authors limited the search by excluding publications before the year 2000. In addition any conference papers, books and notes as well as publications that focus on subject areas outside of the research scope were also excluded from the analysis. As a result the total number was reduced to 676 publications. The abstracts from the first 200 most relevant papers were assessed in order to examine their fit with the scope of the research. As most of the articles identified at this stage focused on the manufacturing and logistics phase a combination of keywords and a filtering process was utilised to ensure that the whole research scope was covered. The use of "supply chain" and "information flow" keywords did not reveal any publication that focused solely on the product development phase. Only by including "product development" and "information" or "collaborative product development" as keywords would relevant publications be returned for this phase. Therefore the second part of the selection and evaluation process which was related to specific searches was used to ensure that the selected keywords would cover the research scope. In this way, no meaningful publications have been missed.
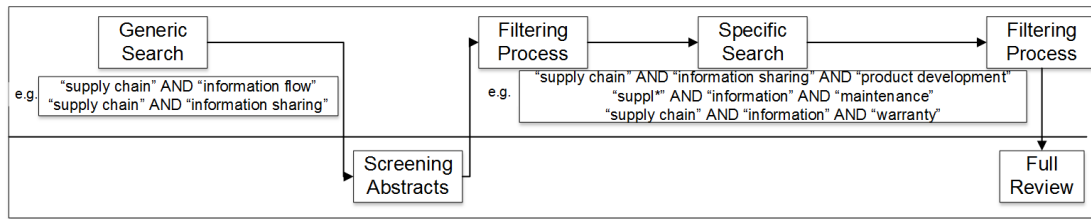
Figure 2-2 Selection and Evaluation Process

From the aforementioned research approach and by excluding papers out of scope a total of 132 publications were analysed. As a number of the articles fit in more than one category, the total number of publications included in the framework is 152. Each article was examined in detail, evaluated and then categorised in the framework. The framework defined in Table 2-1, is a two-dimensional table which is structured to classify articles based on each phase of the product lifecycle and the type of each publication. The author decided to separate PLM as an independent part of the framework in order to include either articles that discuss the information flow through the whole product lifecycle or from a PLM system perspective. This selection was based on the premise that PLM systems have received significant attention over the last 5 years and based on the definition provided in section 2.2.2.1 they cannot be linked to a specific lifecycle phase as PLM systems can be used to store and maintain data from concept to end of life. Therefore this approach allowed the publications related to PLM systems not to be hidden inside the PD phase where currently the main focus lies.

Table 2-1 Framework Definitions

	PLM	Product Development	Manufacturing	Logistics & Maintenance
All the publications included in this table focus on the subject of "Information flow in SCM"	Includes: • Articles that discuss the information flow through the whole product lifecycle or from a PLM system perspective	Includes: • Studies that discuss the information flow in SCM in the PD phase * *Studies that refer to the PLM systems but focuses only in the PD phase are also included in this column*	Includes: • Studies that discuss the information flow in SCM in the manufacturing phase	Includes: • Studies that discuss the information flow in SCM in the logistics and maintenance phases * Studies that refer to the flow from the customer and the retailers back to OEMs are also included in the Logistics & Service phase

Review
• Publications that base their findings in the literature

Proof of Concept
• Publications that through empirical and conceptual research discuss the subject of information flow SCM without using any quantitative analysis

Modelling & Framework
• Publications that propose a generic framework to address issues or through modelling techniques simulate or measure the benefits of the information flow in SCM

System Architecture
• Publications that propose an architecture or a system that improves the information flow in SCM

* Exceptions

Once the table possessed a valid range of publications, each part of the framework was analysed in depth in order to identify current research gaps and provide directions for further research. Articles were not only analysed based on each part of the classification framework but were also reviewed holistically to identify the journals, the country of origin and the year of the publication.

2.2.2. *Literature Classification and Analysis*

As information sharing occurs in each phase of the product lifecycle from concept definition and PD to manufacturing and service, it is important to understand the benefits that information sharing can bring as well as the modelling techniques and the systems proposed in the literature to support the communication among OEMs and the supply chain. Table 2-2 shows the classification of the 132 articles identified within literature through the selection and evaluation process. Articles that fit in more than one category are marked with an asterisk and are highlighted in italics as shown in Table 2-2.

The analysis of the 132 articles showed that there is no journal that is dominating in the area of information flow in SCM. The articles are almost equally spread over 50 journals that cover a wide variety of topics and disciplines such as information management, supply chain management, manufacturing systems, CAD design etc.

The analysis of the articles from a country of origin perspective showed that USA is leading in this area. USA is responsible for 29% of the publications included in the classification framework, the majority of which are in the "proof of concept" and "modelling & frameworks" areas. Similarly, UK publications tend to focus on the "proof of concept" and "modelling-framework" areas with 10% of the total number. Closer examination showed that publications from Asian countries such as China, South Korea and Hong Kong are responsible for the majority of publications in the "System architecture" area.

Table 2-2 Literature Classification

	PLM	Product Development	Manufacturing	Logistics & Maintenance
Review		Buyukozkan and Arsenyan (2012)	* Burgess et al. (2006) Power (2005) * Helo and Szekely (2005) Perreira (2011) Marra (2012) * Swaminathan and Tayur (2003) Huang et al. (2003) Arshinder et al. (2008) * Ho et al. (2002)	*Burgess et al. (2006)* *Helo and Szekely (2005)* *Swaminathan and Tayur (2003)* *Ho et al. (2002)*
Proof of Concept	Waurzyniak (2006) * Kiritsis et al. (2003) Rachuri et al. (2008) * Luh et al (2011) Ming et al. (2005) * Lee et al. (2008) * Merminod and Rowe (2012)	Fliess and Becker (2005) Schiele (2010) Liu and Xu (2001) *Luh et al (2011)* *Merminod and Rowe (2012)* Fagerstrom and Jackson (2002) Reed and Walsh (2002)	Dunne (2008) Tarn et al. (2002) Barratt and Barratt (2011) Childerhouse et al. (2003b) Soroor et al. (2009) Welker et al. (2008) Childerhouse et al. (2003a) Rungtusanatham et al. (2003)	Ergen et al. (2006) *Kiritsis et al. (2003)* Wamba and Boeck (2008) Candell et al. (2009) Baglieri et al. (2007) Puschmann and Alt (2005) Lee et al. (2008) Boersma et al. (2005) Barratt and Oke (2007) Chae et al. (2005)
Modelling & Frameworks	* Jun et al. (2007) Sharma (2005) Belkadi et al. (2008) Duigou et al. (2011) Tang and Qian (2008) Taisch et al. (2011) Sudarsan et al. (2005)	Huang and Chu (2010) Petersen et al (2003) Mishra and Shah (2009) Parker et al. (2008) Chung and Kim (2003) Ettlie and Pavlou (2006) Petersen et al (2005) Ragatz et al (2002)	Denkena et al. (2007) Chang (2002) Du et al. (2012) Chan et al. (2012) Yin and Kooh (2007) Kyu Kim et al. (2011) Wong et al. (2011) Karaesmen et al. (2002) Yao et al. (2007) Li et al. (2006b) Schmidt (2009) Chan and Chan (2009) Croson and Donohue (2006) Sahin and Robinson (2005) Cagliano et al. (2006) Chengular-Smith et al. (2012) Zhou and Benton (2007) Datta and Christopher (2011) Ali et al. (2012) Hall and Saygin (2012) Themistocleous et al. (2004) * Liu and Kumar (2011) * Lau et al. (2004) * Prajogo and Olhager (2012) * Yu et al. (2010) * Li et al. (2009) * Devaraj et al. (2007) * Hsu et al. (2008) * Sezen (2008)	*Jun et al. (2007)* Simchi-Levi and Zhao (2003) Cachon and Fisher (2000) Mishra et al. (2007) Nativi and Lee (2012) Cheng et al. (2010) Croom (2005) Uusipaavalniemi and Juga (2009) Huang and Gangopadhyay (2004) Raghunathan (2003) Kulp et al. (2004) Yao and Dresner (2008) Yu et al. (2002) Tai (2011) Aoyama et al. (2005) Gavirneni (2002) Moyaux et al. (2007) Lee et al. (2000) Trapero et al. (2012) Zhu and Thonemann (2004) *Lau et al. (2004)* *Prajogo and Olhager (2012)* *Yu et al. (2010)* *Li et al. (2009)* *Devaraj et al. (2007)* *Hsu et al. (2008)* *Sezen (2008)*
System Architecture	Choi et al. (2010) Hu et al. (2010) Dai et al. (2006) * Kiritsis (2011) * Mahdjoub et al. (2010) Schilli and Dai (2006) Kim et al (2010b) * Gulledge et al. (2010)	Trappey and Hsiao (2008) Yujun et al. (2006) Xu and Liu (2003) Chu et al (2006) *Mahdjoub et al. (2010)* Kim et al. (2001) Huang and Mak (2000) Zhang et al. (2000) Kim et al. (2010a) Hren and Jezernik (2009) Huang and Fan (2007) Gunpinar and Han (2008) Rodriguez and Al-Ashaab (2005)	* Trappey et al. (2007) Liu and Young (2004) Mourtzis (2011) Feng et al. (2007) *Liu and Kumar (2011)*	*Trappey et al. (2007)* Macdonnell and Clegg (2007) Han and Yang (2006) *Kirittsis (2011)* Zhu et al. (2012) Chow et al. (2007) Sun et al. (2012) *Gulledge et al. (2010)* Bodendorf and Zimmermann (2005)

* Articles that are included in more than one categories

Figure 2-3 shows the number of publications in relation to the country of origin. The other category includes publications from 15 countries that have less than 3% of the total. These articles were published mainly from Europe (e.g. France, Italy, Netherlands) and a few Asian countries (e.g. Singapore, India).
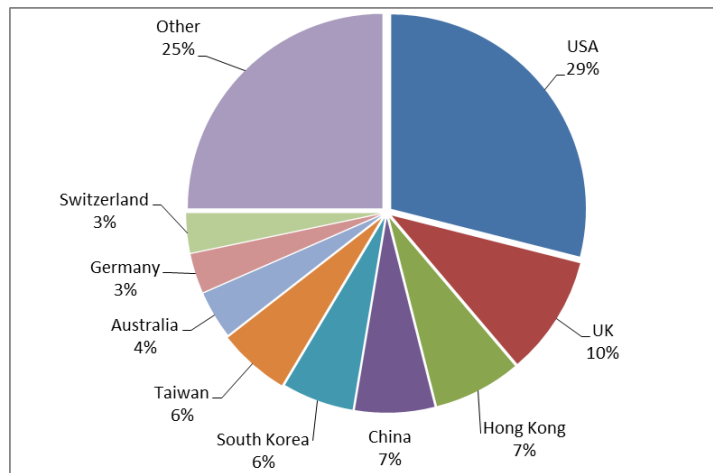
Figure 2-3 Country of Origin for the Selected Publications

The analysis of the classification framework shows that more that 65% of the publications focus on the manufacturing, logistics and maintenance phase of the product lifecycle (Figure 2-4). The majority of these papers examine the benefits that information flow can bring in SCM by validating research or hypotheses models through survey-based data collection techniques. Similarly, other studies use simulation techniques to demonstrate the effectiveness of information flow. Another important outcome that can be observed through the classification framework is that the majority of the publications in the system architecture area are within the PD area. It is interesting to note that most of the studies in PD present system architectures to support product data exchange, allowing globally-dispersed engineers to work in a collaborative environment. Although it can be argued that the PLM area is relatively empty in this framework, this can be justified as PLM systems became more popular later in the decade.

It can be seen from Figure 2-4 that the number of papers published in the area of information flow in SCM has fluctuated over the years. The graph shows that this area reached a high in 2005 and 2007 and there has been a decrease in the number of publications since then. In 2011 there is a slight increase in the number of publications with the same number following on in 2012. Although on its own Figure 2-4 does not represent clearly areas for future directions; what it does demonstrate is that a higher number of articles have focused in the "manufacturing" and "logistics and maintenance" phases. In terms of the type of publication, the figure shows that more than 45% of the total number of articles focus on "modelling & frameworks" area.
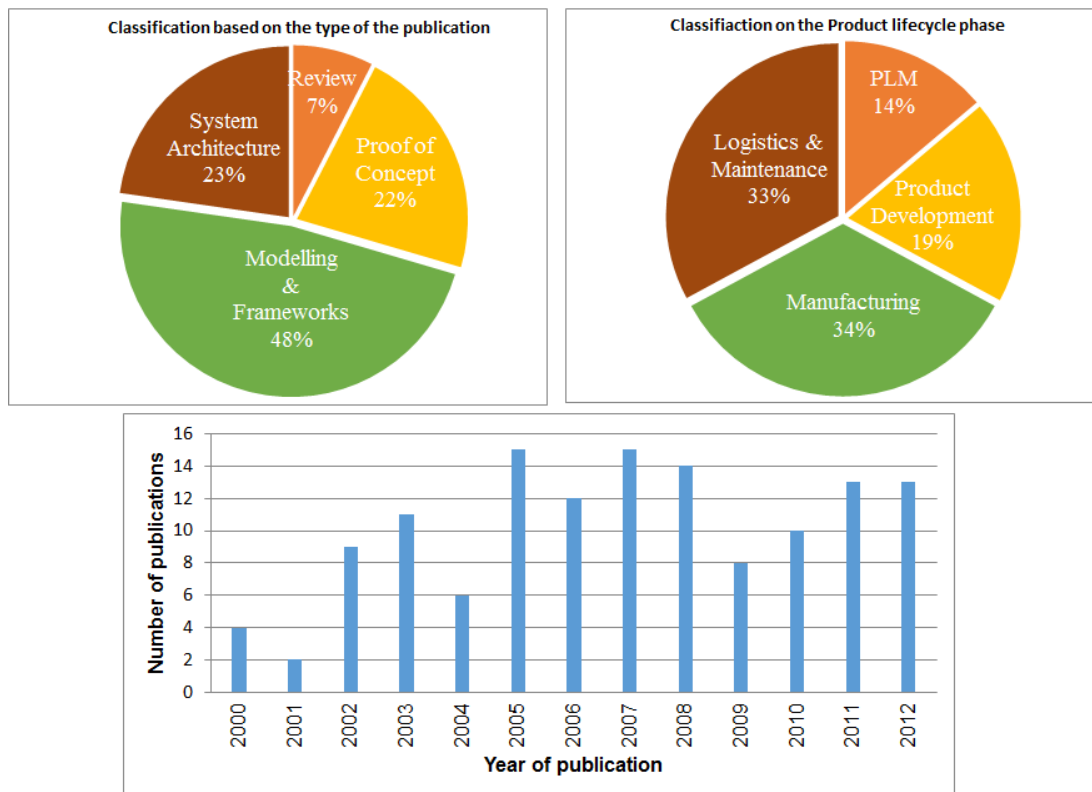
Figure 2-4 General View of Publications in the Product Lifecycle

2.2.2.1. PLM

The literature classification shows that during the last six years the amount of publications in the PLM area has increased significantly. During the last six years, PLM systems received significant attention due to the constantly increasing amount of data sharing between OEMs and suppliers. Moreover, the promise and the potential of PLM systems to reduce the time to market and improve the product quality led to a continuous investment.

Several studies discuss the advantages that PLM systems bring to supplier collaboration and their contribution in sharing knowledge. Another area that is under discussion in the literature is that of system development. Researchers propose various system architectures that aim to link or integrate with PLM systems in order to expand their current functionality and improve supply chain collaboration. Although PLM systems emerged as an application with a potential to integrate systems throughout the product lifecycle, their use and integration still remains at the initial stages of product development (Kim et al., 2010b). Dai et al. (2006) developed a web-based e-commerce system that integrates with PDM/PLM product design environments in order to allow consumers, partners and distributors to take part in product design and share their ideas with suppliers. Mahdjoub et al. (2010)

developed a collaborative approach using a multi-agent system on a virtual reality platform to allow engineers to re-use knowledge when creating new products. The system is integrated with the PLM system and linked with the virtual reality platform. Luh et al. (2011) proposed a customised plan for PLM platform deployment to support the collaborative product development among geographically dispersed sites. This research reveals some of the hardware constraints that companies face while exchanging large quantities of data. Kiritsis et al. (2003) presented the concept of Closed-Loop PLM focusing on the in-service and the end of life phases when in most cases the information flow is interrupted. This study is only one of the few that highlight the advantages that PLM systems can bring during the in-service and the end of life phases of the product lifecycle.

Although in terms of CAD geometry, there are several standards that allow organisations to exchange information among different systems, it was identified in the literature that there is a lack of interoperability among heterogeneous PLM systems. Rachuri et al. (2008) provide an overview of IT standards for PLM systems to support the harmonisation of PLM Standards. Although there are standards developed to support information exchange, particularly in the area of CAD, data exchange among heterogeneous systems still remains a very indirect and manual process. Researchers have identified gaps in communication among heterogeneous systems and propose solutions to address them. The following publications summarise that: (i) Choi et al. (2010) propose a PLM integration system using a standard format to allow communication between heterogeneous PLM systems. (ii) Gunpinar and Han, (2008) propose a system that allows the integration among different PDM systems using PLM Service standards, which enables data exchange via Internet. This system allows companies to access data from two different PDM systems using web-services. (iii) Taisch et al. (2011) presents a data model aiming to collect information from various product-lifecycle phases in order to support the development of a new PLM standard. (iv) Similarly Kim et al. (2010b) propose the Digital Factory Wizard (DFW) as part of a PLM environment which supports the design of manufacturing layouts. DFW is based on PLM adapters which allow interoperability among heterogeneous systems.

2.2.2.2. Product Development

As part of SCM strategies, product development has also moved away from traditional centralised methods where all the activities were carried out by the OEM. It has now progressed towards a more collaborative approach where the OEM

concentrates on the core activities while working collaboratively with suppliers to support and control subsidiary activities (Kim et al., 2010a; Yujun et al., 2006). The purpose of collaborative product development is to integrate knowledge, processes, technologies and resources among the different members of the product creation lifecycle (Huang and Fan, 2007). The level of involvement of each supplier varies from a simple consultation relationship to a fully-integrated co-development partner in the product development process (Petersen et al., 2005; Ragatz et al., 2002). The type of relationship that an OEM has with each supplier will define the level of interaction and the amount of data that will be exchanged. Moreover, different relationships can be established in different phases of the product development lifecycle. Research studies have shown that early supplier involvement can improve the product development and innovation process (Schiele, 2010) and increase the likelihood of achieving product development goals (Petersen et al., 2003).

Significant efforts have been made in research to improve the communication and the information flow between OEMs and suppliers. By examining the results it was concluded that although there are several publications that present modelling and framework techniques, the majority of the articles focus on developing systems to support the exchange of product-related data. The research studies identified on improvement of information flow in SCM can be divided into two categories based on the product development lifecycle: those that focus on facilitating the early supplier involvement in the concept definition phase and those that facilitate the product development after the concept definition phase.

Over the last decade, several studies have proved that significant benefits can be achieved by involving the suppliers as early as possible in the product development process (Huang and Mak, 2000; Tang and Qian, 2008). Therefore OEMs are now facing the challenge of sourcing suppliers as early as possible to support the co-development process in the concept definition phase. Huang and Mak (2000) highlighted that suppliers can provide input during the concept definition phase by using their expertise to identify the latest technology, assisting on "make or buy" decisions, and by providing solutions on part designs. In order to support their opinion and prove the concept, Huang and Mak (2000) developed a fully functional web-based prototype system, named WEBid, to facilitate both customers' and suppliers' new product development processes. The first part of the system is a BOM-oriented model and the second one captures customers' requirements and suppliers' capabilities. Huang and Fan (2007) proposed an engineering portal for

supporting the sourcing and the collaboration process between OEM and suppliers. Schiele (2010) discussed the subject area from a purchasing perspective and included tools and roadmaps used by companies in order to link a firm's strategy with the innovation and the sourcing strategy during early supplier involvement.

Moving forward from the concept definition phase to the design and the engineering phase, the level of information between the OEMs and suppliers has seen a significant increase. Nowadays, PDM and PLM systems allow designers and engineers to share product-related data while working in a collaborative environment with teams that are globally dispersed. The use of web-enabled technologies allowed companies not only to integrate their IT systems but also their processes from a business perspective. As suppliers are characterised as an important knowledge source as customers (Schiele, 2010), they need to invest in building the IT-infrastructure to work in a collaborative environment with OEMs. Suppliers have claimed that they are willing to reduce their offering prices in addition to higher involvement in the development process (Schiele, 2010). However suppliers have also stated that OEMs use their know-how and then give it away to their competitors when bids are let (Ettlie and Pavlou, 2006). Building trust and a culture of collaboration is the key on achieving benefits in collaborative product development.

Several studies propose system architectures that utilise ISO standards in order to improve collaboration and share knowledge among OEMs and suppliers. The following studies propose systems to facilitate the exchange of product data, using STEP (Standard for the Exchange of Product model data) and other neutral formats between heterogeneous computer-aided technologies (CAx). (i) Zhang et al. (2000) proposed a web-based system for exchanging STEP data. (ii) Xu and Liu (2003) developed a web-enabled PDM system that allows OEMs and suppliers to integrate multiple CAD systems by using STEP as a CAD standard in conjunction with CORBA language. (iii) Kim et al. (2010a) proposed a framework for exchanging CAD data using Web-Services. The system's architecture is based on an Extensible Markup Language (XML) and neutral format CAD model with a web interface for retrieving CAD data. (iv) Trappey and Hsiao (2008) developed an information hub to improve the visibility of information and support collaborative product design. This research focuses mainly on supporting the SMEs to participate in the current global landscape. (v) Chu et al. (2006) showed three software prototypes to demonstrate the importance of web-based collaborative visualisation. The three prototypes allow different users of the system to access 3D models through a web-based platform

without the need of CAD or any sophisticated software. (vi) Rodriguez and Al-Ashaab (2005) developed a web-based system for facilitating the information and knowledge sharing in collaborative product development. (vii) Yujun et al. (2006) propose the Internet-based collaborative product development chain (ICPDC) framework and a proof-of-concept system as an example of a collaborative product development environment based on web-services technology to allow users to disseminate, share and manipulate product related data.

2.2.2.3. Manufacturing

Similarly to product development, SCM in the manufacturing phase has seen significant changes over the last two decades. Modern supply chains not only need to be cost-effective but also flexible and adaptable to new unsettled environments where demand is constantly changing. Nowadays OEMs have a strong dependency on their suppliers and partners to deliver the right parts in the right quality at the right time and under the pressure of cost reductions. One of the key enablers, widely recognised in the literature for improving the efficiency of the supply chain, is information sharing within the supply chain. Researchers have highlighted the importance of sharing different types of information such as forecasting data, inventory levels and capacity planning data, demand and order data. Some of these studies prove that inter-organisational information sharing can reduce the bullwhip effect. Croson and Donohue (2006) define the bullwhip effect as "the tendency of orders to increase in variability as one moves up a supply chain". Croson and Donohue (2006) proved, based on results from two experiments, that integrated information systems have the potential to reduce the bullwhip effect. Yu et al. (2010) suggested, based on different information-sharing scenarios, that exchanging information on demand with suppliers and dealers is the key enabler for reducing the bullwhip effect.

Although the benefits of improving the information flow in the supply chain are clear the following studies have evidenced those benefits and highlighted areas where potential failure factors may exist. More than half of these articles were published after 2007. (i) Zhou and Benton Jr. (2007) proved among others that effective information sharing will result in an effective supply chain practice. (ii) Chengalur-Smith et al. (2012) provide empirical evidence that both information sharing and business leveraging will provide business benefits. (iii) Similarly, Wong et al. (2011) performed an empirical study which resulted in findings that proved the beneficial effect of information sharing in cost and customer-oriented operational performance

of SCM in uncertain environments. (iv) The simulation study of Schmidt (2009) showed performance improvements through the exchange of order data, as this study showed improvements in the calculations of inventories stock without affecting the service levels. (v) Datta and Christopher (2011) highlight that information sharing alone is insufficient to handle the supply chain uncertainty and by using an agent-based simulation approach they examined different coordination and information sharing mechanisms to identify the best combination for managing SCM performance under uncertainty. (vi) Liu and Kumar (2011) focus on supply chain configurability in leveraging supply chain information exchange. Therefore in this paper they present the results from a simulation study that proves that the correct configurations can improve the supply chain performance. (vii) Chang (2002) based on data collected and analysed from Taiwanese and UK companies, confirms that improved manufacturing performance can be achieved by integrated systems such as ERP, CIM and SCM. Most of these studies prove that efficient information flow is critical in order to achieve high supply chain performance. However, there are few studies that provide quantitative results on the level of improvement that can be achieved. (viii) Sahin and Robinson (2005) results from a mathematical model and a simulation-based framework showed that fully integrated supply chains can lead to a 47% cost reduction compared to traditional systems. Although information sharing is a key enabler for cost reductions it was highlighted in this study that coordinated decision-making processes are the driver for the main economic benefits.

Some researchers refer to this subject area from a visibility perspective. Kyu Kim et al. (2011) defines inter-organisational information systems visibility as "the extent to which partners firms' information/knowledge related to supply chain cooperation is visible to the focal firm through inter-organisational information systems". Through their study they put forward the opinion that by making information systems visible within the supply chain, benefits in supply chain performance will be achieved. Barratt and Barratt (2011) refer to the importance of visibility in both the external and the internal linkages. Based on their empirical study they provide suggestions on how to evaluate the type of relationship with a supplier and therefore extend visibility and reduce uncertainty.

One of the main differences highlighted between the product development and the manufacturing phase is that during manufacturing both the intra-organisational and the inter-organisational links are critical for successful communication. Developing mechanisms for internal collaboration is critical in order to achieve substantial

benefits from inter-organisational information flow. Several studies presented the importance of improving both intra and inter-organisational communication to reduce uncertainty in supply chains (Dunne, 2008). Currently ERP systems handle most of the information sharing internally. However it was highlighted in the literature that ERP's external links still remain weak (Cagliano et al., 2006). Similarly with the PD phase, it was mentioned that interoperability issues also exist in the manufacturing phase as it is necessary to build links among the different ERP systems used in the supply chain (Chowdhury and Chowdhury, 2010; Pereira, 2009). Similarly with the PD phase, the level of involvement for each supplier will vary. Dunne (2008) states that a non-collaborative relationship does not necessarily lead to an ineffective relationship. In the case study Dunne (2008) showed that building a relationship with a supplier is difficult and resource-intensive as it requires time, resources and managerial skills.

Several works have discussed the subject area through empirical and conceptual studies and even more studies have simulated the information flow in SCM to prove the benefits that can be achieved. Compared to PD, there seems to be fewer studies that propose systems or architectures of systems that will improve the information flow in SCM. Mourtzis (2011) proposes a web-based system that allows customers and suppliers to maintain visual access and consistency in their delivery schedules, order variations and derive an accurate view of the inventory stock levels. This XML-data exchange software framework utilises information sharing and supports collaborative and flexible production planning. Trappey et al. (2007) proposes a centralised cross-functional platform. This system is an XML-data exchange, integrated business and logistics hub (IBLH) which integrates information and material flows to ensure the transparency of the flow in order to reduce inventory costs and provide efficient product distribution. Suppliers, clients and other manufacturing members have electronic access to order, shipment and inventory stock data. Liu and Young (2004) propose the GMC (Global Manufacturing Co-ordination) experimental system based on an object-oriented database management system to allow decision-makers to communicate order information, manufacturing process information and logistics information with the extended enterprise. Feng et al. (2007) proposes a software agent-enabled process integration framework and through a prototype system proves that agents can assist on the automation of tasks in order to reduce human effort during information exchange.

2.2.2.4. Logistics & Maintenance

While PD and Manufacturing phases still face many challenges in terms of information flow, it is widely recognised that during these two phases several software applications have been developed to support the flow, such as CAD/CAM, PDM, PLM, and ERP systems. Moving to the logistics and maintenance phase this link seems to be more fragmented. The amount of information and knowledge that returns back to designers and engineers is less complete (Kiritsis et al., 2011). Publications in the modelling section focus more on discussing information sharing in the area of Demand/Forecasting/ Capacity data from a retailer's perspective. Although the sample is relatively small, the rate of publications in the area of logistics seems steady over the years. The area dealing with system architectures covers systems proposed from researchers to improve both Maintenance and Repair Overhaul (MRO) processes and information sharing from a retailer's point of view.

Maintenance Data

During the last decade an extensive body of literature has been formed to improve maintenance and support efficiency. The use of technology and especially web-based applications has allowed the movement from traditional models of maintenance to e-maintenance (Han and Yang, 2006). E-maintenance is becoming an area that receives significant attention mainly due to the latest movement to the Product-Service System (PSS) models, especially in the aerospace sector. PSS involve transactions made not through a one-time product sale but through signing long term relationship agreements which include a fixed maintenance cost over an extended period of time. PSS systems are defined by Baines et al. (2007) as "an integrated product and service offering that delivers value in use. A PSS offers the opportunity to decouple economic success from material consumption and hence reduce the environmental impact of economic activity. The PSS logic is premised on utilising the knowledge of the designer manufacturer to both increase value as an output and decrease material and other costs as an input to a system." To address the upcoming challenges, researchers are focusing on developing methodologies and tools to enable full utilisation of the product data and information in processes (Candell et al., 2009). Although web-based technologies have significantly improved communication among supply chain members, there are still many challenges to be addressed. One of the main challenges that companies are currently facing is the lack of a central repository to manage and maintain maintenance data. MacDonnell and Clegg (2007) highlight the lack of automation in managing MRO supply chains as until recently organisations had developed multiple internal systems to manage different types of

information and as a result they now face the need to develop transaction standards and integrate those systems. Lee et al. (2008) observes that PLM systems are used 10 times less frequently in the service phase and highlight that the potential of PLM systems in aviation MRO has not been realised.

For the maintenance phase several systems are proposed by researchers. Kiritsis (2011) proposes an architecture of a closed-loop PLM system that supports the middle-of-lifecycle such as use and maintenance and the end-of-lifecycle such as recycling. Kiritsis (2011) study focuses on improving the information flow by linking software platforms and intelligent products. The main components used are Portable Product Embedded Information Devices (PEID), Product Data Knowledge Management (PDKM), and applications for decision support. Candell et al. (2009) emphasises the fact that ICT can be the enabler to support the maintenance process. Han and Yang (2006) developed a web-based e-maintenance system that allows the integration of the required advanced techniques while information is shared through a communication platform. Macdonnell and Clegg (2007) proposes a proof-of-concept MRO supply chain system in order to minimise the maintenance holding costs among different members of the supply chain. This research is based on three levels: firstly, from a process point of view, secondly from an information flow perspective and finally from a computerised information management level. The system proposed was tested with a small number of parts and demonstrated inventory reductions up to 40% without affecting the service levels. Gulledge et al. (2010) proposes a solution for integrating PLM systems and condition-based maintenance in order to convert prognostic and diagnostic information into actionable information that can be directed into a PLM environment using service-oriented approaches.

During the last few years, PLM systems are used more often within the maintenance phase of the product lifecycle to enable greater service performance and improvement. A number of companies such as Siemens and PTC, have introduced off-the-shelf applications integrated with their PLM systems to support companies in reducing service cycle time and costs as well as ensuring compliant and complete service (Siemens, 2014; PTC, 2014) These applications support companies in creating a central location of maintaining service records, scheduling and planning MRO operations and manage effectively spare part logistics. However, these applications do not include root cause analysis within their current offering capabilities (Siemens, 2014; PTC, 2014) which could be one of the reasons why these applications are not used extensively within the automotive sector. Moreover,

similarly with the PD phase, these applications require a significant investment for implementation, license acquisition and IT maintenance which in most cases do not justify the adoption from the extended supply chain.

Demand/Forecasting data

Although most of these studies were thoroughly examined during the manufacturing phase some publications are presented in this section as they examine the same topic from a retailer's perspective. Information integration between suppliers and retailers is perceived in the literature as an effective approach to improve supply chain performance.

Exchanging demand and forecasting data can reduce the demand variability amplification and as a result the bullwhip effect. Some studies demonstrate that the benefits that can be achieved from information sharing are not as significant as those presented in the manufacturing phase. Lee et al. (2000) model showed that although manufacturers can obtain inventory and cost reductions, retailers have no direct benefits from information sharing. Kulp et al. (2004) study shows that the majority of the benefits can be achieved through collaboration and not through information sharing. Based on this study it seems that only information sharing related to the stock inventory levels can be linked with profits while warehouse inventory levels and customers' needs are not associated with supply chain performance. Cachon and Fisher (2000) found more valuable the use of IT to accelerate the flow of physical goods rather than expand the information flow. Other studies argue and provide evidence in order to prove that information sharing could result in benefits. Trapero et al. (2012) provide significant evidence proving that information sharing between suppliers and retailers can increase forecasting accuracy resulting in a 6-8% reduction in forecasting errors. Moyaux et al. (2007) simulated the value of two principles that show how to use information sharing in order to reduce the amplification of order variability caused by lead times. The computational study of Gavirneni (2002) indicates a cost reduction as high as 33% with an average of 10% by making better use of the information flow in SCM. During the research undertaken in this paper, only one system was identified to support the information flow from a retailer's perspective. Bodendorf and Zimmermann (2005) highlight the importance of reacting to unpredictable disruptive events and propose a Supply Chain Event Management (SCEM) system for a logistics service provider.

2.2.3. *Discussion: Information Flow in the Supply Chain*

2.2.3.1. PLM

The continuous investment into PLM systems from various industries, not only aerospace and automotive, and the promise and the potential that PLM systems bring in reducing time-to-market, have caught researchers' attention who since 2005 publish heavily in that space. Although the amount of publications in the PLM area has significantly increased it is widely acknowledged that more research is required to clearly define the functionality of PLM systems. Still PLM systems focus mainly on the PD phase with the majority of studies either proposing system architectures that allow data exchange among heterogeneous PLM systems or systems that expand the functionality of PLM systems beyond the traditional PDM systems. Kiritsis et al. (2003) highlights that information flow during the manufacturing and service phases still seems to be fragmented. Although there are a few PLM vendors that provide solutions on integrating maintenance and service information within the PLM system there are little or no studies that aim to calculate the benefits that can be achieved by integrating maintenance information within the PLM system. In addition, there are fewer studies that demonstrate how design improvements could be achieved using maintenance and warranty information integrated within PLM systems.

Over the last few years a number of authors proposed frameworks to support information sharing in collaborative design and enhance supply chain integration. In addition there are a number of studies that propose frameworks to integrate PLM systems with various systems such as CRM, ERP, SCM across different phases of the product lifecycle. However there are still little or no studies that quantify the benefits that can be achieved by managing information in a central location. While enterprise applications such as ERP and PLM are evolving in order to support each phase of the product lifecycle this may result in a situation where applications are overlapping, with the same information being held in disparate silos.

Another area that is under discussion in research is that of interoperability issues and the lack of standardisation that PLM systems are currently facing. As PLM systems require considerable investment of time and effort, suppliers are now facing the challenge of being able to integrate their systems and share information with various OEMs. Similarly Small and Medium Enterprises (SME) are required to invest in such systems in order to have the capability to exchange information with their extended enterprise. What this study also showed is the importance of developing standards that not only cope with the existing CAD formats but also support the standardisation

of PLM, PDM and ERP systems. The standardisation of systems will allow suppliers to reduce the cost of implementation and maintenance of multiple systems and as a result work in a more collaborative way with customers and suppliers without the need to invest in implementing and maintaining multiple systems.

2.2.3.2. Product Development

The literature review conducted has highlighted that significant benefits can be achieved by involving suppliers as early as possible in the PD process. It is clear that during recent years the amount of publications in this area is relatively constant. This is due to the constant requirement from companies to reduce the time-to-market and improve efficiencies. The advent of Internet technology has also played a key role for this stability. However the link between product development and SCM is not as strong as in the other phases of the product lifecycle. Although research has focused on integrating SCM systems with ERP and CRM, product development seems to be largely separated (Porter, 2001). The analysis of review papers enhances Porter (2001) observation as it demonstrated that publications which discuss the IT-enabled SCM strategy holistically, do not include product development within their scope.

The majority of the articles analysed propose systems that allow OEMs to share product data with suppliers using ISO standard formats through web-based applications. In addition, there are several studies that discuss the exchange of light-weight CAD data to support non-engineers in decision-making. However there seems to be a lack of studies that deal with data exchange other than CAD and its attributes, such as documentation associated with a part, the BOM and all the other metadata that surround a CAD model and are usually held within PDM systems. This review enhances Buyukozkan and Arsenyan (2012) observation that each one of the systems proposed address a specific issue which leads to a lack of a guidance roadmap within literature that will drive the development of the right applications. In addition, most of the systems proposed, lack of practical implementation and testing which could demonstrate the practical benefits that could be achieved.

Although it is widely acknowledged that IT has improved supply chain integration, there seems to be little attention given to studies that quantitatively measure the impact of IT-enabled product development to SCM performance, especially from suppliers point of view. These studies could support researchers and practitioners to justify the development of tools that support supply chain collaboration. Finally, it was identified in the literature that there are a number of studies that focused on clustering the different types of relationships between suppliers. As building the IT-

infrastructure for exchanging data during PD is resource-intensive, that requirement needs to be taken into consideration and needs to be fully defined within each cluster of suppliers.

2.2.3.3. Manufacturing

The literature review conducted has shown that during the manufacturing phase, information flow in SCM is critical and results in achieving significant improvements in terms of cost and efficiency. Over the last decade the number of peer reviewed articles in the area of review, proof-of-concept and modelling has remained high. Most of these studies proved, through empirical and conceptual studies, that significant benefits can be achieved. Modelling techniques are used extensively to demonstrate positive effects among various factors and information flow while simulation techniques are used to quantify the benefits that could potentially be obtained. However, the level of detail and the amount of information that needs to be exchanged with each supplier is not widely discussed within the literature (Huang et al., 2003). Similarly with the other phases of the product lifecycle, there needs to be an association between the amount and the type of information exchange against the different clusters of suppliers, as not all suppliers will require the same level of data exchange. A prioritisation of information types might be useful as it will define what is critical to meet the expected benefits for each cluster of suppliers. As a result, practitioners and researchers can target short term "quick wins" while planning for long term benefits.

One of the main differences highlighted between the manufacturing phase and the other phases of the product lifecycle is that during manufacturing both the intra-organisational and the inter-organisational links are critical to achieve successful communication. Developing mechanisms for internal collaboration is critical in order to achieve substantial benefits from inter-organisational information flow. Compared to PD, there seems to be fewer studies that propose systems or system architectures that aim to improve the information flow in the supply chain. Currently, ERP systems handle most of the data transactions but their external links remain weak. Therefore, although the benefits that can be achieved are very well recognised it still remains unclear how IT systems can support supply chain collaboration during the manufacturing phase. Researchers need to define a roadmap with the most suitable technologies for implementation. In the opinion of the author, ERP systems are expanding to support more manufacturing processes while at the same time, PLM systems are expanding to integrate more systems and as a result create a

centralised database. There needs to be a clear distinction between PLM and ERP systems moving forward, as there might be a point where these two enterprise systems will start to overlap and as a result cause operational issues.

2.2.3.4. Logistics & Maintenance

Through the analysis, it was identified that most of the publications in the area of modelling approaches focus on measuring the benefits that can be achieved by improving the information flow between OEMs and retailers. Similarly with the manufacturing phase these studies highlight how information sharing can reduce the bullwhip effect, although there might be a need for prioritisation among the different factors and benefits that can potentially be achieved. That will allow companies to use this knowledge for both quick wins and benefits but also plan longer term results. In terms of system proposed there needs to be an investigation on architectures that utilise Internet resources compare to the traditional channels.

In the area of service and maintenance most of the peer reviewed articles identified propose an actual system or the architecture of a system to improve the information sharing between OEMs and suppliers in order to reduce maintenance costs. System development has attracted low attention from researchers and still remains more related to the aerospace sector. Other sectors with high data transaction and significant maintenance and warranty costs such as automotive, marine and transportation can benefit from research conducted in the aerospace sector. This article supports Lee et al. (2008) findings that the potential of PLM systems in MRO procedures are not yet realised. Further research is required to establish and define the integration of PLM systems in the service and maintenance phase of the product lifecycle. This will allow utilisation of knowledge and data across the product lifecycle that will support not only the external supply chain but also internal decision makers. In addition, further research is required to ensure that after-sales information and knowledge from maintenance and service experts will feed back to the product development engineers (Kiritsis, 2011). Although during recent years there are several studies that focus on the maintenance area, it seems that this area will gain more attention in the near future.

2.2.3.5. Cross-Phase Examination

Although useful conclusions have been identified in the literature by examining each phase of the product lifecycle, a few interesting conclusions can be extracted through cross-phase examinations. SCM is perceived narrowly during the manufacturing and logistics phases rather than the whole product lifecycle. The types and amount of

information that needs to be shared during the manufacturing phase are comprehensively examined in the literature. While during the manufacturing and logistics phases the majority of publications focus on modelling and simulating the information flow in order to measure the benefits that can be achieved, there are insights on which enterprise applications can support the information flow. During PD, systems such as CAD, PDM and PLM are well defined with several system architecture studies proposed to enhance the information sharing both internally and externally. However the majority of these studies still focus on exchanging engineering data with no indication on which type of information is more critical and beneficial during the PD phase. While enterprise applications such as ERP and PLM are evolving in order to support each phase of the product lifecycle this may result in a situation where applications are overlapping, with the same information being held in disparate silos. In the opinion of the author there is a need to identify the systems utilised in each phase of the product lifecycle and identify the integration points in order to create a continuous information flow from PD through manufacturing, service and back. Although individually most of the systems are very well established, further research is required to integrate systems and processes across multiple phases of the lifecycle. To achieve that, standardisation of data is becoming more essential. Finally it is important to highlight that overall the literature identified potential benefits of information sharing in SCM but there is only limited evidence of this coming from industrial case studies. The use of SOAP and XML seems a common theme across all the systems proposed in each phase of the product lifecycle.

2.3. Root Cause Analysis and Warranty

In today's global market, OEMs are constantly under pressure to improve service processes as these are closely linked to customer satisfaction and brand reputation. As stated in the introduction chapter, warranty management is among the top priorities for vehicle manufacturers, as warranty failures add significant costs in terms of additional service/work, replacement of faulty parts and brand reputation (Mannar et al., 2006). These costs represent 2.5-3.0% of the OEMs revenue (Sairamesh et al., 2004; Sureka et al., 2008). While in some cases in-service vehicle faults due to physical damage or customer misuse are easy to diagnose, most of the failures are not visually diagnosed (Mannar et al., 2006). A recent study from J.D. Power & Associates and What Car? (2013) showed that ownership costs which include cost of service and repairs are the second key driver for overall customer satisfaction. In addition vehicle quality/reliability received a significant impact, with more than 20% on the notion of customer satisfaction. Figure 2-5 shows the results in detail.

Vehicle Quality/Reliability
22%

Problems experienced with the vehicle across eight areas:

• Exterior
• The driving experience
• Features/Controls/Displays
• Audio/Entertainment/Navigation
• Seats
• Heating, ventilation and air conditioning (HVAC)
• Interior
• Engine/Transmission

Vehicle Appeal
31%

Satisfaction with the vehicle's performance, design, function and styling across nine areas:

• Vehicle exterior
• Vehicle interior
• Storage and space
• Audio/Entertainment
• Seats
• Heating, ventilation and air conditioning (HVAC)
• Driving dynamics
• Engine/Transmission
• Visibility and driving safety

Ownership Costs
25%

• Fuel consumption
• Insurance
• Cost of service/repairs

Service Satisfaction
22%

• Service initiation
• Service adviser
• Service facility
• Vehicle pick-up
• Service quality

Figure 2-5 Factors Contributing to Overall Vehicle Ownership Satisfaction (Source: J.D. Power & associates and What car?, 2013)

In order to reduce the warranty cost and the number of in-service part failures, OEMs have introduced electronic databases to collect and analyse warranty claims and vehicle diagnostics. OEMs use the electronic databases to capture and store millions of data which are then analysed to extract knowledge such as trends and patterns of reoccurring in-service product failures. The extracted knowledge may lead to significant reduction in the overall warranty cost. In most cases, systems developed to support complex warranty processes are very rigid and offer little or no integration capabilities with other information systems. Moreover, the structure of distributed information does not follow a standardised format which can cause difficulties when integrating multiple systems. Sairamesh et al. (2004) proposes a solution to allow OEMs and dealers to work collaboratively through contextual collaboration and information integration using service-oriented approaches. The solution proposed aims to integrate 3D parts catalogues with warranty processes and purchasing processes. Esterman et al. (2005) propose a framework to support product developers to manage and predict warranty performance during product development. The framework proposes the integration of three areas: 1) scenario-based FMEA 2) Bayesian methods to integrate engineering data and 3) Cost models to support warranty policies. The Center for Automotive Research-CAR (2005) analyse the warranty processes followed from three OEMs, four suppliers and one dealer and discuss the drivers and the key issues associated with the flow of warranty information. This technical report demonstrates the flow of warranty data once an in-service product failure occurs and discusses some of the challenges that

OEMs and suppliers face in analysing product failures. Figure 2-6 shows the process map as captured in the Center for Automotive Research-CAR (2005) report and demonstrate the tasks required whenever an in-service product failure occurs and until the part and the claim details are returned back to the OEM and the supplier responsible for the faulty part.
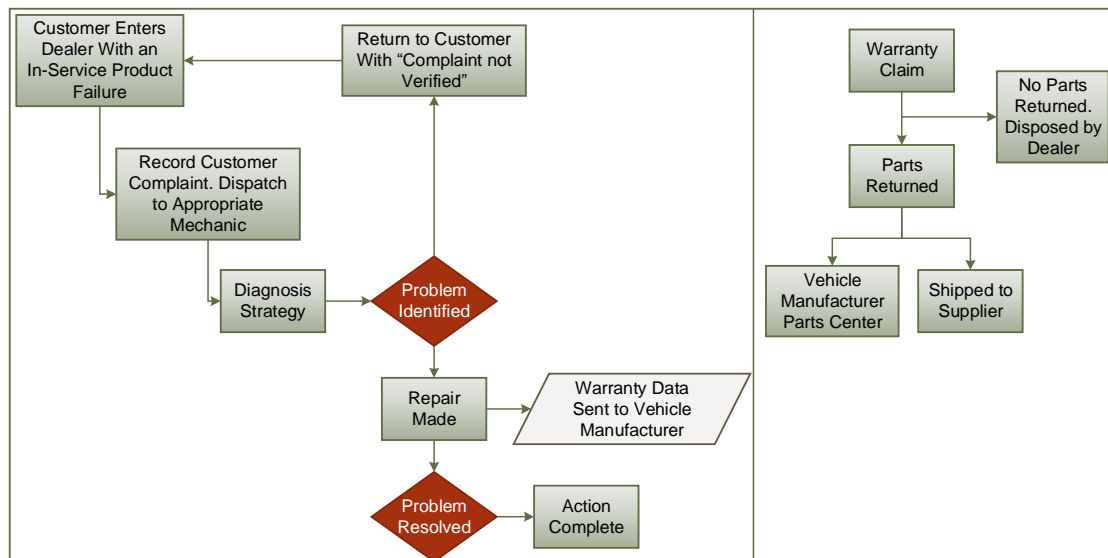
Figure 2-6a "In-service Identification" Process (adopted by CAR, 2005)

Figure 2-6b Parts Returned from the Dealer (adopted by CAR, 2005)

2.3.1. *Warranty Analysis*

Regarding the data analysis aspect the warranty area has been researched widely. Djamaludin et al. (1995) listed more than 1500 articles in this area. Recent reviews can be identified in the literature. Wu (2013) categorises the different types of "coarse" warranty data and reviews relevant techniques in analysing those data. This review provides explanation of why warranty data can be heaped, censored and missing. Karim and Suzuki (2005) through a literature review, classify the analysis of warranty data in nine categories based on the different statistical models and methods used. The study of Wu (2012) is an excellent review article that clusters the different warranty analysis techniques in five areas: early detection of reliability problems, suggestion on design modification, filed reliability estimation, claim/cost prediction, claim/cost estimation. In order to understand the previous work completed the following areas have been reviewed.

i. *Warranty claims analysis*: Over the last 40 years several studies have been published and aim to use statistical models and methods to analyse warranty claims based on different attributes and factors such as manufacturing conditions or the environment where the product is used (Li, 2000), hazard rate from incomplete

warranty data (Rai and Singh, 2003), or even warranty policies for non-repairable items (Kim and Rao, 2000). The outcome of these studies focuses in improving product reliability, supporting product design decisions and managing warranty policies.

ii. *Warranty cost:* During the same period, several publications have been published and aim to develop cost models that forecast the expected warranty claims. From an OEM's point of view this prediction is essential in order to manage appropriately warranty policies (Pal and Murthy, 2003; Karim et al., 2001). Rai and Singh (2005) propose a modelling framework for assessing the impact of new time/mileage warranty limits against the volumes and the cost of warranty claims of components or sub/systems. The method proposed is for comparative studies only as the dataset used for the analysis was selected from previous model year vehicles. Park and Pham (2012) use a two-dimensional warranty cost model to investigate the warranty cost using failure times and repair times. The outcome of the model is a cost estimation for both the warranty and post warranty periods by considering both the manufacturer and the customer.

iii. *Data mining*: Another area that has received significant attention, especially during the last decade, is that of data mining techniques mainly due to the complexity and the amount of data involved in the process. Researchers propose algorithms to support OEMs in structuring warranty claims which in many cases are returned as un-structured data (Esterman et al., 2005; Sureka et al., 2008; Buddhakulsomsiri et al., 2006). Choudhary et al. (2009) literature review discusses the different knowledge discovery and data mining techniques used in the area of manufacturing. Sureka et al. (2008) present a rule based text analysis prototype system which was developed to support automotive warranty analysts in obtaining better understanding into product defects reported from the dealer. The prototype system developed by Sureka et al. (2008) uses look-up tables to extract name entities and it has been tested using the air-conditioning sub-system. Buddhakulsomsiri et al. (2006) discusses five categorises that can classify data mining problems in warranty analysis: Association rule mining, Classification and prediction, Sequential pattern analysis, Text mining and Data visualisation. The outcome of Buddhakulsomsiri et al. (2006) study is a new rule-generation algorithm for mining automotive warranty data that aims to identify relationships between product attributes (production rate, repair date, mileage at repair etc.) and the decision outcome.

2.3.2. *On-board Fault Diagnostics and Prognostics*

During the last decade technologies related to fault diagnostics and prognostics systems especially in the aerospace and the automotive sectors have become available. The on-board fault diagnostics and prognostics systems are responsible for continuously monitoring the critical operation of each system such as the engine temperature, fuel injection, air bag deployment etc. In case of a malfunction, the system is responsible for generating a Diagnostic Trouble Code (DTC) which is then stored within the on-board computer of a vehicle. Every DTC code is associated with a textual representation that describes the fault (Rajpathak, 2013). DTCs generated over a period of time can be extracted by dealers using the appropriate software tool. This information provides insights into the nature of the fault as well as assistance in the determination of corrective actions that need to be performed on the vehicle (Chougule et al., 2011). Each DTC is associated with a vehicle module such as the "fuel tank" or the "Anti-lock brake system", the failure modes and the corrective actions. One of the most important benefits of the on-board fault diagnostics system is that it captures data that are not subjective to the technician's or the customer's interpretation but represents data captured real-time from the sensors. Gusikhin and Rychtyckyj (2007) provide an review study on the different ways that the automotive industry has ultilised artificial intelligent (AI), soft computing and other intelligent system technologies in multiple areas including warranty analysis and design. Gusikhin and Rychtyckyj (2007) study discusses the area of intelligent system applications both from a technology-centric approach (i) fuzzy-neural vehicle systems control, ii) neutral-network-based virtual sensors, iii) speech recognision, intelligent vehicle technologies, iv) on-board fault diagnostic and prognostics) and from a function centric approach (i) Design, Vehicle production, iii) After-sales service and warranty management iv) Corporate knowledge management). Similiarly, Venkatasubramanian (2005) provides an overview of the various approaches to automated fault diagnosis and highlights current challenges and future opportunities. Several studies have been identified in the literature that utilise data captured from vehicle sensors to support decision-making. Mannar et al. (2006) propose a methodology for identifying relations between warranty failures and manufacturing measurements in order to diagnose warranty failures and perform tolerence revaluation. This study provides an extensive discussion in the area of field performance information. Khare et al. (2012) using real time diagnostic data collected from Telematics demonstrated that: i) the accumulation of miles is approximately linear with age and ii) the distribution of mileage accumulation rate in vehicles with no

claims is the same as those with at least one claim. The results of this study could be used to allow companies to achieve accurate early detection of problems using mileage. Liu et al. (2007) developed a decision model to support product design management to estimate the cost of designing diagnostics against the benefits and the warranty cost reductions that the designed diagnostics will bring. Chougule et al. (2011) developed a novel approach for integrating warranty claims and vehicle diagnostics to support engineers in identifying anomalies in the field, performing root cause analysis and capturing training needs for dealers. Chougule et al. (2011) are looking to extend this work in order to include service manuals, service bulletins and engineering documents. Rajpathak (2013) proposes a novel ontology-based text mining system in order to analyse unstructured textual diagnosis data collected from automotive OEMs during the warranty period. This study is a very good example of utilising ontologies in analysing and structuring textual warranty data. Saxena et al. (2005) propose a hybrid reasoning architecture for integrated fault diagnosis and health maintenance of fleet vehicles to support maintenance decision making and capture knowledge.

Another area that received significant attention from researchers is that of Integrated Vehicle Health Management (IVHM). Benedettini et al. (2009) published a literature review to report the state of the art of IVHM research. Within Benedettini et al. (2009) study, IVHM is defined as "the capture of vehicle condition, both current and predicted, and the use of this information to enhance operational decisions, support actions, and subsequent business performance." IVHM systems are used within the aerospace and the defence sectors to provide an integration between sensors, communication technologies and AI as well as provide vehicle-wide abilities to diagnose problems and recommend solutions. Recent studies suggest that IVHM systems could also be used to support the automotive sector. Holland (2008) introduces the concept of IVHM adoption in the automotive sector and demonstrates some of the advantages that could be achieved. IVHM systems could potentially provide optimisation that could be linked back to manufacturing and product development, but equally provide an important link out to the supply chain for feeding back requirements, coordination of spare parts and scheduling service (Holland, 2008), areas that are very well standardised within the aerospace and the defence sectors. Amor-Segan and Jones (2011) discuss the use of IVHM in the automotive sector and recognise the importance of adopting common IVHM standards.

2.3.3. *Failure Mode and Effect Analysis (FMEA)*

FMEA is a decision making tool used to prioritise corrective actions in order to enhance parts/systems performance by eliminating or reducing failure rates (Vinodh and Santhosh, 2012). Although FMEA has been used in the automotive industry since late 1970s it still attracts researchers' attention. Ford (2004) define FMEA as a systemised group of activities intended to:

a) recognize and evaluate the potential failure of a product/process and its effects,

b) identify actions which could eliminate or reduce the chance of the potential failure occurring, and

c) document the process. It is complementary to the process of defining what a design or process must do to satisfy the customer.

FMEA is used to rank potential failure modes based on three criteria: occurrence, severity and difficulty of detection (Bradley and Guerrero, 2011). Several studies can be found in the literature that aim to improve the prioritisation of failure modes and ensure more accurate rankings. Vinodh and Santhosh (2012) demonstrate the benefits that could be achieved by applying FMEA in an automotive leaf spring manufacturer. Sharma (2005) integrates the use of fuzzy logic with expert database with FMEA to improve the prioritisation of failure causes. Bradley and Guerrero (2011) propose a new ranking method using a data elicitation technique and compare their results against the traditional RPN and the fuzzy logic methodologies.

FMEA is a preventive and proactive tool used to evaluate a process before its implementation and differs from the root cause analysis which is used when an adverse event occurs. One of the most important inputs to the FMEA is the quality history of part/sub-system or system, as previous quality issues will guide engineers and prevent reoccurrence (Ford, 2004). Failure modes and their effects as well as rankings on occurrence, severity and detection come from various test results, field data and engineers' experiences (Gan et al., 2012). Quality history may refer to warranty data, vehicle diagnostics, previous FMEAs, lessons learnt and any other applicable document. If historical data are not available for this specific part or process, a subjective assessment is used based on the experience of the engineer along with any historical data available for similar processes. Companies utilise historical data to produce a comprehensive list of previous failures and their root causes. Adding the supply chain element to it then this task can become very difficult and resource intensive. Teng et al. (2006) states that every member of the supply

chain need the right level of access to obtain their customer warranty information in order to conduct an FMEA for their designed or produced parts. Although FMEA is usually conducted on the OEM's site, they still require suppliers to submit an FMEA as part of the PPAP (Production Part Approval Process) documentation. Teng et al. (2006) documented some of the most observed challenges that companies face and proposed a tool to support companies when conducting an FMEA analysis across the supply chain. A subset of these challenges are described below:

- o Information provided in the FMEA are too generic or vague which may cause misunderstanding among the supply chain engineers.
- o Supporting documents required for the FMEA are missing which may cause inconsistency in rankings.
- o Inconsistent format of the FMEA software and documentation used in the supply chain.
- o Quite often, design requirements are not defined in quantifiable terms which can cause different interpretation among the supply chain members.

Jiang et al. (2011) propose a quality management system for supply chain which utilises Voice of the Customer (VOC) data as an important input in the FMEA to ensure that customer requirements were converted into engineering goals and functionality. Gan et al. (2012) propose an automated FMEA approach to enhance FMEA in supply chain through a fuzzy approach and an internet-based interface. The system utilises record from the data library that retains previous records.

2.3.4. *Discussion: Root Cause Analysis and Warranty*

Although the aforementioned studies prove significant benefits that can be achieved and demonstrate significant cost reductions they take into consideration one important assumption. All the models proposed and the data mining techniques discussed assume that all the data sets analysed are stored in one database and therefore the algorithm can be easily applied. As Buddhakulsomsiri et al. (2006) state: "unless the IT systems are designed to capture the desired information and can easily piece together the disparate pieces of data, the quality of the knowledge extracted from the data may be uncertain". Buddhakulsomsiri et al. (2006) propose that future research should concentrate on the development of data integration techniques from different sources. In addition, most of the data mining techniques developed discuss the importance of analysing data held in the OEM's domain without taking into consideration test data and engineering data held on the suppliers' side. Our findings enhances Choudhary et al. (2009) review paper which identified

that little work has been carried out in the area of supply chain with only five examples out of 150 papers analysed. In addition, most of the studies analyse data such as warranty claims returned from dealers. Another area that receives attention from researchers is that of on-board fault diagnostics and prognostics. Nowadays vehicle sensors capture a vast amount of data which can provide insights for the PD engineers as they are not affected by subjective criteria. Several studies have been identified in the literature that utilise data captured from vehicle sensors to support decision-making. However, only a few studies have discussed the possibility of utilising both warranty claims and vehicle diagnostics for root cause analysis. Analysing warranty claims in relation to vehicle diagnostics could potentially provide better and more accurate results especially for faults related to electrical systems.

Regarding the FMEA, several studies have been identified in the literature that aim to support engineers in prioritising and ranking failure modes. Some of the most important inputs highlighted in these studies are previous experiences and data records used. However none of these articles define what a data record is and how it can be used to generate knowledge that could benefit PD engineers. As during the last decade suppliers offer black box systems it became apparent that suppliers need to be more involved in the process as there is a cost associated with product failure.

2.4. System Architecture Approaches

The literature classification in section 2.2 showed that since 2000, there has been a significant body of literature aiming to develop a more integrated use of IT in order to aid companies to improve collaboration with suppliers and exchange product data more efficiently. Section 2.2 demonstrated that the majority of articles which propose system architectures focus mainly in the area of PD where data exchange in terms of size and volume is high. This section analyses the IT integration at a physical level which concerns the development of technologies that enable applications to physically exchange and share data. Table 2-3 shows the area of the classification framework that this section analyses in order to identify best practises and methodologies used by researchers. The outcome of the analysis will support the development of a novel system architecture that allows engineers to integrate PLM systems with cross supply chain maintenance information to improve root cause analysis.

Table 2-3 Target Area from the Classification Framework

	PLM	Product Development	Manufacturing	Logistics & Maintenance
All the publications included in this table focus on the subject of "Information flow in SCM"	Includes: • Articles that discuss the information flow through the whole product lifecycle or from a PLM system perspective	Includes: • Studies that discuss the information flow in SCM in the PD phase ** Studies that refer to the PLM systems but focuses only in the PD phase are also included in this column*	Includes: • Studies that discuss the information flow in SCM in the manufacturing phase	Includes: • Studies that discuss the information flow in SCM in the logistics and maintenance phase ** Studies that refer to the flow f the customer and the retailers b to the OEMs are also included i the Logistics & Service phase*

Review
- Publications that base their findings in the literature

Proof of Concept
- Publications that through empirical and conceptual research discuss the subject of information flow SCM without using any quantitative analysis

Modelling & Framework
- Publications that propose a generic framework to address issues or through modelling techniques simulate or measure the benefits of the informat flow in SCM

System Architecture
- Publications that propose an architecture or a system that improves the information flow in SCM

* Exceptions

2.4.1. *Distributed Data Sharing Architectures*

The distributed data sharing architectures provide access to the remote data and ensure that any multiple copies of the data remain totally synchronised (Bakis et al., 2007). Each of the software applications is designed to work with its own database and as they are purchased from multiple vendors they are designed using different database management systems. Distributed data sharing architectures are meant to provide the functionality required that cuts across separate applications with minimum effort. The analysis of the articles demonstrated that the articles can be split into two major categories: (i) the traditional approach using distributed object-based data sharing architectures and (ii) the latest XML-based data sharing architectures.

2.4.1.1. *Distributed Object-based Data Sharing Architectures*

The traditional approach for data sharing utilises distributed object data sharing architectures such Common Object Request Broker Architecture (CORBA), Component Object Model (COM) or Java Remote Method Invocation (Java RMI). Kim et al. (2010a) states that "the role of the distributed object technology is to enable the applications to call on the services of distributed software components (objects) in a transparent manner, hiding the details of the underlying networks, platforms, and implementation languages". Most of the publications included in the framework were published before the year 2005. Researchers utilised CORBA approaches to allow CAD exchange among heterogeneous systems (Zhang et al. 2000, Xu and Liu, 2003) or share information and knowledge (Rodriguez and Al-Ashaab, 2005). Other studies utilise Java RMI to allow the communication of product design data from PDM/PLM systems (Dai et al. 2006), to allow CAD collaboration on

the Web (Kim et al. 2001; Hren and Jezernik, 2009) or utilise JavaBeans to support planning and coordination of manufacturing activities through information sharing (Mourtzis, 2011). Liu and Young (2004) utilise DMBS and Visual C++ to allow information integration and sharing while Chu et al. (2006) utilise a set of C++ Application Programming Interface (API) and Java based technology to facilitate 3D information sharing.

Although distributed object technology has been used to develop software applications that allow companies to work collaboratively and share data, during the recent years their use have started to decline. CORBA and COM+ offer a rich functionality but failed to support the ever increasing need for collaboration outside the company's domain, such as the Internet. One of the reasons that CORBA failed to meet high implementation rates was mainly due to their difficulty in passing messages across firewalls (Henning, 2006; Bakis et al. 2007); they are also platform dependant (Kim et al. 2010a). This is the main reason why CORBA is currently used mostly to integrate components within a company's network where communication is protected from the outside world by a firewall (Henning, 2006). CORBA was also criticised for its complexity specifically the complexity of its APIs (Henning, 2006). Probably another major reason for the reduction in the use of distributed object technologies was the publication of SOAP in late 1999 and especially SOAP version 1.2 which became a W3C recommendation in 2003.

2.4.1.2. XML-based Data Sharing Architectures

An alternative to the distributed object based data sharing architectures is the XML-based architecture. This type of architectures allows applications to exchange and receive XML messages in a controlled and synchronised way (Bakis et al. 2007). The two most important standards that are used within the XML-based architectures are the Web Services Description Language (WSDL) and the Simple Object Access Protocol (SOAP). W3C (2004) define a Web service "as a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically WSDL). Other systems interact with the Web service in a manner prescribed by its description using SOAP-messages, typically conveyed using HTTP with an XML serialization in conjunction with other Web-related standards". A WSDL file which is written in XML is used to describe the interface of the Web service and provides clear explanation of the functionality that the service is delivering. SOAP is defined as a lightweight protocol intended for exchanging structured information in a decentralized, distributed

environment (W3C, 2007). The framework has been designed to be independent of any particular programming model and other implementation specific semantics.

The use of XML-based architectures could potentially overcome some of the challenges identified in the object-based architectures and this is the reason why they have attracted more research interest. Although some studies showed that Web-Services can be slower in terms of performance with higher consumption of memory, bandwidth and CPU compare to the object-based architectures, they are still considered as the best solution for exchanging messages over the Internet mainly due to their integration scalability and flexibility (Artemio et al., 2012; Gray, 2004). They are also considered more suitable for asynchronous types of communication that involves the sharing of a large amount of data (Kim et al. 2010a). Table 2-4 shows a comparison of the two types of architectures. Since 2005, researchers have been publishing heavily, system architectures that utilise web services to exchange data over the internet. In the framework discussed in section 2.2.2 several of these studies were identified. Web services have been used to allow data exchange among heterogeneous PLM systems (Choi et al., 2010; Gunpinar and Han, 2008) for exchanging neutral CAD data (Kim et al. 2010a; Hren and Jezernik, 2009), to support sharing procurement data (Sun et al., 2012) or even to support maintenance procedures and the end of life-cycle (Zhu et al., 2012; Gulledge et al., 2010; Kiritsis, 2011).

Table 2-4 Differences Between Data Sharing Architectures (adopted by Kim et al. 2010)

Distributed object technologies	Web Services
Better at synchronous communication	Better at asynchronous communication
Better at frequent exchange of small amounts of data	Better at exchange of large volumes of data
Difficult to pass through firewalls	Easily pass through firewalls
Platform-dependent	Platform-independent

2.4.2. *Role of Standards*

This section provides a brief overview of the standards that are relevant to this thesis. Therefore standards that are not used in the system architecture developed will be introduced briefly.

2.4.2.1. Visualisation Standards and the Use of JT

Probably the most used visualisation format in the literature is that of Virtual Reality Markup Language (VRML). VRML is a language for representing interactive

simulation of 3D models particularly over the internet (Kim et al., 2001). VRML was not originally designed for engineering applications, however several researchers have used it to share virtual models over the internet in order to support collaboration across the supply chain (Dai et al., 2006; Yujun et al., 2006; Hren and Jereznik, 2009; Kim et al., 2001). Therefore VRML standard supports engineers to view 3D data stored in the PDM system without having to install the native application. One of the main issues identified in the use of VRML is their lack of ability to maintain all the information after the converting process (Hren and Jezernik, 2009).

JT is a lightweight 3D visualisation format developed by Siemens PLM software (formerly known as UGS) and is used to support representation of CAD geometry. Later versions have been expanded to include the specification for Ultra-Lightweight Precise (ULP) and semantic product manufacturing information (PMI, product metadata) among others (Handschuh et al., 2013). JT allows companies to exchange 3D product data among heterogeneous CAD and PLM software applications. On December 2012, JT was approved by ISO as a standard for viewing and sharing lightweight 3D product information (14306:2012), as an attempt to allow manufacturers to free themselves from proprietary formats (Siemens, 2012). One of the main benefits of JT is its ability to support the visualisation of very large assemblies offered in a reduce file size as shown on Figure 2-7.
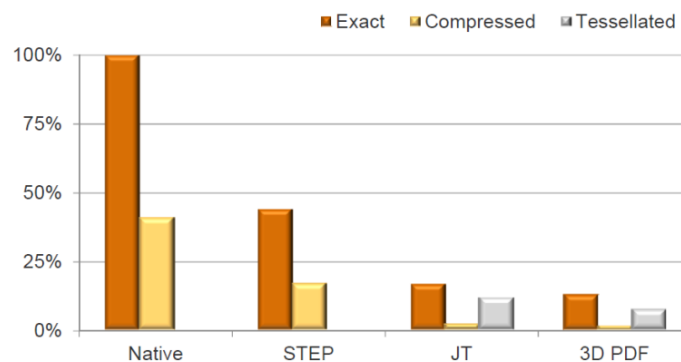
Figure 2-7 File Size Differences for Different File Formats (Adopted by Handschuh et al. 2013)

Although VRML was not used in this research project it was considered as an alternative option. JT was considered as the best option not only for its ability to reduce the file size significantly but also as it allows the file to carry meta-data and PMI information. JT was also considered as a more suitable file format for immersive environments such as CAVEs and Powerwalls. Other standard file formats used extensively in the literature are STEP and IGES.

2.4.2.2. OSA-CBM (Open System Architectures – Condition-based Maintenance)

OSA-CBM is a standard architecture for moving information in a condition-based maintenance system (MIMOSA, 2013). This standard was developed by the US Navy as an attempt to reduce the cost of creating new or propriety architectures whenever a new application was developed and to allow the standardisation of information exchange specifications within the community of CBM users. OSA-CBM is defined using UML and it separates the information that can be exchanged and the technical interfaces for extracting the information. The standard is developed based on six functional blocks as shown on Figure 2-8. In this research project the OSA-CBM standard is relevant to the use case discussed in section 8.2 which was used to evaluate the applicability of the system architecture proposed in the defence sector.

Advisory Generation (AG)
Prognostics Assessment (PA)
Health Assessment (HA)
State Detection (SD)
Data Manipulation (DM)
Data Acquisition (DA)
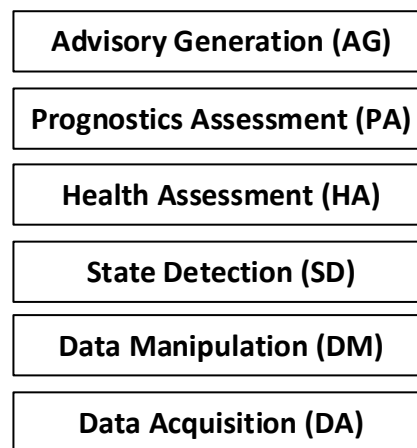
Figure 2-8 OSA-CBM Functional Blocks

2.4.2.3. S1000D

S1000D is an international standard for the production and procurement of technical publications for the aerospace, defence and capital-intensive equipment applications (S1000D, 2013). The core principle of the S1000D standard is to enable information reuse providing a standard structure of both a wide variety of electronic formats as well as printed manuals. S1000D (2013) states that some of the benefits that can be achieved through the use of this standard is the reduced documentation cost, the improved information accuracy as well as the decreased time to market. In this research project, the API provided by the S1000D standard was used in section 8.2 to extract technical publications for the evaluation UML use case.

Discussion: System Architecture Approaches

The analysis of the different distributed data sharing architectures demonstrated that XML-based architectures are more relevant for this type of study due to their integration scalability and flexibility, and their ability to exchange messages over the

internet. Although during the last decade several researchers utilised XML-based architectures to exchange data, most studies still propose solutions to support engineers in exchanging product data such as CAD data. There seems to be fewer studies that utilise XML-based architectures to share maintenance information or integrate PLM systems with maintenance information. Gulledge et al. (2010) is one of the few examples of this type of research.

In terms of the use of standards, the majority of studies utilise VRML and STEP data formats to exchange CAD data while OSA-CBM is used for developing maintenance applications. The JT format has attracted low attention by researchers as only recently it became an official ISO standard for viewing and sharing lightweight 3D product information. This research, through the use of JT, transforms native CAD data into a light-weight format in order to reduce the CAD file sizes and improve system performance.

2.5. Research Gap

Sections 2.2.3 and 2.3.4 discussed the current research challenges and future research directions on each area analysed. In this section the key research gaps are presented to aid the formulation of the main research gap that this thesis will address.

1. The first gap was identified through the analysis of articles related to PLM systems. Although PLM systems are defined as a strategic business approach that supports collaboration from concept to end of life (CIMData, 2002), the analysis of literature demonstrated that they still remain very isolated from the maintenance procedures. The outcome of the analysis enhances Lee et al. (2008) results which showed that PLM systems are used 10 times less frequently in the maintenance phase and their potential in MRO has not been realised yet. The integration of PLM systems with maintenance will allow the utilisation of knowledge and data across the product lifecycle and support not only internal decision makers but also the external supply chain. In addition, it will allow after-sales information and knowledge from maintenance and service experts to feed back to the product development process.

2. The second gap is related to the analysis of information flow across the supply chain during the maintenance phase. The analysis of articles demonstrated that although PLM systems are used to support data exchange during the PD phase, with ERP systems handling most of the data exchange within the manufacturing phase, during the maintenance phase of the product lifecycle, information sharing seems to be more fragmented. Currently there is a lack of a central repository to manage,

maintain and share maintenance data. Until recently organisations have developed multiple internal systems to manage different types of maintenance information and as a result they now face the need to develop standards and integrate those systems. Web-based technologies have significantly improved communication among supply chain members, however there are still many challenges to be addressed. Maintenance and warranty systems, although high in numbers, work as intended when the task or problem exploration area follows predefined paths within a fixed internal data landscape. It is when the task or problem resolution necessitates accessing data sources across the supply chain that issues start to appear.

3. The third gap was identified through the analysis of "system architectures" across each phase of the product lifecycle. The analysis showed that during the maintenance phase of the product lifecycle, system development has attracted low attention from researchers and primarily focused in the aerospace sector. Other sectors with high data transaction and significant maintenance and warranty costs such as automotive, marine and transportation could benefit from research conducted in the aerospace sector. System architectures proposed in the area of PLM systems focus primarily on exchanging product data and CAD models and rarely include other types of data that could be useful to engineers.

4. The fourth research gap was extracted through the analysis of literature in the area of root cause analysis and warranty. The analysis showed that all the models proposed and the data mining techniques discussed assume that the data sets analysed are stored in one database and therefore the algorithm can be easily applied. Unless the information technology systems are designed to capture the desired information and can easily piece together the disparate pieces of data, the quality of the knowledge extracted from the data may be uncertain (Buddhakulsomsiri et al., 2006). In order to reduce the warranty cost and the number of in-service part failures, OEMs have introduced electronic databases to collect and analyse warranty claims and vehicle diagnostics. In most cases, systems developed to support complex warranty processes are very rigid and offer little or no integration capabilities with other information systems. Moreover, the structure of information distributed does not follow a standardised format which can cause difficulties when integrating multiple systems.

Therefore in relation to the above research gap this research will identify areas where significant benefits can be achieved through the use of maintenance information and propose a novel system architecture that:

1. integrates PLM systems with maintenance information to allow the utilisation of knowledge and data across the product lifecycle by supporting not only internal decision makers but also the external supply chain.
2. treats network as a virtual warehouse where maintenance data are integrated and shared with the supply chain
3. supports maintenance and warranty procedures by utilising product data in conjunction with maintenance information
4. integrates the disparate pieces of data where later data mining techniques could potentially be applied

Bringing all these together, this research will fulfil the research gaps identified by proposing a novel system architecture that integrates a continuum of data types from complex PLM systems through electronic technical publications to diagnostics and warranty systems and share information across the supply chain. In order to support the root cause analysis there is a need to extend the current level of data source integration which will then enable data and information reuse to add value and to enable the value of data to be accessed through collaboration within the supply chain. Although XML-based data sharing architectures have been developed during the last decade, this research will use the XML-based data sharing architecture in a novel way to allow the integration of PLM systems with maintenance information across the supply chain. A potential solution to the research gap identified is provided by the aim and objectives of this thesis.

2.6. Chapter Summary

In this chapter, a literature review was provided with regards to information flow across the supply chain mainly during maintenance and warranty procedures. In addition, literature was reviewed to identify existing techniques and system architectures proposed by researchers to aid information exchange across the supply chain.

The review of "information flow in supply chain" literature provides a comprehensive analysis of representable articles for each phase of the product lifecycle in order to offer an overall view of the subject area and reveal research gaps. The analysis showed that although individually most of the systems are very well established, further research is required to integrate systems and processes across multiple phases of the lifecycle, especially during the maintenance phase where system architecture development to support supply chain collaboration is relatively low.

The analysis of the "root cause analysis and warranty" literature showed that although researchers have focused extensively in proposing models and algorithms to improve root cause analysis and reduce the warranty cost they assume that data are physically co-located. Therefore there is a need to develop systems that bring the appropriate data together in order to extract the required knowledge.

In order to identify the best techniques and methodologies that researchers have used to develop system architectures, a literature review was conducted. The outcome of the analysis allowed the author to choose the most appropriate distributed data sharing architecture and build on the previous work done.

Based on the review, research gaps relevant to the research were identified. Research gaps identified define the aim and objectives of this research as well as shape the research methodology adopted.

Research Methodology

Driven by the literature review presented in Chapter 2, this chapter explains how this research was carried out and demonstrates the research methods used. The first part of this chapter presents the aim, objectives and the research questions that this research has addressed. The second part of this chapter aligns the objectives of this research project against the hourglass notion of research proposed by Trochim and Donnelly (2006). Furthermore the overall research methodology, the data collection approach and the methods applied for each objective are described in this section. The research methodology proposed is divided into four phases: Define, Design, Develop, and Deliver. Each one of the four phases is presented through two key sub-sections, the data collection approach and the methods applied.
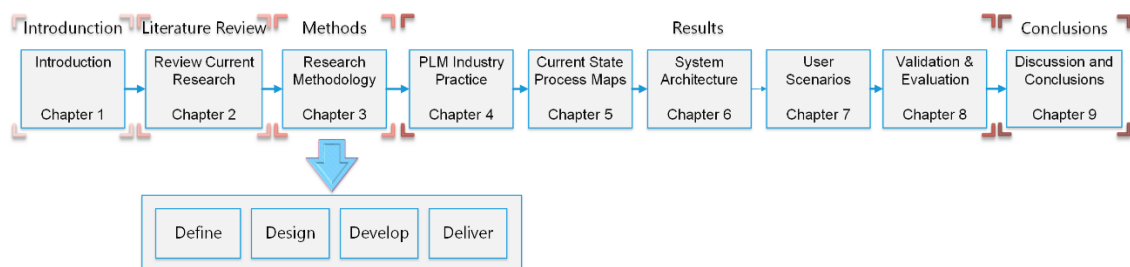
3.1. Research Aim and Objectives

The aim of this research is:

To develop a system architecture for integrating PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise cross supply chain data in a single environment. By integrating product-data from PLM

systems with warranty claims, vehicle diagnostics and technical publications, it is expected that engineers will be able to improve the root cause analysis and close the information gaps.

The literature review presented in chapter 2 allowed the following research questions to be raised:

- What are the current challenges in the area of information flow and the use of PLM systems in supply chain?
- What is the information required by engineers from PLM and maintenance systems to conduct root cause analysis?
- Can we develop a system architecture that allows engineers to integrate cross supply chain data and as a result improve the root cause analysis procedures?

By answering these questions, this research seeks to address the research gap identified in chapter 2. To guide the research process a list of objectives were set:

1. Review current challenges associated with information sharing in supply chain during multiple phases of the produce lifecycle including maintenance
2. Capture industry practice and challenges related to information flow and the use of PLM systems in supply chain
3. Capture current state process maps to demonstrate the flow and use of maintenance information using an automotive case study
4. Develop a system architecture for integrating PLM systems with maintenance information across the supply chain to support root cause analysis
5. Develop scenarios to demonstrate the usability of the system architecture in terms of its support to root cause analysis using an automotive case study
6. Validate the system architecture using an automotive case study and evaluate the applicability of the architecture using a defence case study

3.2. Research Approach

This section summarises the approach followed so as to meet the aim and objectives of this research project. The research objectives followed a structured approach which can be explained using the hourglass notion of research. The hourglass notion of research states that every research project starts with a broad area of interest which can be then narrowed down by formulating a hypothesis or a focus question. At the narrow point, researchers would generate their results. At the last step of every research project, researchers will generalise the results of the specific study to

other related situations (Trochim and Donnelly, 2006). Figure 3-1 shows the hourglass notion of research adopted by Trochim and Donnelly (2006) and modified to include the objectives of this study. The literature review allowed the identification of the research gap and allowed the formulation of broad research questions (objective 1). In addition, current industry practices and challenges related to information flow and the use of PLM systems in supply chain were captured through semi-structured interviews with experts from 15 multinational automotive companies (objective 2). These two objectives represent the identification of high level challenges that the proposed solution aims to support. The outcome from the literature review (objective 1) and the analysis (objective 2) feed in the development of the proposed system architecture. Once the scope was clearly defined, current state process maps were captured to demonstrate the flow and use of maintenance information within the automotive use case. These process maps define areas where the system architecture will support and demonstrate the specifics of this research (objective 3). Based on the challenges identified from the first three objectives, a system architecture was developed using three UML modelling views: use case, static and dynamic (objective 4). In order to demonstrate the usability of the proposed system architecture, three scenarios were developed (objective 5). The proposed solution is specific to the automotive sector and supports the business processes captured. The outcome of the analysis and the proposed solution were validated through semi-structured interviews with experts from the automotive sector. To evaluate the applicability of the architecture in a different industry sector in order to prove the generalisation of the solution, a use case from the defence sector was captured and used to further test the architecture (objective 6).
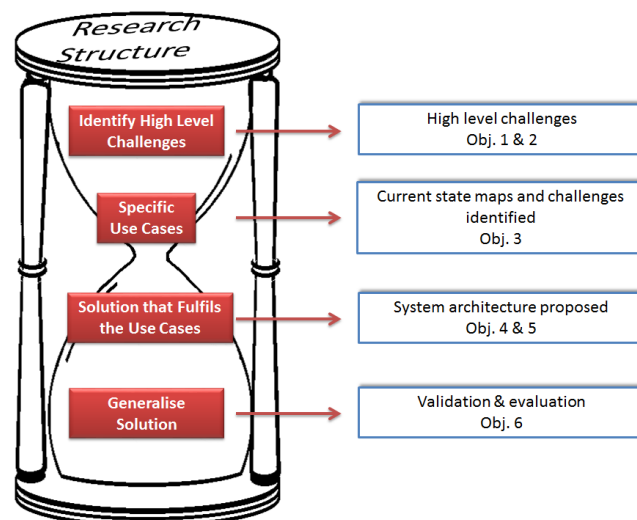
Figure 3-1 Breakdown of Objectives within the Hourglass Notion of Research

The adopted research approach was divided in four phases (4D: define, design, develop, deliver) as shown in Figure 3-2. The research approach combines multiple approaches and methods depending on the requirements and the type of each objective. Although the circular diagram shows each phase neatly separated and structured into chapters, the approach followed was more iterative and evolutionary. Hence the outcome of each objective fed into the next phase which allowed the constant development of the system architecture. For example, the outcome of the "deliver" phase fed back in the "design" and "develop" phases and modified elements of the architecture to accommodate recommendations captured from the experts. Each phase is divided in two key sub-sections, the data collection approach and the methods applied.
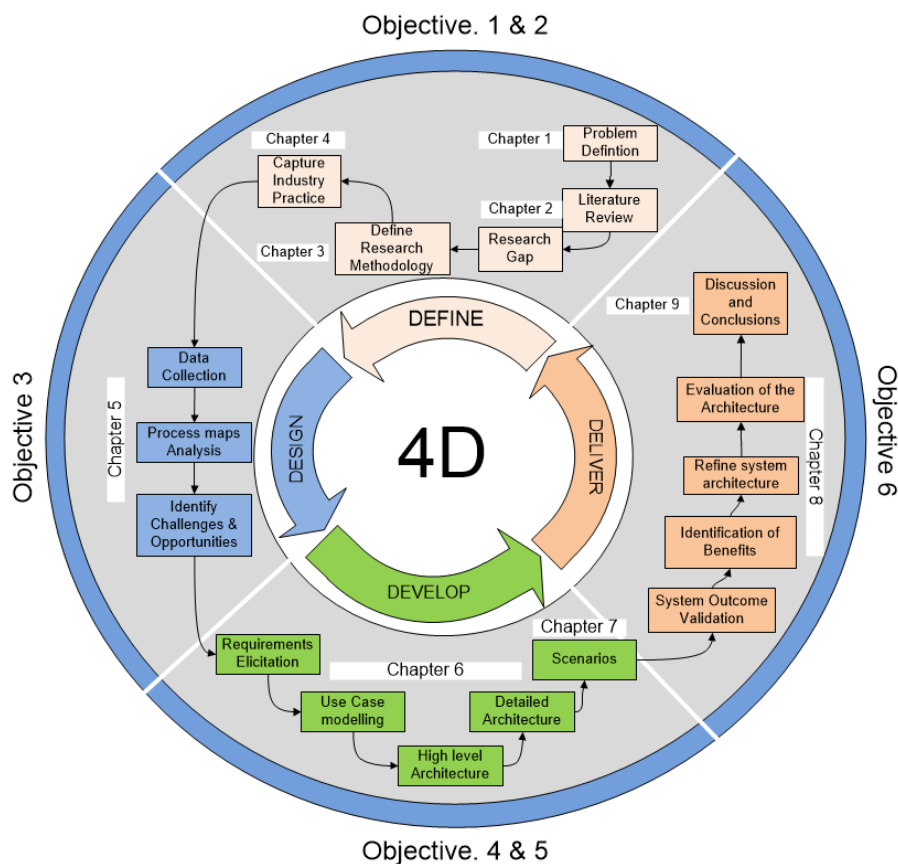
Figure 3-2 Research Approach

Prior to data collection for each objective, an ethics form was requested and approved from the Cranfield Science & Engineering Research Ethics Committee. This form seeks ethical approval of research projects involving human subjects. Therefore as this research project required data collected from semi-structured interviews with experts from the automotive sector it was deemed necessary to request a low risk approval. Through this form the author agreed to ensure that the

information collected remain strictly confidential. Therefore company names and contact details are not presented in the data analysis. By the end of the data collection, only cumulative results are presented. In addition, the interviews were preceded by introducing the aim and objectives of the research, explaining how the data will be used and guaranteeing the anonymity and privacy of those who participate in this research.

3.2.1. Define (Objective 1 & 2)

Table 3-1 Define Phase

Phase Input	Phase output	
	• Research aim and objectives • Literature review • Research gap • Key barriers to information flow in supply chain and the use of PLM systems	This phase answers the Why?

The define phase is responsible for defining the aim, objectives and scope of this research project. In order to identify the research gap and as a result formalise the research questions, a comprehensive literature review was conducted. The initial stage of the literature, reviewed the area of information flow in SCM across the product lifecycle. Although the literature review revealed gaps in each phase of the product lifecycle the main focus of this research project was around the maintenance phase of the product lifecycle and its integration with PLM systems. Therefore, literature review was extended to include areas such as root cause analysis during warranty procedures, on-board faulty diagnostics and prognostics and FMEA analysis.

To ensure that the research gaps identified are linked with the challenges that businesses are currently facing, a structured approach was followed to obtain the current industry practice and challenges related to information flow and the use of PLM systems in supply chain.

3.2.1.1. Data Collection

Literature Review

In order to capture secondary data, a comprehensive literature review was conducted. Once the scope of the literature was defined, the selection process involved searching in the SCOPUS online database (www.scopus.com) for peer-reviewed journal articles. The Cranfield University Kings Norton Library was also

used for searching books and online PhD thesis. The outcome of the review includes the analysis of more than 200 research papers in the area of information flow in the supply chain during multiple phases of the product lifecycle as well as the areas of root cause analysis and warranty procedures. A detailed data collection approach is presented in section 2.2.1.

Supply Chain Issues Relating to Information Flow and the Use of PLM Systems

To explore the supply chain issues relating to information flow a series of semi-structured interviews were conducted. For the purpose of this study, 15 multinational companies operating in the automotive sector were chosen. All the companies interviewed are operating globally but have a UK-based presence. The definition of multinational companies was based on the EU definition for SMEs (European Commission, 2005). Therefore the 15 chosen companies included companies with a number of employees higher than 250 and an annual turnover higher than 50 million Euros. The selected sample of companies provided a good spread of OEMs (1); Engineering and Service suppliers (4); Tier 1(7) and Tier N (3) suppliers distributing both mechanical and electronic components.

Semi-structured interviews was deemed as the most appropriate technique for collecting data due to the type of data required for this research. All semi-structured interviews arranged, were face-to-face and included people from various roles such as Business Improvement Leaders, UK Managing Directors, Programme Managers, CAD managers, Supplier Integration managers all of whom were experts regarding supplier integration and data exchange. In several cases, interviews were conducted with a group of people in order to include technical people and engineers that represent the end users of the systems used. The average length of each interview was 90 minutes. Whenever required follow up telephone conversations were arranged to ensure clarity of information and obtain feedback. In order to facilitate candid responses, confidentiality was agreed. During each interview a guide was used. The author was responsible for designing the interview guide, analysing the data collected and supporting three semi-structured interviews. Hence the rest of the interviews were conducted from Theorem solutions who were part of the wider project and are considered experts in supply chain integration and PLM systems. To ensure proper communication and explain the interview guide, a training session with all the people involved from Theorem Solutions was arranged. The interview guide consisted of an introduction pack that was used to explain the objectives of this research study and manage expectations. The main part of the guide was a data

collection sheet that was used to capture processes where supplier integration was required, along with information systems used to exchange data and any data conversions required. In addition, the data collection sheet included an open area for capturing issues in each step of the process. Although the approach followed was structured, the discussion of issues was open to the interviewees to prevent the possibility of biasing the outcome. The outcome of each interview was captured through the data collection sheet and notes. Key issues were then extracted from the data collection sheet and notes and analysed through Hicks et al. (2006) methodology. The filtering and classification process and the outcome of the analysis are presented in sub-sections 4.2 and 4.3.

3.2.1.2. Methods Applied

Literature Review

A detailed view of the literature methodology is presented in sub-sections 2.2 and 2.2.1. The literature review methodology is divided into three stages:

i) the initial stage which is responsible for reviewing the area of information flow in supply chain in order to identify current challenges and research gaps

ii) the specific stage which explores the area of root cause analysis and warranty for extending the depth of the literature and ensure that no meaningful publications have been missed

iii) the methods stage which seeks to review existing techniques and methodologies used in the literature that would allow the author to build in the previous work completed.

Supply Chain Issues Relating to Information Flow and the Use of PLM Systems

To successfully achieve the purpose of this objective, it was identified that a qualitative research methodology was required. From the literature review conducted, it was decided that the methodology developed by Hicks et al. (2006) was the most appropriate for this type of study. The selection of Hicks et al. (2006) methodology was based on a detail review of methodologies used in the area of supply chain issues and barriers of information exchange. The review was divided into two streams (the detailed review can be found in Appendix A): 1) studies that utilise structured questionnaires to weight and prioritise issues identified within the literature using statistical methods, with data collected from practitioners (Fawcett et al., 2008; Pujara et al., 2011; Jharkharia and Shankar, 2005; Archer et al., 2008) and 2) studies that use the outcome from the literature to support interviews but the actual supply

chain issues and barriers captured are open to the interviewees (Childerhouse et al., 2003a; Cheikhrouhou et al., 2012; Evgeniou and Cartwright, 2005; Hicks et al., 2006; Garengo and Panizzolo, 2013; Tsinopoulos and Bell, 2010; Sheriff et al., 2012). Hicks et al. (2006) methodology was chosen as it allows the consolidation of data through clusters as well as the calculation of dependencies among different clusters. In addition, it allows the transformation of qualitative information into quantitative results. While previously this methodology was used to analyse issues on information management across engineering SMEs, in this study it will be used to identify, measure and prioritise the perceived importance of supply chain issues related to information flow and the use of PLM systems within the automotive industry. The methodology followed two phases: data collection and, filtering and classification process which is presented in detail in section 4.2.

3.2.2. Design (Objective 3)

Table 3-2 Design Phase

Phase Input	Phase Output	
The outcome of the "Define" phase justifies the selection of process maps and the initial design of the system	• Current state process maps • Challenges and opportunities	This phase answers the Who, When?

The "design" phase consists of collecting all the information required to capture the current processes, the tools used and the information exchanged between an OEM and its suppliers, once an in-service product failure occurred. The process maps describe the flow and the use of maintenance information, such as warranty claims and vehicle diagnostics, reported from a service representative (dealer) to the OEM and then to the component supplier. Process maps are used to define the areas where the proposed system can be utilised in order to address the business challenges identified. Although the current state process maps capture more information than the proposed solution could achieve, they demonstrate clearly areas that the system architecture will support.

3.2.2.1. Data Collection - Current State Process Maps

Data collection was achieved through a combination of semi-structured interviews, by studying the internal documentation and by testing the systems used. Using a combination of data collection techniques provided validity and reliability to the results and reduced any potential bias. The author had access to all the systems involved in the development of the system architecture except from the PLM system.

Accessing the warranty systems allowed the author to understand the functionality that these systems provide as well as capture the challenges that engineers encounter. All semi-structured interviews arranged were face-to-face and included people from various roles such as Quality Managers, Warranty Managers and Service Engineers for the warranty use case, Product Development Engineers and Managers for the DFMEA use case. In addition, Quality Data Managers and IT System architects were also interviewed for understanding the infrastructure and the systems involved in the process. As a result, the selected sample allowed the user to understand the processes both from an end users perspective but also from an IT, infrastructure perspective. To obtain a better understanding of the processes, a number of follow up interviews were arranged with key stakeholders. The full details of the interviews conducted are presented in Table 3-3. The questions for each semi-structured interview were adjusted based on the role of each interviewee. For example, the warranty spend reduction leader was asked questions related to the process, the decision points and the systems used while the Quality data manager was asked questions related to the integration of the systems, the database structure, inputs and outputs. A set of questions is presented in Appendix B. All the interviews were face to face and the information captured from each interview was used to develop the current state process maps. The outcome of each interview was formally documented and sent back to the interviewees to review and comment. This approach ensured that any potential bias was minimised as each interviewee reviewed and validated the outcome. The internal documentation provided by the OEM and a few suppliers assisted in developing the current state process maps.

In addition two workshops, including the proof of concept software developers, were arranged. The purpose of the two workshops was to bring a variety of stakeholders together, such as IT experts, domain experts and quality data analysts in order to obtain a better understanding of the information and the systems used as well as capture the challenges that currently engineers experience. Moreover, four supplier-quality review sessions were attended in order to view real-time the processes that suppliers follow. These four supplier-quality review sessions are related to the process map described in section 5.2.

Table 3-3 Data Collection: Current State Process Maps

No.	Company	Role	Area of Discussion	Number of Interviews
1	Case-study company	Business Process Manager	Supplier Integration	1

2	Case-study company	Global Supplier integration Manager	Supplier Integration	1
3	Case-study company	PD Chassis Engineer	PLM - Supplier Integration	1
4	Case-study company	Business Process Manager	PLM integration - BOM	1
5	Supplier A – Tier 1	Project Manager	PLM integration - BOM	1
6	Case-study company	Service Team Leader	DFMEA - Processes, Systems, Information involved	3
7	Case-study company	Process Business Analyst	DFMEA - Systems, Information involved	1
8	Case-study company	PD Team Leader – Powertrain	DFMEA - Processes, Systems, Information involved	3
9	Case-study company	Warranty Spent Reduction Leader	Warranty Processes, Systems, Information involved	3
10	Case-study company	Quality Data Manager	Warranty System / Information Involved	2
11	Case-study company	Senior Quality Manager	Warranty process overview	1
12	Case-study company	1. Quality Data Manager 2. Quality Business Analyst 3. Warranty System Architect 4. IT System Architect 5. IT System Architect	Workshop - Warranty Systems / Information Involved	2
13	Case-study company	Quality Data Analyst	Data involved	2
14	Case-study company	Electrical Warranty Manager	Warranty Processes / Systems Involved	1
15	Supplier B Tech. Pubs supplier	Project Manager	Tech. Pubs system	2
16	Supplier C – Tier 1	Quality Manager	Processes, Systems, Information involved	2
			Total	**27**

3.2.2.2. Method Applied - Current State Process Maps

Flowcharts were selected as a method to model the processes captured. Flowcharts offer a simple and standardised approach to communicate processes with multiple stakeholders, as they have low training requirements (Milosevic, 2003). Prior to selecting the flowcharts as a modelling method both IDEF (Integrated DEFinition Methods) and the ICD (information channel diagram) were tested for their applicability. As discussed above, flowcharts were identified as the most appropriate technique for this specific aspect of this research. The process maps were separated into high level maps and include references to lower level process maps. The

outcome of this methodology is presented in sections 5.2 and 5.3. Process maps provide a strong input to the requirements analysis described in section 6.2 as they clearly define areas where the proposed system architecture could apply in order to improve the root cause analysis.

3.2.3. Develop (Objective 4 & 5)

Table 3-4 Develop Phase

Phase Input	Phase Output	
The outcome of the "Design" phase demonstrate the areas where the proposed system architecture will operate	• Requirements analysis • System architecture "Use-case view" • System architecture "Static view" • System architecture "Dynamic view" • Scenarios	This phase answers the What, How?

The "develop" phase consists of all the necessary tasks required to transform the requirements captured into system functionality. UML diagrams were used to document and communicate the system functionality, the sequence of events followed, the applications integrated and the way that different clusters of data are linked. This phase demonstrates, through the use of three different architectural views (use case, static, dynamic) the interactions among the end users and the proposed system, the structure and the dependencies between the different elements of the architecture, and the sequences of tasks that occur within the system over time. The outcome of this phase defines the functionality required and demonstrates how the proposed system architecture will address some of the challenges identified within the process maps in the "design" phase. To demonstrate the use of the system architecture, three scenarios were captured, one for each key use case. The scenarios explain how the system architecture could be used, by showing examples of: (i) the search criteria defined by the user, (ii) the user interactions with the system throughout the root cause analysis, (iii) the data presented in the User Interface (UI), and finally (iv) the root cause analysis outcome.

3.2.3.1. Data Collection

Requirements elicitation was conducted through semi-structured interviews and workshops with various members of the case study company and other members in the supply chain. These semi-structured interviews are an addition to the interviews conducted for the current state process maps as their aim is to define the functionality required from the end users. Therefore these interviews were focusing more on the to-be state rather than the as-is. Furthermore, half of the interviews conducted, focused on defining how data are linked and how the proposed system

architecture could be used to extract and integrate those data. In addition, interviews with IT system administrators helped in capturing non-functional requirements that could possibly restrict the implementation of the proposed system architecture in a real production environment. As part of the requirements elicitation process, experts supported the prioritisation of requirements using the MoSCoW approach. By engaging key stakeholders within the prioritisation of requirements, the author ensured that any potential bias was minimised. The details of the prioritisation approach are explained in section 3.2.3.2 where methods are discussed. All interviews arranged were face to face and included people from various roles. In several cases, interviews were conducted with a group of people in order to include technical people and engineers who are the actual users of the systems involved. Table 3-5 shows the full list of the semi-structured interviews conducted. Some of the questions asked can be found in Appendix B. The outcome of the requirements elicitation process is discussed in section 6.2.

Table 3-5 Requirements Elicitation

No	Company	Role	Area of Discussion	Number of Interviews
1	Case Study Company	Virtual Reality Manager	Use of CAVE and VR Applications	1
2	Tier 1 Supplier B	1. Project Manager 2. Diagnostics Project Manager 3. System Architect	Workshop - Tech. Pubs Integration	1
3	PLM Supplier D	PLM Support Engineer	PLM Integration + Component Mapping	1
4	Case-study company	Technical Specialist – System administrator	Vehicle Feedback Database integration + component mapping	2
5	Case Study Company	Service Team Leader	Req. Elicitation: Functionality for DFMEA Use case	2
6	Case Study Company	PD Team Leader – Powertrain	Req. Elicitation: Functionality for DFMEA Use case	2
7	Case-study company	PD Team Leader – Chassis	Req. Elicitation: Functionality for DFMEA Use case	1
8	Case-study company	1. Quality Data Manager 2. Quality Business Analyst 3. Warranty System Architect 4. IT System Architect 5. IT System Architect	Workshop - Warranty System Integration	1
9	Case-study company	Quality Data Manager	Warranty System integration	1
10	Case-study company	Principal Engineer	Warranty System overview and data connection	2

11	Case-study company	Senior Quality Manager	Req. Elicitation: Functionality for Warranty Use case	1
12	Case-study company	Warranty Spend reduction Leader	Req. Elicitation: Functionality for Warranty Use case	2
13	Tier 1 Supplier C	Quality Manager	Req. Elicitation: Functionality for Warranty Use case	1
14	Case-study company	Quality Business Analyst	Data integration: Primary keys and systems used	1
15	Case-study company	Electrical Warranty Engineer	Req. Elicitation: Functionality for Warranty Use case	1
16	Case-study company	Snr. Manager - PLM	System Overview – Future directions	1
			Total	**21**

3.2.3.2. Methods Applied

Figure 3-3 shows the holistic approach that was followed to gather, analyse, manage and document requirements. The requirements engineering process by Debra et al. (2010) was used as a basis to construct the methodology discussed in Figure 3-3. Within the red boxes, this figure shows the interaction between the "develop" phase with the other two phases of the research methodology (design and deliver). The outcome of this methodology is presented in chapter 6.

Through the requirements elicitation approach a requirements catalogue was created to capture requirements for each use case and form the basis for the development of a proof-of-concept system. The requirements catalogue captures the functionality that experts recognised as important. However, it does not take into consideration how the intended solution will achieve this functionality. As Schulz (2001) defines this catalogue answers the what? question rather than the how?. Requirements were then prioritised according to the MoSCoW ratings (Tudor and Walter, 2006; Hatton, 2007). Hatton (2007) demonstrates different prioritisation methods and states that significant benefits can be achieved through early prioritisation. The MoSCoW method is probably the best choice as it is simple to perform and defines very accurate priorities.

- (M)ust have: Requirements that represent the core elements of the proof-of-concept system. Failure to meet these requirements will have an impact on the success of the project.
- (S)hould have: Represents high-priority requirements that would be an advantage to have in the early prototypes. Selection of these requirements depends on the project resources.

- (C)ould have: Features that are usually considered as "under development". These requirements are desirable to have but they can be omitted if necessary.
- (W)on't/(W)ant to have: These requirements are not unimportant but they are recognised as requirements that will not be part of the proof-of-concept system. These requirements are an important element in an incremental approach as they can be used during future phases of the development.
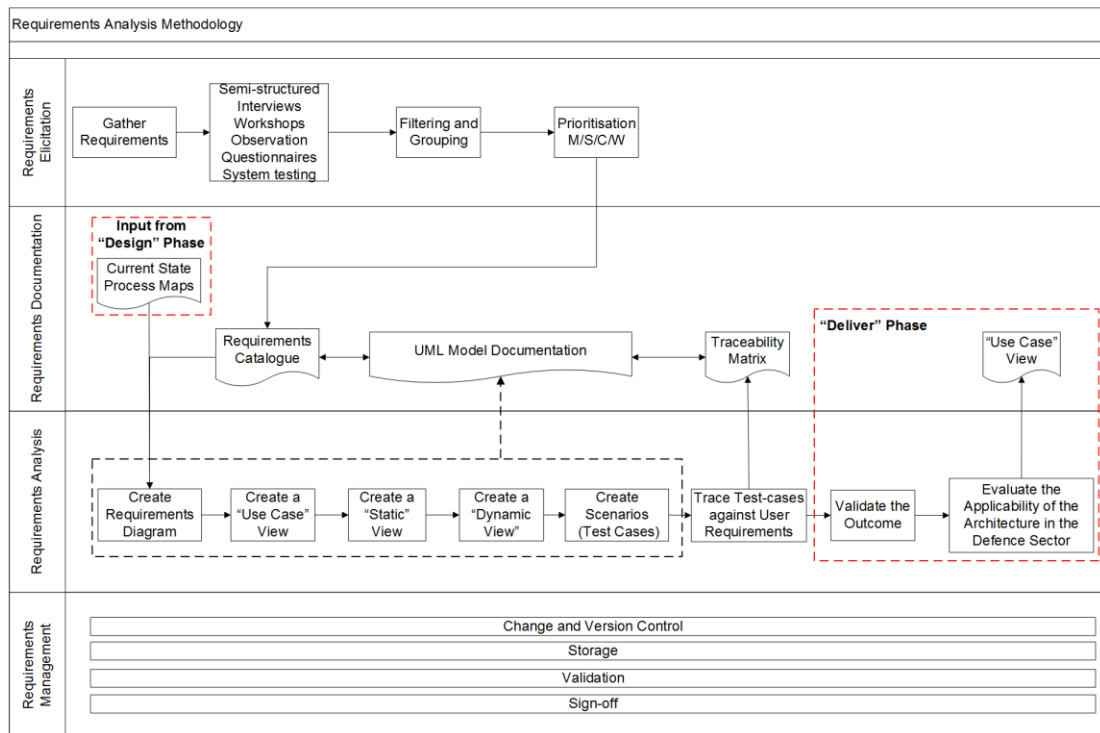
Figure 3-3 Requirements Analysis Methodology

The requirements analysis defines the end users of the system, applications that needs to be integrated, functionality that needs to be developed and non-functional requirements that needs to be considered before moving to the development phase. The outcome of the requirements analysis is the "use case" view of the system architecture. UML diagrams such as requirements diagram, use case diagram, and sequence diagrams were created to transform the user requirements into system functionality. During the last decade UML and SysML diagrams have received significant attention as they provide a common language in order to better understand the developed systems. Lankhorst (2009) states that "UML is currently the most important industry-standard language for specifying, visualising, constructing and documenting the artefacts of software systems". Chaudron et al. (2012) provided empirical evidence to demonstrate the effectiveness of UML

modelling. UML was considered as the most appropriate language for modelling the system architecture as it is a standard language used both in industry and academia (Lankhorst, 2009). Data flow diagrams were also considered for demonstrating the flow of data and the interaction between systems. However the author decided to use UML in order to have the same modelling approach across the different models developed for each view of the proposed system architecture. UML is widely used and contributes in transforming user requirements into system behaviour while at the same time offering a shared understanding and enabling more effective communication through a standardised language. Leaving out the technical details, UML are acknowledged as an easily understandable language for illustrative purposes to business engineers and specialists (Lankhorst, 2009). Therefore, UML diagrams created, as part of this research, were also used as a communication method between stakeholders and system developers to share a common understanding of the system architecture proposed. In addition, UML models were used as a validation point throughout the development of the system. Furthermore, three scenarios were developed, one for each key use case to demonstrate how the proposed system architecture will be used to support root cause analysis. The scenarios demonstrate the flow of the system by examining all the steps followed, starting with the search criteria defined by the user, the interactions with the system throughout the root cause analysis, the example data presented in the UI, and finally the outcome of the root cause analysis. Scenarios were used as part of the validation process. A traceability matrix was created to ensure that requirements can be linked to use cases and as a result the outcome of the system architecture meets customers' expectations. This tool helped in tracing the source requirements to their low/test level and from their low/test level back to source (Soonsongtanee and Limpiyakorn, 2010). The methodology followed ensures that the system developed will satisfy business requirements and as a result brings benefits to the business and its supply chain.

Within literature, several viewpoint frameworks are presented such as Zachman framework (Zachman, 1987), 4+1 view model (Krunchten, 1995), TOGAF (The Open Group, 2002). Liang and Su (2010) presented a fourth-Party Logistics (4PL) platform using four different UML views: subject domain division, use case, behavioural model, object model. Dong and Hou (2011) presented a modelling process for software development using a use case, a static and a dynamic modelling approach. Similarly, Cui et al. (2008) demonstrated a drug delivery system based on four different UML analysis: use case, static, dynamic and implementation. All these

frameworks have been used to ensure that all relevant aspects of the architecture are covered (Lankhorst, 2009). Therefore the approach of the four views (use case, static, dynamic and implementation) was adopted as it was easy to communicate with key stakeholders, it utilises different elements of the UML methodology and verifies the consistency and completeness of the system architecture. Implementation view was considered out of scope as the outcome of this research was a system architecture and therefore modelling the IT infrastructure was not considered relevant. The outcome of this methodology is presented in chapter 6.

In order to have a centralised repository for all the requirements captured and the UML models created, a software application called Enterprise Architect (EA) from Sparx systems was used. EA provides complete traceability from requirements to analysis and design models and is widely used in software development. Therefore all the UML models presented in this thesis were developed using the Sparx EA software.

3.2.4. Deliver (Objective 6)

Table 3-6 Deliver Phase

Phase Input	Phase Output	
The outcome of the "Develop" phase is validated here. In addition the "Deliver" phase is used to evaluate the applicability of the architecture in a different industry sector.	• Validation using the automotive case study • Evaluation using defence case study • Discussions	This phase validates the Why?

The "Deliver" phase consists of all the necessary tasks required to validate the outcome of this research and evaluate its applicability in a different industry sector. The system architecture was validated through interviews with experts from the automotive sector. In order to examine the applicability of the proposed solution in a different industry sector, the defence case study was selected. This case study demonstrates that the outcome of this research could benefit both the automotive and the defence sectors. The defence case study is also called as the evaluation case study in this thesis, as its purpose is to evaluate the applicability of the system architecture in a different industry sector. In the case study captured, fleet maintenance engineers are looking to utilise the proposed solution in order to resolve an in-service failure that requires short term action in addition to longer term design changes to avoid a repeat of the issue. To aid this process, IVHM corrosion data, engineering data from PLM systems, in terms of specifications and CAD for the

suspected component as well as electronic publications on how to replace a part need to be involved in the process.

3.2.4.1. Data Collection

Validation Using the Automotive Case Study

Validation was achieved through semi-structured interviews with automotive experts both from a vehicle manufacturer and from a component supplier. For the validation process, sub-section 8.1 provides a clear description of the experts involved in the validation process, their role in relation to each use case and shows the outcome of the process.

Evaluation of the System Architecture Using the Defence Case Study

For the evaluation case study, data collection was achieved through semi-structured interviews. The company operating in the defence sector was part of the wider project which lasted two years and therefore they provided input throughout the development of the system architecture. However four formal semi-structured interviews were arranged to cover the details and ensure that the evaluation case study satisfies user requirements. Semi-structured interviews with key stakeholders were used to gather and prioritise requirements in order to test the functionality of the proposed system architecture. Table 3-7 shows the details of the interviews arranged. All semi-structured interviews were face to face and lasted on average one hour. Follow up conference calls were arranged to validate the outcome of the use case. The outcome of the evaluation process is discussed in section 8.2.

Table 3-7 Data collection: Evaluation Case Study

No	Company	Role	Area of Discussion	Number of Interviews
1	Case Study Company – Defence sector	Principal Scientist	Use case, information, systems used	1
2	Case Study Company – Defence sector	Human factors scientist	Use case, information, systems used	1
3	Case Study Company – Defence sector	Principal Scientist	System architecture, data integration	1
4	Company – Defence sector	Principal Scientist	Web-services, data extraction, OSA-CBM/ S1000D standards	1
			Total	**4**

3.2.4.2. Methods Applied

Validation Using the Automotive Case Study

Semi-structured interviews were deemed as the most appropriate technique of validating the outcome of the proposed system architecture. All semi-structured interviews arranged, were face-to-face and lasted on average 90 minutes. A technical report with all the current state process maps, the requirements catalogue and the proposed solution was provided to all the experts who reviewed the report and provided feedback.

A presentation pack was used to demonstrate how the proposed system architecture delivers the functionality required for each one of the three main use cases. All experts were aware of this research due to their involvement in capturing and validating the current state process maps and in supporting requirements gathering prior to the development of the proposed system architecture. As the POC system was under development when the validation meetings occurred, the presentation pack was used to explain the functionality of the system. High level scenarios in conjunction with screen shots and a small video from the POC system were used to demonstrate: i) how the user interacts with the system, ii) how the system aggregates the data and ii) what the system presents to the end user.

For the validation process, sub-section 8.1.3 demonstrates how the outcome of the validation meetings fed into the "design" phase as the recommendation captured from the experts were used to improve the system architecture and the functionality delivered. Interviewees were asked to provide feedback on the following questions.

- Do you agree with the information being aggregated from the proposed system?
- Is there anything not covered from the system, in terms of information or functionality?
- How is currently the integration of PLM systems occur within the processes discussed?
- What are the anticipated benefits of the proposed system?
- What would you consider as next steps?
- Have you seen anything similar within your organisation?

Evaluation of the System Architecture Using the Defence Case Study

For the evaluation case study, the methodology presented in the "develop" phase in sub-section 3.2.3 is used to capture user requirements and trace them against the

system functionality developed (section 8.2). As a result, a UML "use case" view was developed to model the functionality required. The UML "static" and "dynamic" views presented within the evaluation case study, are a modification of the views developed for the automotive use case. Similarities and differences among the two sectors were captured and provided insights on best practices that could be shared among the two sectors.

3.3. Chapter Summary

This chapter presented the aim of this research as the development of a system architecture for integrating PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise cross supply chain data in a single environment. Section 3.1 presented the aim, objectives and the research questions. Trochim and Donnelly (2006) hourglass notion of research was used to demonstrate the flow of this research project and rationalise the objectives defined. The core part of this chapter is presented in section 3.2 which explains in detail the 4D research methodology followed with its inputs and outputs. Each one of the 4 phases was presented through two key sub-sections: i) the data collection approach and ii) the methods applied. Justification of each one of the selected methods is also provided within this section. The development of the following chapters is linked with the data collection approaches and the methods defined within this chapter.

Industry Practice Related to Information Flow and the Use of PLM Systems within the Automotive Industry

The purpose of this chapter is to identify, measure and prioritise the perceived importance of supply chain issues related to information flow and the use of PLM systems within the automotive industry. This chapter analyses empirical data captured from semi-structured interviews with 15 multinational companies operating in the automotive sector as discussed in section 3.2.1.1. Data collected are analysed using the Hicks et al. (2006) methodology as explained in section 3.2.1.2. The individual issues captured are classified against 14 clusters that represent the core and the fundamental supply chain issues in information flow. This analysis showed that half of the issues captured are related to the inadequacy of the information systems used. By identifying, measuring and prioritising the importance of supply chain issues this analysis provides a good understanding on how PLM systems are currently utilised which will feed into the development of the proposed system architecture.
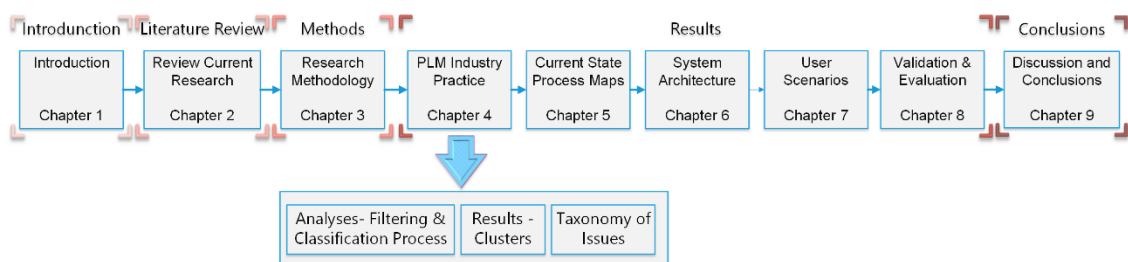
4.1. Introduction

The purpose of this chapter is to identify, measure and prioritise the perceived importance of supply chain issues related to information flow and the use of PLM systems within the automotive industry. Although the literature review in chapter 2 provided insights into the processes and the information exchanged within the warranty and the maintenance procedures, the area around PLM systems still remains unclear. While PLM systems are considered as a solution that can manage product-data from concept to end of life it was identified that currently PLM systems concentrate primarily on the PD phase and remain very isolated from the maintenance phase. Semi-structured interviews were deemed as the most appropriate technique of data collection due to the type of data required for this research. Fifteen multinational companies operating in the automotive sector were chosen. Data collected were then analysed using a methodology proposed by Hicks et al. (2006) as discussed in section 3.2.1.2. During data collection it was identified that none of the automotive companies interviewed utilise PLM systems as a way to manage and store maintenance information. Although this piece of work falls naturally in the PD phase which is not the primary focus of this research it provides greater insights on supply chain issues related to information flow and the use of PLM systems within the automotive industry. It also demonstrates areas that could create barriers in supply chain integration even if PLM systems were extended to incorporate maintenance information. By identifying, measuring and prioritising the importance of supply chain issues this analysis provides a good understanding on how PLM systems are currently utilised which will feed into the development of the proposed system architecture.

4.2. Analysis - Filtering and Classification Process

Initially a filtering process occurred to eliminate issues that were outside the scope of this study. The initial number of issues extracted from the data collection sheet and notes was 145. Through the filtering process the number of issues was reduced to 118 which represent the recorded issues related to the scope of this study. The issues discarded were considered outside of scope as they were either relevant to the IT dimension of Information Management (IM) such as the IT infrastructure and the network connection or to specific processes used within one company. Once the issues list was finalised, the individual issues were divided in the three dimensions of IM (Information, Information Systems and Overall management) as discussed by Hicks et al. (2006). The definition of each one of the three dimensions is presented in this section. The individual issues identified were then grouped into 14 categories

based on their similarities. These 14 clusters demonstrate the core supply chain issues related to information flow. However it is unlikely that each cluster will be independent of another, therefore based on the amount of company citations and the dependencies among the clusters, each core cluster of issues was ranked and prioritised. This approach concluded on the top six fundamental clusters that represent the high priority barriers of information flow in supply chain. Figure 4-1 shows the flow of the filtering and classification process.
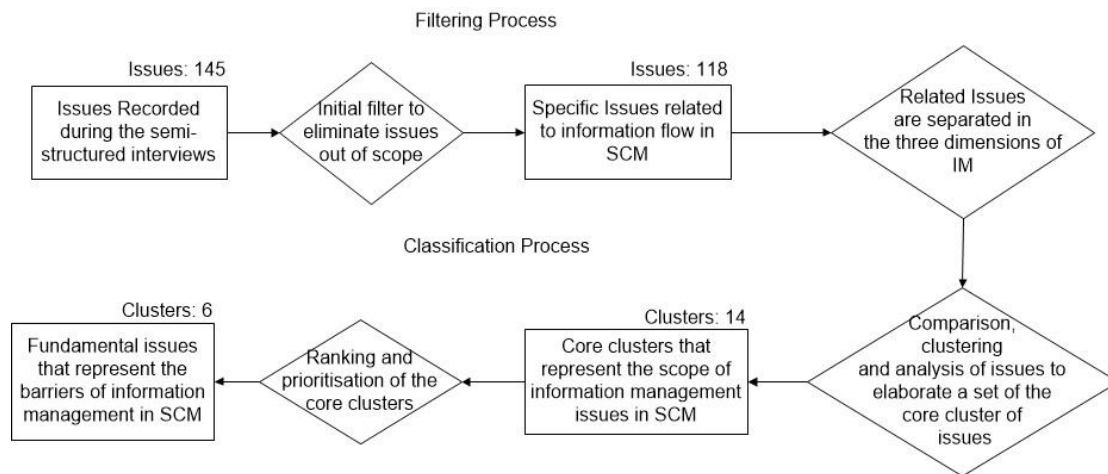
Figure 4-1 Filtering and Classification Process

4.2.1. *Information*

Information in this context represents the actual information and data required to perform a task or a process that involves information exchange with the supply chain or a customer. These information may range from complex product-related data such as CAD data, BOM structures and their associated documentation to production and forecasting data and project management information required prior to production launch. Moreover it may include contractual data such as requests for quotation (RFQ) and financial orders exchanged with suppliers.

4.2.2. *Information Systems (IS)*

IS refers to applications and databases used across various business units in order to perform an information exchange task or process within the supply chain. IS represents the applications and the databases used for creating, storing and exchanging information. IS includes both the systems used to create the information such as CAD/CAM/CAE systems but also systems used to manage and share information. These systems may vary from complex enterprise systems such as PLM, PDM, ERP systems to FTP servers and e-mail. The level of data sharing and the depth of collaboration with a supplier will define the information systems used and the type of connection. Tang and Qian (2008) categorise suppliers into two

types, the quasi suppliers and the fully integrated suppliers. Based on Tang and Qian (2008) the fully integrated suppliers are directly connected usually through a PDM or PLM system while the quasi-suppliers are connected through a "black box" Tier-1 supplier. The volume of data transactions and the brand power of a key customer or supplier will influence the adoption of an enterprise solution (Archer et al. 2008). In this study it was identified that in several cases suppliers were not directly connected with OEMs' enterprise systems but they chose to exchange product data via secure File Transfer Protocol (FTP) servers. Therefore issues related to this mean of information exchange are also discussed in this chapter. Moreover, the IS dimension includes systems that are used primarily from Purchasing and Finance departments to exchange purchasing orders and RFQs using ERP systems.

4.2.3. *Overall Management*

Overall Management includes issues that relate to both the management and maintenance of existing systems or to barriers that restrict future system implementations. Introducing a new enterprise system such as PDM, PLM and ERP poses a significant investment and a major challenge. Although significant improvements can be achieved by using an enterprise system, there are also a variety of issues associated with their implementation. Researchers highlight tangible and intangible benefits from ERP systems (Kale et al., 2010) as well as issues that companies face during the implementation phase of an ERP system (Li, 2011; Mandal and Gunasekaran, 2003; Xu et al., 2002; Kumar et al., 2003). Similar challenges were also identified while implementing PDM systems (Siddiqui et al., 2004) and the latest PLM systems (Cantamessa et al., 2012). Companies implementing enterprise systems have still to integrate their internal processes while winning the acceptance of the new system by the employees (Archer et al. 2008). Moreover once these enterprise systems are implemented they can become a big overhead for suppliers who work with multiple OEMs due to the licensing, the maintenance and the training costs involved. Hicks et al. (2006) highlights that little work has been undertaken to understand issues of existing systems for a group of organisations. This study will support this research gap by capturing both pre-implementation and post-implementation issues identified from multinational automotive companies.

4.3. **Results - Classification of Issues**

From the 118 issues identified within the scope of this research a filtering process was applied to divide the issues in the three dimensions on IM. The next phase of the

analysis included the comparison, classifying and prioritising the issues which revealed the 14 clusters that represent the high level clusters of supply chain issues related to information flow. The clusters were also divided against the three dimensions of IM to demonstrate both the variation of the 118 issues and the 14 core issues against the three dimensions.

4.3.1. *Clusters*

From the 118 issues analysed it was recognised that some of the issues were identical, captured from a number of companies, while others had similar causes and effects and as a result could be grouped within the same cluster. The analysis revealed 14 clusters of issues which were then divided into core and fundamental. The fundamental clusters represent high priority issues selected based on their rankings (high number of citations or high number of individual issues) and their dependencies with the other clusters. The core clusters represent lower priority issues compared to the fundamental but still demonstrate areas that need to be taken into consideration moving forward. Table 4-1 summarises the number of individual issues identified for each cluster, the percentage of issues, the number of citations and the relation that each cluster has against the three dimensions of IM.

Table 4-1 Relative Spread of Clusters

Name	Number of Individual Issues	% of issues	Number of Companies Citations	Three Dimensions of IM		
				Information	IS	Overall Management
IS Functionality	17	14.41%	6		X	
Accessibility	15	12.71%	9	X	X	
Information Systems Use and Maintenance	12	10.17%	6	X	X	X
Communication	10	8.47%	8		X	
Information Availability	10	8.47%	8	X	X	X
Implementation Cost	9	7.63%	6			X
Information Consistency	7	5.93%	4	X		
Manual Systems and Data Entry	7	5.93%	5	X	X	
Information Exchange	7	5.93%	5		X	
Information Quality	6	5.08%	5	X		
Interoperability	6	5.08%	4		X	
Notification Process	5	4.24%	5		X	
Authorisation	4	3.39%	3			X
Security	3	2.54%	3		X	X
Total	118					

4.3.1.1. Information Consistency

This cluster of issues was cited from four companies and represents 6% of the total issues. Information consistency focuses on the issues that suppliers face with inconsistent naming and numbering conversions, inconsistent file formats used from multiple systems, and the versioning control while working with multiple customers.

4.3.1.2. Information Quality

This cluster represents issues that were identified mainly from CAD engineers who invest a significant amount of time in validating information received. Usually these issues occur from suppliers that are not directly connected to OEMs' PDM/PLM system or operate in environments where multiple PDM and CAD systems are used and as a result data conversion from neutral formats such as STEP and IGES to native formats is required.

4.3.1.3. Interoperability Issues

This cluster of issues was highlighted as a minor one with 5% of the total. Although four companies mentioned interoperability issues around CAD data conversion it was highlighted that neutral formats such as STEP and IGES support the information sharing without major problems. In a few cases it was highlighted that interoperability issues can cause iterations due to the multiple CAD systems involved in the process. This issue has a strong dependency with the "authorisation" and the "information systems use and maintenance" clusters.

4.3.1.4. Manual Systems and Data Entry

This cluster of issues was highlighted from six companies and relates to the manual conversion and data input in the PLM/PDM system that can cause delays in the information sharing process. It was highlighted as a minor issue on its own as it is pertinent to the number of systems involved in the process and there are tools in place that could be used to automate this process.

4.3.1.5. Notification Process

Issues concerning the notification process were cited from five interviews. This cluster was acknowledged from both the suppliers and the OEM for its importance as any possible changes should be notified, planned and resolved as soon as possible. On several occasions companies highlighted the poor notification process as the cause of why financial orders and RFQs can sit in systems for weeks.

4.3.1.6. Security Issues

The cluster of security issues was the least cited although it was acknowledged as an important one in the literature. Interviewees stated that in many cases there is no control on data exchange and the level of transparency within the PLM and ERP systems used which can cause risks due to the Intellectual Property involved.

4.3.1.7. Information Exchange

This cluster of issues was identified as a major issue from five companies. Companies mentioned that a significant amount of office documentation and project management information are shared using e-mail. Power (2005) highlights that e-mail provides a cost effective and easy to use mean of communication that can be used to transfer word processor files, design documentation and CAD files. Experts stated that currently they use e-mail to transfer files due to the lack of access for suppliers to their customers' information systems. This situation usually occurs for legacy systems used to manage information which are not maintained within a PDM or ERP system. However, all the experts agreed that e-mail should not be used to transfer files as files are not secure and are accessible by only one user.

4.3.1.8. Authorisation

This cluster was one of the least cited issues. Three companies mentioned that they use resources to ensure that the right data will be sent to the right people, both internally and externally. Therefore companies use resources to monitor and validate data as well as handle all the communications with their customers.

Fundamental Issues

4.3.1.9. Information Availability

Issues concerning information availability were cited eight times and represent the 8.5% of the total. This was highlighted, by engineers, as an issue that is time-consuming and resource intensive in its mitigation. Due to the high number of people and systems involved in the process, information availability becomes a significant issue. A few suppliers stated that they have resources based on their customers' site to enable the information availability and ensure that engineers are working on the latest version of information. In several cases interviewees mentioned that information are not always available on time which makes planning and forecasting difficult. Another issue that was highlighted in this cluster is that historical data may have been lost after the migration to a new PLM system.

4.3.1.10. Accessibility

Accessibility was the most cited cluster, mentioned by nine companies as a key obstacle of information sharing in supply chain collaboration. This cluster is responsible for almost 13% of the total issues captured. This cluster includes issues linked with both the information and the IS dimension of IM. Some of the individual issues captured focus on the importance of making programme information available to support suppliers in production forecasting. In addition it was highlighted that non-CAD engineers and managers are restricted on accessing PLM or PDM systems which in several cases can create obstacles when working collaboratively.

4.3.1.11. Communication Issues

Communication was highlighted as an important cluster during the interviews. It was stated mainly from suppliers that most of the communication is done by e-mail or conference calls. Issues were highlighted due to the complexity of the organisations and the number of people involved in the process. A company mentioned that tighter communication would allow them to react more effectively as currently only conference calls and e-mails are used.

4.3.1.12. Information Systems Functionality

IS functionality included 17 out of the 118 issues and is responsible for the 14.4% of the total number of issues. This cluster was top in terms of the number of individual issues and was cited by six companies. This cluster relates to issues identified from in-directly connected suppliers. This is the route that many companies choose to use instead of being directly connected through a PDM/PLM system. Issues include the inability of the FTP servers to carry meta-data related to a part, carry the BOM structure as well as maintain versioning control and naming conventions. Moreover these systems have no control over data exchange which in many cases allows engineers to push the wrong data. This cluster of issues was perceived as fundamental not only due to the high number of individual issues but also due to its dependency with the other two fundamental issues, "implementation cost" and "information systems use and maintenance". One of the reasons why companies choose to work with an in-direct application is closely linked with the cost of implementing an enterprise system or the inability to link their internal systems with those that their customers are using.

4.3.1.13. Implementation Cost

Implementation cost is one of the main barriers for suppliers in order to invest into integrating their ERP and PLM systems with the OEMs' systems. Issues related to

implementation cost were captured from six companies. Due to the licensing cost involved and the infrastructure required, suppliers prefer to use less expensive ways of sharing information. The main reason for this decision is linked with the investment required in order to mirror multiple OEMs system and the high risk of losing a customer once the working project ends. Companies mentioned that they need to get involved earlier in the process to incorporate the cost of system integration within their quotes. Some companies highlighted that they are willing to get directly connected for customers that they have a long-term partnership with, while others stated that they have made a strategic decision not to get directly connected with any of their customers.

4.3.1.14. *Information Systems Use and Maintenance*

Issues regarding the information systems use and maintenance represent the 10% of the total issues recorded and refer to the cost that companies have to invest in order to deal with multiple systems used with their suppliers and customers. Linked with the implementation cost cluster, this core issue represents the training cost and the need to maintain multiple CAD and PDM licences in order to work with their customers. Moreover Tier 1 suppliers need to maintain their internal systems in order to share data with their own supply chain. Maintaining multiple CAD file formats in both neutral and native format in order to work with multiple companies can be a challenge for companies. A graphical representation of the classification process and the distribution of the identified clusters is presented in Figure 4-2.
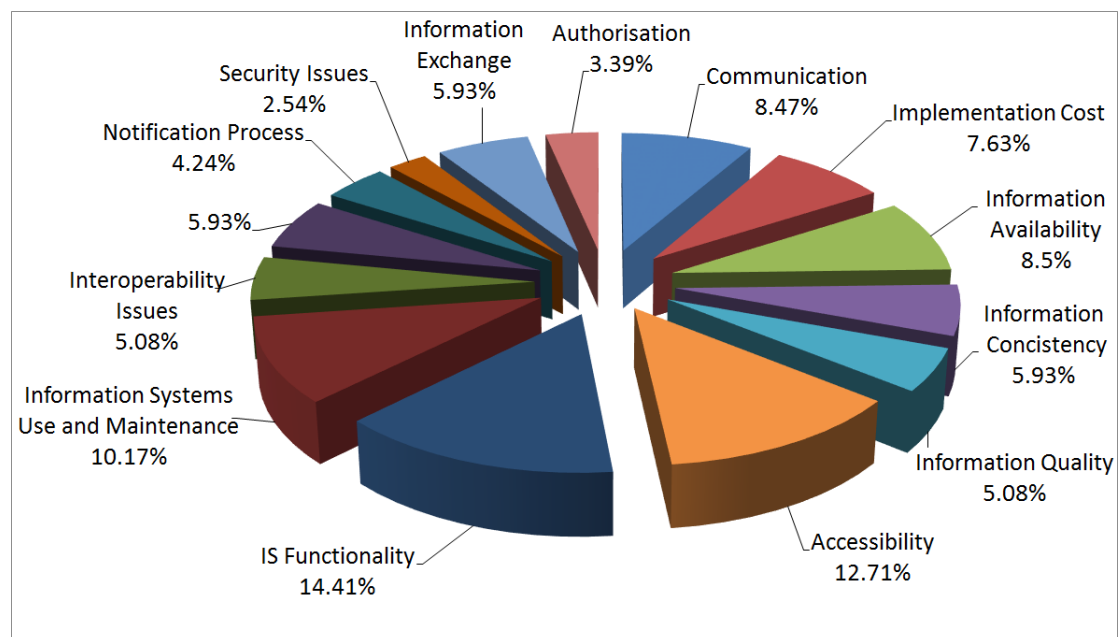
Figure 4-2 Distribution of Individual issues Against the Clusters

One of the critical elements of the Hicks et al. (2006) methodology is the division of issues against the three dimensions of IM. The results in Figure 4-3 show that half of the issues relate to the inadequate IS used, 27% of the issues relate to the Information dimension and 22% to the overall management. Similarly through Table 4-1 it can be identified that 10 out of 14 clusters have a relation to the IS dimension of the IM. Although on its own this division does not represent clearly areas that require improvement; what it does demonstrate is that greater benefits could be achieved by developing better and more efficient information systems.
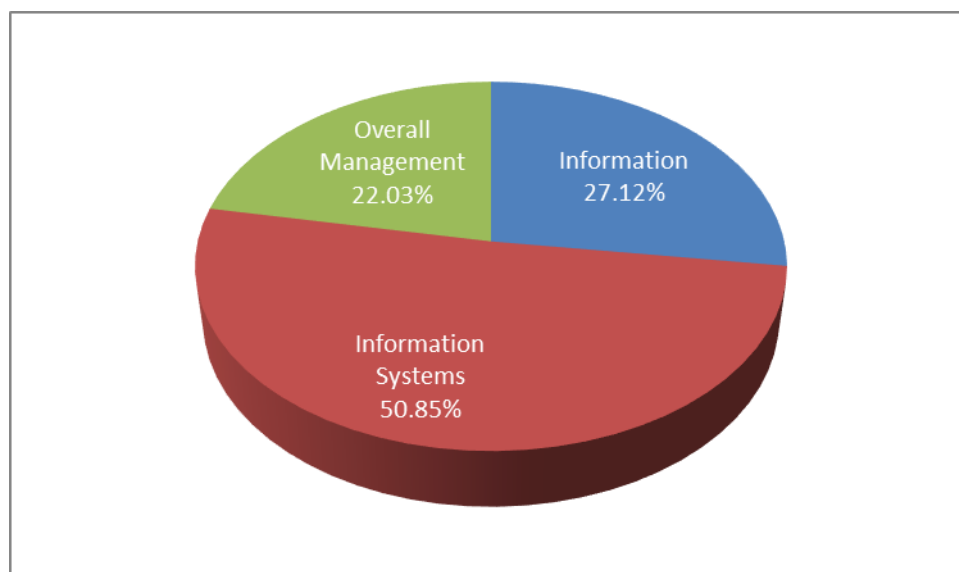
Figure 4-3 Issues Classified Across the Three IM Dimensions

4.3.2. *Taxonomy of Issues*

The analysis in the previous sections concluded in grouping the 118 issues captured in 14 categories against the three dimensions of IM. This categorisation was then prioritised and analysed based on importance and dependencies in order to extract the final clusters. The results of this study can be used to construct the taxonomy shown in Figure 4-4 that summarises the outcome in a visual representation. The first level of the taxonomy shows the spread of issues against the three dimensions of IM. As multiple individual issues were used to define a cluster, on some occasions a cluster might be relevant to one or more dimensions of IM. This can be viewed in the taxonomy through the different types of links used. The second level shows the core clusters and a range of individual examples from the issues captured from the interviews as well as their dependency with the three dimensions of IM. The third level shows the fundamental issues with a range of individual examples and their dependencies with the three dimensions of IM. The percentages that each cluster obtained against the overall number of issues is presented on the top of each box.
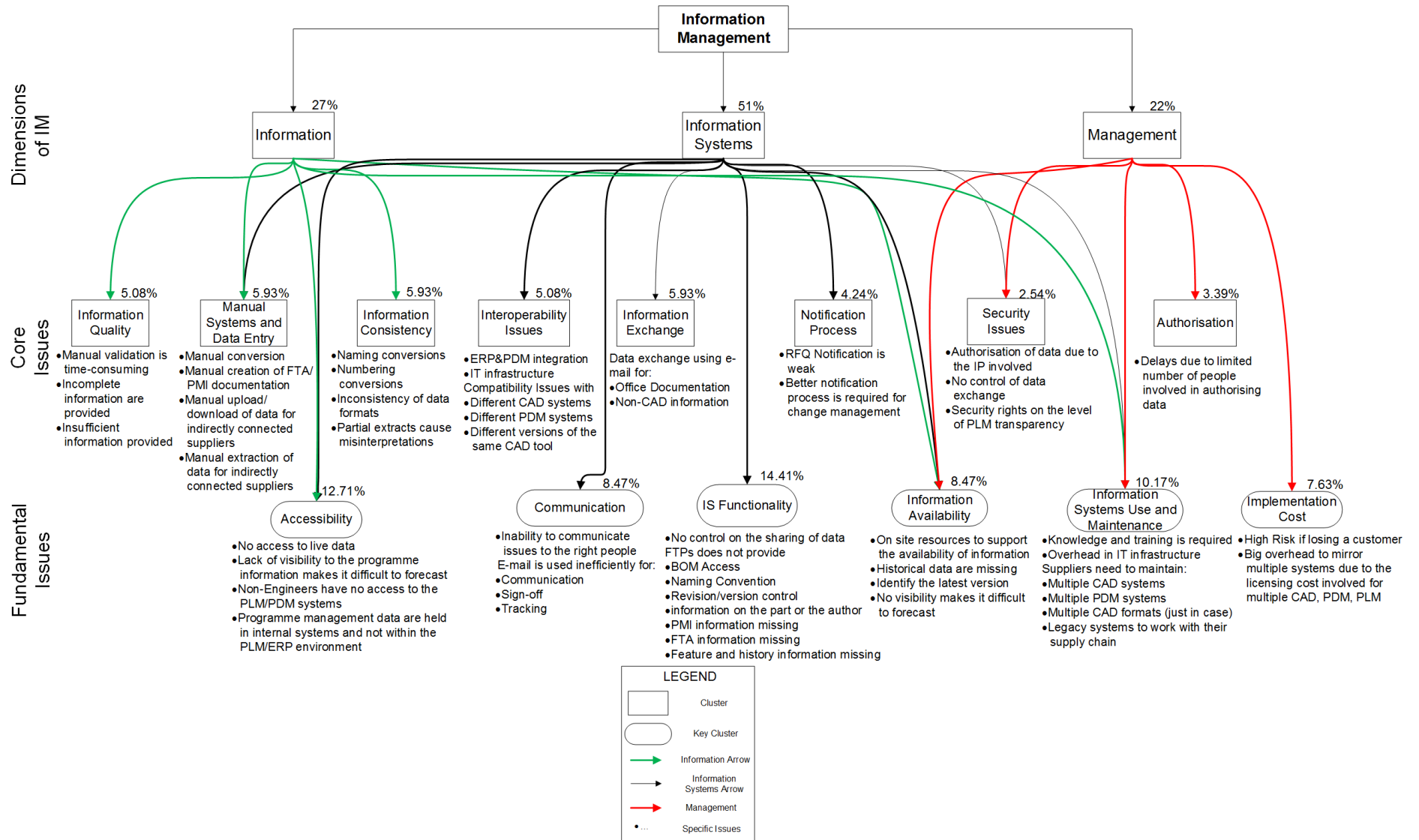
Figure 4-4 Taxonomy of issues

4.4. Discussion of Results

As discussed within the literature review in chapter 2, the benefits that can be achieved through supply chain collaboration are significant. By identifying, measuring and prioritising the importance of supply chain issues in relation to information flow and the use of PLM systems, this study provides a strong input in developing better tools and defining more efficient processes.

4.4.1. *Issues and Dependencies*

This study showed that the "IS functionality" cluster was the one with the highest number of individual issues. It was identified that major issues occur due to the functionality of the File Transfer Protocol (FTP) servers used by the majority of suppliers to exchange product-data instead of being directly connected through an enterprise system. Issues occur as the in-direct methods used (FTP servers) are not capable of maintaining historical information, versioning history, hold any BOM structure or any other data related to a part. Another issue related to the in-direct methods used is the manual process involved which requires engineers working, both in OEMs and the supply chain, to manually extract and share data from a PDM/PLM system. Data received simultaneously on the other end needs to be validated and then loaded manually to the PLM/PDM system. In several cases, CAD conversions among different data formats are also required to perform that task. Although during the semi-structured interviews, it was identified that this method of information exchange should be more relevant to suppliers with a small amount of data transactions, experts agreed that in many cases multinational companies will never acquire licenses or build the infrastructure to support each one of their clients. This is mainly due to the licensing and maintenance cost involved in relation to the high number of customers they support.

Two of the fundamental clusters identified in the analysis, "Information systems use and maintenance" and "implementation cost", are closely linked with the previously discussed cluster. Enterprise systems especially PDM, PLM and ERP systems are not always easily adopted throughout the supply chain. It is worth mentioning that multinational Tier-1 suppliers still need to maintain their enterprise systems used for exchanging data with their own supply chain. Six companies highlighted that the implementation cost required, for each individual OEM that they work with, can be a big overhead and a major barrier for supply chain integration. As PDM and PLM systems are highly configurable, suppliers need to maintain different licences and systems for each OEM they are working with, even for enterprise systems purchased

from the same software vendor. In many cases large OEMs may force their business partners in the supply chain to adopt an online solution. However this may cause operational problems unless they become genuinely involved (Archer et al. 2008). During this study some suppliers mentioned that in order to satisfy their customers they choose to acquire a limited number of licenses for the customer's PDM system and therefore get directly connected. This however causes operational issues as in reality they use an IS without genuinely integrating their processes. Therefore they need to allocate resources who are responsible for maintaining and authorising data exchange using these limited licensed systems. In regards to the multiple CAD systems involved during PD, it was highlighted that maintaining multiple CAD systems can be a big overhead mainly due the training and the licencing cost involved. Using ISO-standard formats was perceived as a solution to this issue as data translations were not mentioned as a major issue. Data validation was acknowledged as a time-consuming task but a necessary one. Although STEP, IGES and all the other ISO standards allowed OEMs and suppliers to exchange data and work collaboratively, they have added one more step in the process which is in many cases the conversion between ISO standard formats to native formats that suppliers or OEMs can work with.

The "accessibility" cluster was the most cited one and relates mainly to the information accessibility of financial orders and programme plans. Due to the tight timeframes involved accessing the right information at the right time is critical for meeting an early time to market, as the lack of information makes it difficult for suppliers to produce an accurate forecast. In several cases major issues occur due to the use of e-mail in exchanging data other than CAD. These issues are closely linked with clusters concerning security and information accessibility, as data attached on e-mails are not accessible from the multiple people involved. Lack of communication is another area worth pointing out as it is a very good example of situation where companies share and exchange data but they do not work collaboratively. The traditional internet based communication channels such as e-mail and teleconferencing were characterised as inefficient to support distributed collaboration among OEMs and suppliers.

4.4.2. *Input to the System Architecture*

The issues captured and analysed provided a good understanding of the key supply chain issues in relation to information flow and the use of PLM systems that will feed in the development of the proposed system architecture. Regarding the IS dimension

the analysis demonstrated, similarly with Hicks et al. (2006), the importance of developing automated systems that are able to integrate with multiple systems and as result share accurate and complete information. What this study also showed is the importance of developing standards that not only cope with the existing CAD formats but also support the standardisation of PLM, PDM and ERP systems. The standardisation of systems will allow suppliers to reduce the cost of implementation and maintenance of multiple systems and as a result work in a more collaborative way with customers and suppliers without the need to invest in implementing and maintaining multiple systems. Such an approach will significantly reduce the number of issues identified and discussed for the three top priority fundamental clusters. In the case where standardisation is inevitable, Service Oriented Architectures (SOA) can be used to develop systems that automate the data exchange among heterogeneous PLM, PDM and ERP systems without the need to acquire multiple licences. Any IS developed needs to be able to support the automation of conversion and exchange of data among heterogeneous enterprise systems. Experts agreed that in many cases multinational companies will not acquire licenses or build the infrastructure to support each one of the PLM systems that their clients choose. Therefore even if PLM systems were used as a way to manage and store maintenance information, integration issues would still exist. The use of SOA will support in reducing the accessibility issues identified as non-engineers will be able to access data extracted from the PLM system without the need to acquire a license. Moreover when designing the proposed system architecture, ways of achieving more efficient communication and notification channels need to be taken into consideration as they will support in resolving some of the independent issues identified in those two fundamental clusters. The proposed system architecture will also aim to address some of the information availability issues identified by providing a solution that is accessible over the Internet in order to support suppliers in reducing on-site resources which are used to ensure the availability of information. Having a solution accessible online will also support in reducing some of that challenges that interviewees highlighted where significant amount of office documentation and project management information are shared using e-mail. This is mainly due to the lack of access for suppliers to their customers' IS. Therefore the proposed system architecture will reduce this type of issues as data can be extracted via a secure and control way using SOA. The solution needs also to take into consideration data conversion capabilities to address any interoperability issues among the different systems used.

4.5. Chapter Summary

This chapter provides an insight to the supply chain issues related to information flow and the use of PLM systems and discusses areas where the proposed system architecture could be designed. A total of 118 issues were captured from semi-structured interviews conducted with 15 multinational companies operating in the automotive sector. Initially these issues were divided along the three dimensions of information management based on a methodology developed by Hicks et al. (2006) and then grouped against 14 core clusters. As it is unlikely that each cluster is independent of the others, the clusters where then ranked and prioritised concluding in the six fundamental clusters of issues.

This study showed that half of the issues captured are related to inadequate IS used. The cluster that had the majority of individual issues is related to suppliers who are not directly connected with their customers through an enterprise system such as PLM, PDM or ERP. Indirectly connected suppliers face major issues due to the functionality of the FTP servers involved in the process. However it was identified that two of the fundamental clusters justify the decision of suppliers not to invest in the IT infrastructure required in order to become a directly connected supplier. Implementing and maintaining multiple enterprise systems can be an overhead for multinational companies working with a large number of customers. The risk of losing a customer after the delivery of a vehicle programme does not justify the investment and makes companies reluctant to change. Although during the last few years there is a research interest in the standardisation of enterprise systems this study shows the criticality of PLM, PDM and ERP standardisation. In cases where this is inevitable service oriented approaches can be used to automate the process of exchanging data from heterogeneous enterprise systems.

Current State Process Maps to Demonstrate the Flow and Use of Maintenance Information

This chapter presents two business process maps that describe the flow of maintenance information, including tasks and information systems used and highlights significant challenges and critical operating issues. Process maps were captured through a combination of semi-structured interviews, by studying the internal documentation and by testing the systems used as discussed in section 3.2.2.1. Challenges and issues identified are then used to scope the requirements analysis process and drive the development of the proposed system architecture.
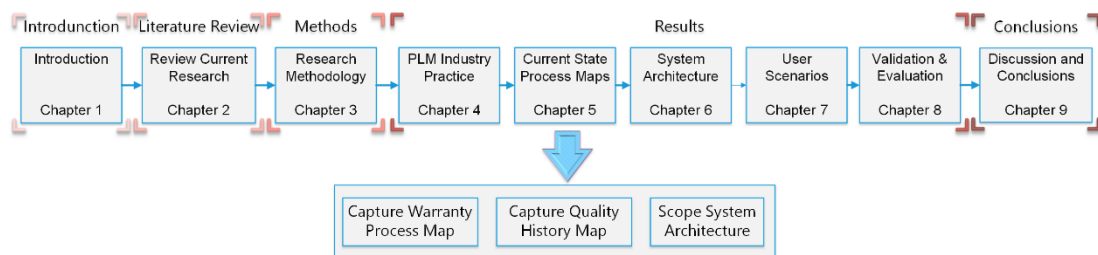
5.1. Introduction

Over the last two decades the automotive industry has undergone a major transformation. Nowadays, due to market change and the increased inclusion of electronic parts in vehicles, the automotive industry is producing different and more complex products while facing the challenge of maintaining their flexibility by delivering more content to consumers at reduced prices. As selling prices drop, and the years of warranty period are increasing to satisfy customers, vehicle manufacturers are forced to reduce the warranty cost by improving product reliability

and by increasing their ability to react whenever an in-service product failure occurs. This chapter describes two high level processes where automotive vehicle manufacturers and component suppliers utilise maintenance data to conduct root cause analysis. The first process map shows the flow and the use of in-service product failure data, such as warranty claims and vehicle diagnostics, reported from a service representative (dealer) back to the OEM and then to the component supplier to conduct a root cause analysis of a product failure that occurred on a specific vehicle. The second process map, shows the utilisation of maintenance data to produce a comprehensive list of past failures, concerns and their root causes to support PD engineers to understand previous faults prior to the design of a new part or sub-system. Challenges identified in each part of the process will scope the requirements analysis and base the development of the system architecture. The current state process maps capture more information than the proposed solution could achieve but demonstrate clearly areas where the system architecture will support. Process maps validation is explained in details in section 8.1.1.

5.2. "In-service Product Failure Identification and Root Cause Analysis" Process

The high-level process map of the "in-service product failure identification and root cause analysis" is shown in Figure 5-1. Each task of the process map is described and key challenges are identified. Some process steps do not have a challenge section due to the fact that they were not relevant to this research or interviewees did not specify any challenges.

ID.1 - Customer identifies an issue and reports to the dealer: The starting point of the process is when a customer identifies an issue and reports to the dealer to resolve. Capturing what the customer complaint about is key as the customer's verbatim feeds into the OEM's warranty system and provides an initial understanding of the fault.

ID.1 – Challenge: The way the issue was communicated, analysed and captured can vary significantly among multiple dealers, especially from dealers recoding issues in their native languages. Key words and phrases used when recoding the customer's verbatim can offer great insights for the OEMs and component suppliers when analysing the root cause of a claim.
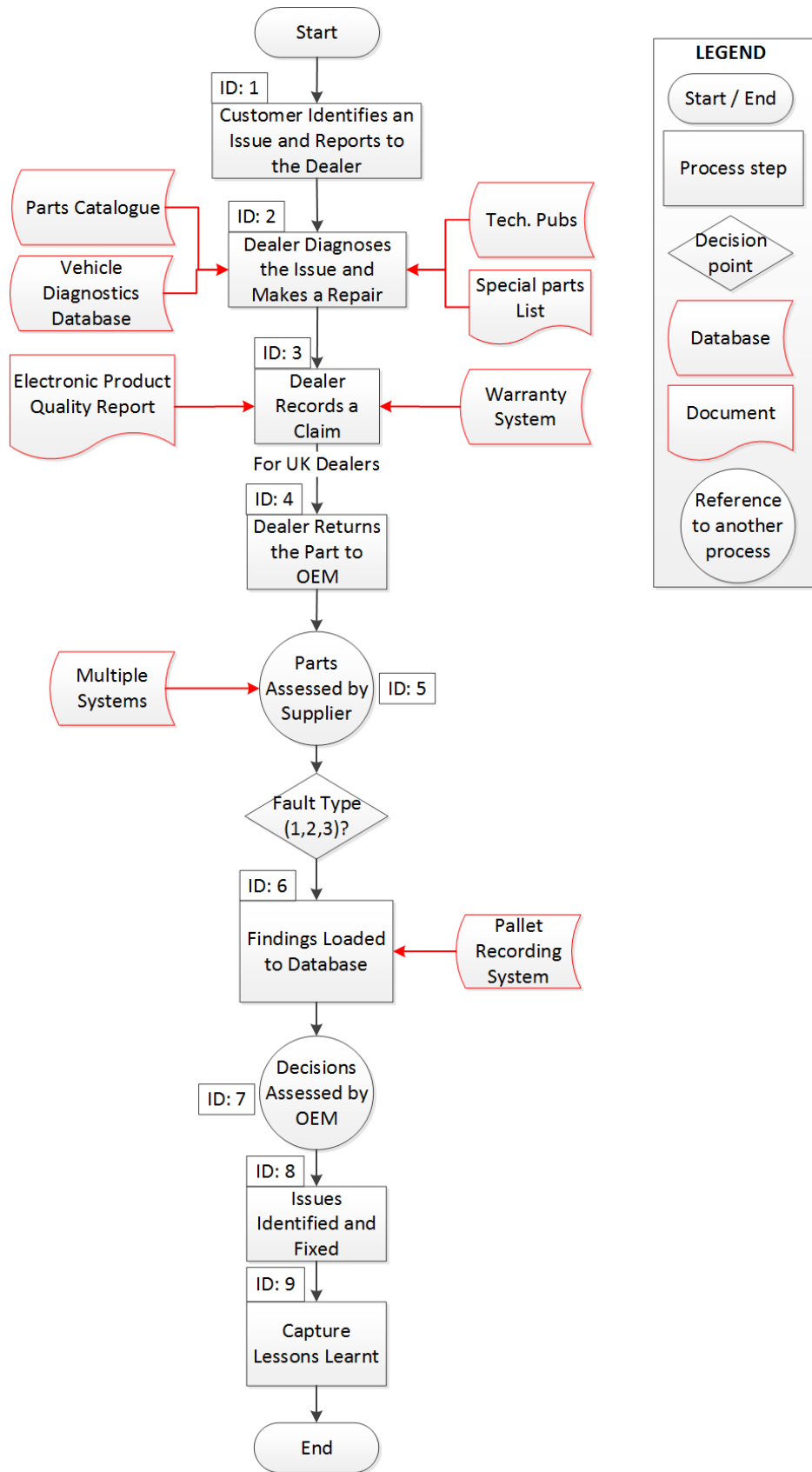
Figure 5-1 "In-service Product Failure Identification and Root Cause Analysis" Process

<u>ID.2 - Dealer diagnoses the issue and makes a repair</u>: Once the dealer captures the customer's verbatim, the next step is to identify the part failure. In many cases identifying the failing part is quite straight forward, however identifying the root cause of an issue is not readily apparent. Using a variety of information from multiple systems such service manuals, technical service bulletins, instructions provided from the vehicle manufacturer and diagnostics extracted from the vehicle, the dealer will determine the failure part and make a repair. Performance and diagnostics data captured through the vehicle control unit are automatically sent to the OEM's vehicle diagnostics database which is also accessible from the component suppliers.

<u>*ID.2 – Challenge:*</u> In several cases, dealers failed to identify the most up-to-date technical service bulletin within the system and without following the proper instructions they were unable to resolve entirely the fault, which can lead to either an increased cost due to the replacement of the wrong part or customer dissatisfaction in cases where customers had to revisit the dealer in a short period of time. Occasionally, OEMs and component suppliers have not provided instructions with the right level of detail to the dealers which can cause misinterpretation when resolving an issue. Identifying gaps in bulletins and diagnostics is an area that interviewees highlighted as a challenge which needs to be resolved as early as possible for reducing the warranty cost and improving customer satisfaction.

<u>ID.3 - Dealer records a claim</u>: Following up on the repair procedure, dealers are responsible for recording a claim in the OEM's warranty system. Dealers will record electronically different clusters of information, such as:

- **Vehicle Identification Number (VIN)** which automatically defines the brand, model name, model year, engine type, transmission type etc.
- **Claim information** such as the customer verbatim described in ID1, the technicians verbatim, claim description, causal part number, trouble code, part description, the sub-system description, labour cost, material cost etc,
- **Dealer information** such as country operating, dealer code, dealer name.

For special and unique issues, dealers fill an electronic quality report in order to capture additional information that the OEM or the component supplier could use to assess a part.

<u>*ID.3 – Challenge*</u>: Similarly with ID1, key words, phrases and failure codes that dealers' use to specify and describe an in-service part failure will have a significant influence on the root cause analysis process.

ID.4 - Dealer returns the part to the OEM: Once the claim is recorded in the warranty system, dealers either scrap the part or return the causal part to the OEM's warranty centre. For the case-study company examined, all the UK and selected US based dealers are required to ship the parts back to the warranty centre for assessment. Vehicle manufacturers may select additional dealers from different markets to send a limited number of parts for inspection creating a sample for study (Center for Automotive Research-CAR, 2005). Parts are held in pallets where each pallet is associated with a specific component supplier. A Pallet recording system is responsible for maintaining the connection among the parts in the pallet and the associated claims recorded from the dealer.

ID.5 - Parts assessed by supplier: The analysis of the causal part from a supplier provides great insights for understanding systematic failures and identifying the root cause of an issue. It allows suppliers to have a close view of the part and if required to recreate the failure conditions in a testing vehicle. It also allows suppliers to compare the results of a testing conducted to the returned part with the quality data obtained before the part was initially shipped to the OEM. As a result they can see degradation trends among different markets and conditions. Data captured from the previous steps described, are very important in order to assess a returned part. Suppliers follow a detailed check list in order to make a decision and assign a liability against each claim. Some of the questions that suppliers need to answer are:

- *Was this a known issue?*
- *Was it the causal part?*
- *Did the dealer have enough information to make a repair?*
- *Were the instructions followed?*
- *Is there an existing project to resolve similar issues?*
- *Did the part need to be replaced?*

To identify the root cause of an issue, suppliers need to access all the information related to the reviewed claim. Figure 5-2 shows a pictorial representation of all the information that feeds into the ID.5 process. Suppliers need to capture:

- **Vehicle's history** is important as previous in-service failures might have an impact on the latest claim. It will also show the supplier the conditions and the markets that the vehicle was operating in.
- **Breakdown recovery reports** can also support in understanding the conditions that the vehicle operated in. "**Voice of the customer"** data such as in-service

surveys are significant in order to have a clearer view of the vehicle and functions that did not satisfy customers. Breakdown recovery reports and survey data do not differ with a claim in terms of structure. They are capturing similar amount of information using the same format structure.

- **Vehicle diagnostics** captured through the vehicle control unit, as described in step ID.2, are used to understand the conditions that the vehicle was operating in and what the sensors recorded during the occurrence of a fault such as mileage, temperature, diagnostic trouble codes etc.

- **Technical publications** used from dealers reveal information gaps that need to be addressed. During the root cause analysis, suppliers need to ensure that dealers had enough information to assess a fault and make a repair.

- **Test data** captured from tests conducted to the returned part from suppliers are also important to understand how the part is currently operating compare to how the part should operate.

- **Product-related data held in PDM/PLM** systems such as CAD models, BOM, specifications and documentation associated with the part.

- **Part Submission Warrant (PSW) status** is part of the Advances Product Quality Documentation Planning (APQP) system and shows that suppliers and quality engineers agreed on specific quality criteria as specified within the document. In this instance analysts would require to view that a PSW document has been agreed and signed.
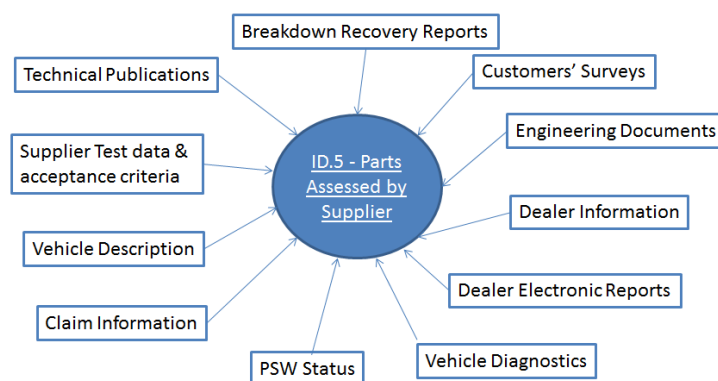
Figure 5-2 Clusters of Data Used within the Assessment Process

ID.5 – Challenge: Accessing all the systems involved is currently a great challenge as identifying the information required is a very manual and time-consuming process. The depth of the information used in each review usually depends on the skills and the experiences of the engineer involved. It was identified that the root cause analysis varies among suppliers and different OEM business units. Accessing data

held within the PLM system is currently limited as warranty and quality engineers usually have only restricted access to the system.

Suppliers mentioned during the interviews that they usually review a pallet every 20 days, for their key customers. Formal reviews including a wider team of OEM's warranty engineers and analysts are also held every three months for every key supplier. The number of reviews that suppliers carry for each one of their customers demonstrate the amount of resources required in terms of people and time. In addition, supplier engineers highlighted that they spend a significant amount of time to collect the data required for each individual part assessment as well as prepare for the formal reviews.

ID.6 - Findings loaded to the pallet recording database: Once the component supplier makes a decision, the outcome will be recorded in the pallet recording system. Claims can be described as Type 1 faults (OEM's liability), Type 2 faults (Supplier's liability) or Type 3 faults - NTF (No Trouble Found). Each decision that suppliers make has a cost liability for the companies involved. Reducing NTF is vital for the OEMs as these faults represent customer issues that suppliers could not replicate in a testing environment or incorrect diagnosis from dealers. In addition, these faults represent customers' issues that were not resolved which can lead to reduced customers' satisfaction and damaged brand reputation.

ID.7 – Decisions assessed by the OEM: The OEM assess decisions that suppliers recorded within the system in order to ensure that suppliers meet the expected test criteria levels. Quality or warranty departments are usually responsible for assessing suppliers' decisions. What the analysts are looking for is to ensure that the testing criteria and the data used are fit for purpose. Although OEMs follow a similar check list with the one described in ID.5 there are some additional questions that needs to be assessed:

- *Is symptom and failure mode understood?*
- *Does supplier assessment check for each failure mode?*
- *Does assessment replicate actual installation environment?*
- *Are specifications compatible with customer usage cycle?*
- *Did the dealer have enough information to make a repair?*

ID.7 – Challenge: Analysts within the OEM face similar challenges with the ones described in ID.5. There is a need to be able to collectively access multiple systems as well as suppliers' test data in order to assess each decision made. Usually this

process is very manual and in many cases very resource intensive. Accessing data held within the PLM systems is currently a very manual process as warranty and quality engineers are usually restricted from accessing the PLM system. Again the amount of effort required in terms of people and time, is significant. Similarly to the ID.5 assessment, OEM engineers stated during the interviews that identifying gaps in bulletin and diagnostics that dealers use is key in reducing NTF faults.

ID.8 – Issues identified and fixed: OEM warranty engineers and analysts will group all the claims that have a similar root cause, including claims coming from other markets. Grouped claims are assigned against a project which is tracked within the warranty database. Projects can be allocated to different teams depending on the root cause. Therefore projects can be allocated to an engineering, manufacturing, service or even a supplier's team. Projects are related to a VIN range or a vehicle programme and aim to reduce the amount of issues that occur.

 ID.9 – Capture lessons learnt: The outcome of the project is captured in the warranty database which can be accessed by OEM engineers. Lessons learnt captured can be used from PD engineers when designing a new part or sub-system to ensure that new vehicles will not carry over previous faults.

5.3. "Quality History for DFMEA" Process

The purpose of this process map is to demonstrate the utilisation of maintenance data to produce a comprehensive list of past failures, concerns and their root causes to support PD engineers in understanding previous faults prior to the design of a new part or sub-system. Kiritsis (2011) states that the flow of data, information and knowledge from service and maintenance experts back to the PD engineers is fragmented. An area that PD engineers described that they use maintenance data to improve the design of a part or sub-system is through the quality history process which provides an input to DFMEA (Ford, 2004). Quality history offers an important input in the DFMEA as it utilises various information sources to produce a comprehensive list of past failures, concerns and their root causes based on internal and external data. Quality history is not only capturing hard failures which relate to parts that did not operate within the desirable objectives but also soft failures which relate to parts that operated within the desirable objectives but still failed to meet customers' expectations. Engineers consider the following as failures: (i) it does not do what it should do (ii) it does something it should not do (iii) it does less than the customer was expecting. The key steps of the quality history process are shown in

Figure 5-3 and are described below. Process steps that are not described in detail are considered out of scope for this research.
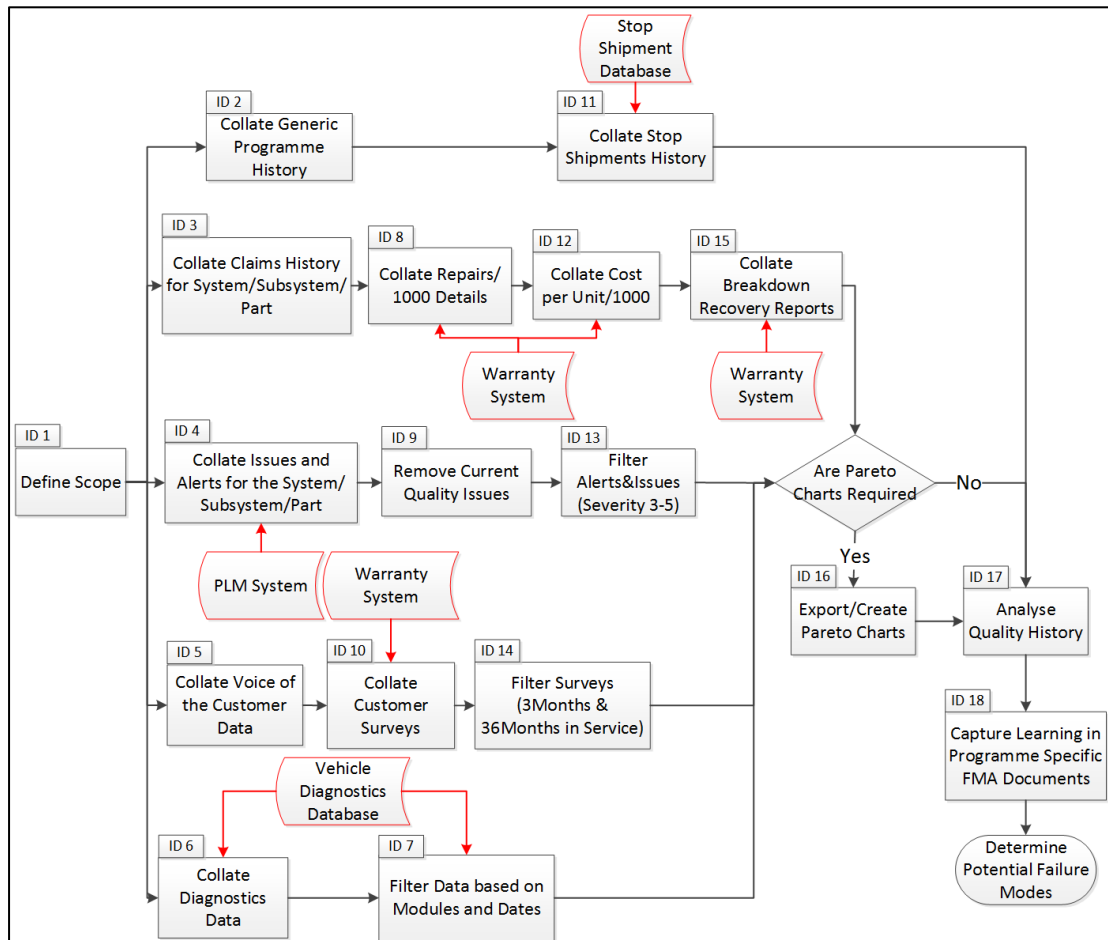
Figure 5-3 "Quality History for DFMEA" Process

ID.1 – Define Scope: The starting point of the process is when the PD engineer is required to conduct a DFMEA analysis. The scope of a DFMEA defines what is included and what is excluded from the analysis. The scope of the DFMEA can be either on a system, sub-system or component level.

ID.2 – Collate generic programme history: The purpose of this set of tasks is to obtain generic programme history from previous programmes that are relevant to the DFMEA scope. This task allow engineers to collate programme information such as stop shipments and recalls in order to understand critical system failures. The Transportation Recall Enhancement, Accountability and Documentation (TREAD) Act enacted in 2000 in the US shows the importance of reviewing previous vehicles faults in order to prevent reoccurrence. This step is linked with process step ID.11 which requires engineers to collate stop shipments data in order to understand the root cause that prevented vehicles to be shipped in previous relevant programmes.

ID. 3 – Collate claims history for system, subsystem, or component: This set of tasks is relevant to the quality history of a specific system, sub-system, part which depends on the DFMEA scope. The level of granularity is defined from the DFMEA scope and aims to reveal trends and patterns in hard failures. In order to reduce the amount of data that needs to be analysed, warranty data can be filtered based on the vehicle's period in service. Claims occurring during the first three months in service and during three years in service provide enough information to build a robust list of previous faults. Electronic quality reports and breakdown recovery reports (ID. 15) for the same period can provide a valuable input in the process. Pareto charts (ID. 16) are used to group the different failure codes against the associated cost in order to have a summary view of the claims history. This process step is linked with process steps ID. 8 and ID. 12 that requires engineers to extract claims KPIs. Repairs/1000 and Cost per Unit/1000 represent key KPIs that show the number of failure occurrence and their associated cost.

ID. 4 – Collate issues and alerts for the system/subsystem/part: This process step requires engineers to collate design issues and alerts that were raised from internal PD engineers or suppliers on previous programmes. The filtering process followed by steps ID.9 and ID.13 allows engineers to reduce the amount of returned results into a manageable data set. Alerts and Issues are held within the PLM system.

ID. 5 - Collate voice of the customer data: The "voice of the customer" data refer to the surveys that customers provided and are used to reveal trends and patterns in soft product failures (ID.10). PD engineers want to identify parts and sub-systems that operated within the desirable objectives but still failed to meet customers' expectations. Usually OEMs acquire surveys form third party companies that focus on key markets across different vehicle periods. Some surveys are conducted during the first three months in service while others in twelve months in service. This step is linked with ID.14 that requires engineers to reduce the amount of returned results by excluding any surveys that are related to vehicles operating between 3 months in service and 36 months in service.

ID. 6 - Collate diagnostics data: This data source was highlighted as key in understanding hard failures trends and patterns, especially for electronic failures. Similarly with the warranty claim analysis, DTC captured from the sensors can be used to identify or predict system failures. Hierarchical charts can be used to group DTCs for a selected period against the number of appearances in order to create a

summary of diagnostic signals. This step is linked with ID.7 that requires engineers to filter data based on specific modules or dates.

Figure 5-4 shows a pictorial representation of the types of data required to fulfil a quality history process. The data shown in red represent sources that are similar with the "in-service product failure identification and root cause analysis" process.
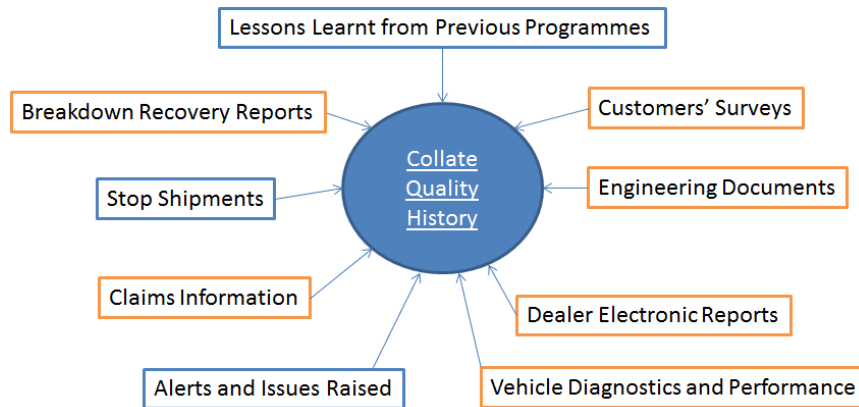
Figure 5-4 Clusters of Data Used within the Quality History Process for DFMEA

Process Challenges: Engineers highlighted that the number of systems and their complexity, create obstacles in the process and causes issues when gathering the amount of details required to run a robust DFMEA. Similarly with the previous process described, the quality history process is very manual and time-consuming and in many cases is subjective to the engineer's level of skills. The lack of in-depth quality history can cause misinterpretations when prioritising failures modes and effects. In many cases engineers highlighted that without a robust quality history the potential causes written within the DFMEA template can be vague and subjective which can have a significant effect when measuring potential causes against severity and occurrence. Interviewees mentioned that the approach followed for each business unit and each supplier is different as there is no standardised process for capturing quality history. Moreover in several cases, engineers were unable to find the appropriate amount of information required for the DFMEA, although they have accessed all the systems that the process defines. Suppliers stated that in many cases access to the quality history for previous programmes is restricted. Access to stopped shipments and recalls is usually restricted to PD engineers and suppliers due to the confidentiality of data. Interviewees highlighted that there needs to be a way to allow PD engineers to review those data without the need to fully access the system.

5.4. Discussion of the Process Maps Captured – Challenges and Opportunities

The process maps captured from the Case Study Company and suppliers, showed very similar processes to the ones identified within literature (Car, 2005). However there are a few important differences among the two which can be justified as the evolution of technology has allowed companies to integrate more data in order to support the root cause analysis. One key difference is around the utilisation of vehicle diagnostics and the "voice of the customer" data during the "In-service product failure identification and root cause analysis". Another key difference is that within the literature, PLM systems were not mentioned as an information source that could support warranty and maintenance engineers. Through the semi-structured interviews, warranty engineers highlighted that data held within the PLM systems such as CAD models and product-related documentation, could be of a great value for supporting root cause analysis.

Current state process maps showed that the high number of multiple systems used within organisations to support root cause analysis are usually bespoke solutions, developed internally or from third party companies with the OEM's support. The findings of this analysis enhances Macdonnell and Clegg (2007) observation that these systems provide little or no integration capabilities and therefore companies now face the challenge of developing standards to integrate those systems. In addition, engineers mentioned that currently there is not a centralised location for warranty and maintenance information compare to the PD phase where PLM systems dominate and the manufacturing phase where ERP systems are mainly used. However it can be observed that when the task or problem exploration area follows predefined paths within a fixed internal data landscape then there are mechanisms that could be set up to allow the information flow among multiple systems. It is when the task or problem resolution necessitates accessing data sources outside the norm that issues start to appear. Accessing data across the supply chain in a standardised way, was recognised through the processes as a great challenge.

Both the "In-service product failure identification and root cause analysis" and the "Quality history for DFMEA" processes can be characterised as very manual and time-consuming and in many cases subjective to the engineer's level of skills. The multiple systems used and the knowledge that each engineer has for each one of the systems involved, provide difficulties in standardising the processes across the

supply chain. Making data available to suppliers is critical but there needs to be a way of controlling the level of access and the amount of information shared. Moreover interviewees mentioned that engineers are not necessarily interested in which systems the data has come from but they need to feel comfortable that the amount of data reviewed provides sufficient understanding of the faults and their root causes.

The proposed system architecture discussed in Chapter 6 will provide the required functionality to support steps ID.5 – Parts assessed by supplier and ID.7 – Decisions assessed by the OEM from the "In-service product failure identification and root cause analysis". In this instance, engineers need to review data for a specific issue recorder on a specific vehicle. However, the "Quality history for DFMEA" process requires PD engineers to have a high level view of the part and its quality history. These two processes utilise data the majority of which can be extracted from the same silos and therefore the system architecture proposed will support both processes.

5.5. Chapter Summary

In this chapter, the current state process maps have been examined to understand the challenges and issues that will be used as a baseline for the development of the proposed system architecture. The "in-service product failure identification and root cause analysis" and the "quality history for DFMEA" processes were captured within the case study company and its key suppliers through semi-structured interviews. Gaps and challenges identified within the processes support the requirements analysis process and provide a baseline in defining the required system functionality. A comparison among the process maps captured from the industry with those identified in the literature was conducted to ensure the wider validation of the processes (section 5.4). The system architecture proposed in Chapter 6 supports the processes described and addresses some of the challenges and issues identified within the current state maps.

A System Architecture for Integrating PLM with Maintenance Information across the Supply Chain to Support Root Cause Analysis using an Automotive Case Study

The purpose of this chapter is to analyse and model the requirements captured as well as demonstrate the different views of the system architecture developed for integrating PLM systems with maintenance information across the supply chain to support root cause analysis. Requirements elicitation was conducted mainly through semi-structured interviews and workshops with OEM and supplier engineers from the automotive sector as discussed in section 3.2.3.1. UML diagrams such as a use case diagram, sequence diagrams and package diagrams were created to transform user requirements into system functionality. This chapter defines, through the use of three different architectural views (use case, static and dynamic), the interactions among the end users and the proposed system, the structure and the dependencies between the different elements of the proposed system, and the sequences of tasks that occur within the proposed system over time.
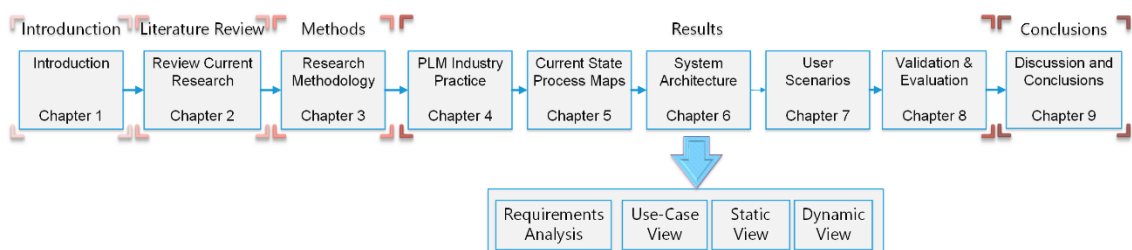
6.1. Introduction

This chapter presents the analysis and prioritisation of the requirements as well as the modelling techniques used to transform user requirements into system functionality. Section 6.2 shows the outcome of the requirements analysis. Functional requirements captured define the boundaries of the proposed solution. Moreover a list of "non-functional" requirements is presented to show the technical constraints that need to be considered when designing the system architecture. Functional and non-functional requirements were captured, analysed and then prioritised using the MoSCoW approach as discussed in section 3.2.3.2. Section 6.3 presents the "use case" view which determines the high-level use cases and the information required to perform a task. UML diagrams were developed as they provide a good graphical representation of the functional requirements by showing the different use cases, the actors and their interactions with the system. In this sub-section the proposed solution is treated as a "black box" as every task that occurs within the proposed solution will be explained in sections 6.4 and 6.5. Section 6.4 of this chapter shows the "static" view of the system architecture. The "static" view reveals the "black box" system by decomposing the high level architecture into low level packages that show the system structure as well as the dependencies among the different elements of the architecture. In addition this view includes a class diagram that determines the relationships among the different data sets used. The last part of this chapter demonstrates the "dynamic" view of the proposed system architecture. A UML sequence diagram is used in this instance to show the sequence of tasks and the messages exchanged among the different packages over time. This view determines how the different packages within the architecture communicate with each other in order to deliver the desired functionality.

6.2. Requirements Elicitation and Analysis

Davis et al. (2007) defines requirements engineering as the discipline of determining, analysing, pruning, documenting, and validating the desires, needs and requirements of stakeholders for a system. Requirements engineering is a critical activity for the success of every software system. It allows engineers to capture user requirements and transform them into system functionality. Moreover requirements engineering can be used as the basis for planning, validating and testing the system (Konrad and Gall, 2008). There are several techniques for capturing and analysing requirements. Jiang et al. (2008) evaluated the most common techniques used in each phase of the requirements engineering process and proposed a methodology called Methodology for Requirements Engineering Techniques Selection (MRETS) to support the

selection process by enabling engineers to link the attributes of the project with the attributes of each requirements engineering technique. Requirements elicitation was conducted through semi-structured interviews and workshops with automotive OEM and supplier engineers. Hofmann and Lehner (2001) highlighted that involving customers and users through the requirements engineering process is critical as it provides better understanding of real needs.

"The purpose of this set of activities is to initially understand and determine the requirements at a high-level, and then document the requirements with sufficient detail to validate understanding of the requirements, to ensure concurrence with stakeholder expectations, and to permit software development to begin."

<div align="right">(Loniewski et al., 2011)</div>

Initially requirements were captured and documented in a textual format using the requirements catalogue. The catalogue includes both functional and non-functional requirements. Requirements demonstrate the functionality and the constraints that stakeholders stated without taking in consideration how the solution delivers the expected functionality. As Schulz (2001) defines the requirements catalogue answers the what? question rather than the how?. Figure 6-1 shows a high level view of the requirements groupings.
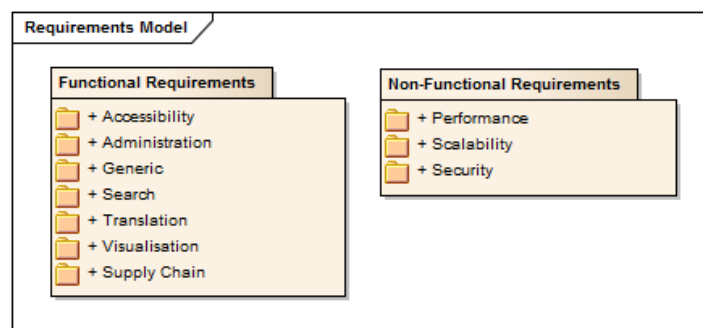
Figure 6-1 Requirements Groups

A functional requirement is defined as a requirement that is concerned with a function that the system should provide, i.e. what the system needs to do (Debra et al. 2010). Functional requirements were captured from automotive experts that represent the end users of the system as discussed in section 3.2.3.1. These stakeholders are the domain experts that know the current process challenges, the information systems used and the data required to perform a task. These stakeholders are the same experts who supported the documentation of the current state process maps. Although the process maps presented in chapter 5 showed the AS-IS, the requirements catalogues capture the TO-BE. Figure 6-2 shows the different groups

of functional requirements captured as documented within the EA software. Detailed view of each requirement can be found on Appendix C.

custom Functional Requirements

Translation
- ☑ + REQ1- Repurpose the returned results
- ☑ + REQ2- Repurpose a CAD model into a light-version visualisation file

Search
- ☑ + REQ20- Search using a part/sub-system code
- ☑ + REQ21- Search using a part/sub-system code related to a claim
- ☑ + REQ22- Search using a VIN number

Visualisation
- ☑ + REQ47- Visualise the vehicle description
- ☑ + REQ48- Visualise the vehicle history
- ☑ + REQ49-Visualise a vehicle representation
- ☑ + REQ50-Generate heatmap on a CAD model
- ☑ + REQ51- View Product structure
- ☑ + REQ53- View the data sources
- ☑ + REQ54- Visualise graphs
- ☑ + REQ61-User Interaction
- ☑ + REQ62-Visualise the CAD representation
- ☑ + REQ64-Multiple platforms

Administration
- ☑ + REQ36- Login to the system
- ☑ + REQ37- Error message for login failure
- ☑ + REQ38- Administration login
- ☑ + REQ39-Silo registration
- ☑ + REQ40- Define/Modify workflow

Supply Chain
- ☑ + REQ24- Access supplier test data
- ☑ + REQ25- Exchange informaton through the supply chain

Accessibility
- ☑ + REQ-19 Access the BOM Structure
- ☑ + REQ10- Extract breakdown reports
- ☑ + REQ11- Access PDM/PLM to extract product data
- ☑ + REQ12- Access information provided to the dealers
- ☑ + REQ13- Access customer verbatim and dealer diagnosis
- ☑ + REQ14- Access PDM/PLM to extract product data related to a claim
- ☑ + REQ15- Access Vehicle history (RC)
- ☑ + REQ16- Access Vehicle diagnostics (VIN)
- ☑ + REQ17- Access PSW status
- ☑ + REQ19- Access the BOM structure
- ☑ + REQ2- Access stopped shipments
- ☑ + REQ23- Access quality projects related to a claim
- ☑ + REQ3- Review the history of a part/sub-system/system
- ☑ + REQ4- Filter the returned results
- ☑ + REQ5- Review the quality history of a part/sub-system
- ☑ + REQ56-Access documents related to a part number
- ☑ + REQ59-Access vehicle description
- ☑ + REQ6 - Access the "voice of the customer" data (QH)
- ☑ + REQ66-Access vehicle diagnostics (module)
- ☑ + REQ7- Extract survey data
- ☑ + REQ8- Review the cost of a part/sub-system/system
- ☑ + REQ9- Review the sufficiency plans

Generic
- ☑ + REQ26- Annotate actions
- ☑ + REQ27- Collate quality history to run a robust FMEA
- ☑ + REQ28- Assess returned parts and assign liabilities
- ☑ + REQ29- Support in identifying gaps in bulletin and diagnostics
- ☑ + REQ30- Save a session for future reference
- ☑ + REQ46- Review categorised claims
- ☑ + REQ55- Generate graphs
- ☑ + REQ58-Package information in a single object
- ☑ + REQ60-Follow standards
- ☑ + REQ65-Predefine search results

Figure 6-2 Functional Requirements Groupings and Titles

A non-functional requirement is defined as a constraint or performance measure with which the system or the functional requirements must comply (Debra et al., 2010). Non-functional requirements were captured from stakeholders that are either the administrators of the integrated IS or IT experts that have a good knowledge of the IT infrastructure. Figure 6-3 shows the list of non-functional requirements against the different groupings. These requirements were not all critical to the development of the proof-of-concept system but they establish some key criteria that need to be considered for improving the performance while ensuring the security and scalability of the system. Non-functional requirements that were specific to the IT infrastructure of each specific company examined are not captured in this catalogue.

- Performance requirements define the workload of the system and the response time after a search is initiated. These requirements specify the minimum acceptance criteria that need to be taken into consideration when designing a POC system.

- Security requirements captured define the basic security objectives. Defining a complete security model is out of scope in this research.

- Scalability requirements determine that any solution developed needs to be scalable to the number of systems used and the number of transactions that they can cope with.
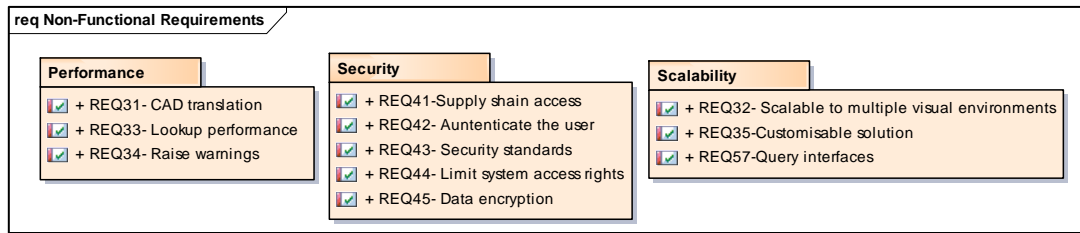
Figure 6-3 Non-Functional Requirements Groupings and Titles

Once the catalogue was complete, requirements were validated and prioritised by key stakeholders. The input from the stakeholders is critical as any test cases developed for the proposed system should satisfy and link with the requirements catalogue. Once the catalogue was approved, it was kept under change control. The validation process is explained in detail in section 8.1. In addition, the interviewees were asked to prioritise each requirements using the MoSCoW ratings. Therefore each requirement was associated with a prioritisation attribute (Must, Should, Could, Would like to). The outcome of the prioritisation fed into the next step of the analysis which involved the development of a SysML requirements diagram. The SysML requirements diagram is a standardised way for visualising and analysing requirements. It allows the representation of requirements as model elements and offers a way of showing the relationships among functional and non-functional requirements. It also represents the relationships drawn from text-based requirements with additional modelling elements (OMG, 2012). Finally, having all the requirements in a single model instead of textual catalogues allows the decomposition and the creation of new requirements by derivation. The basic template of a SysML requirement diagram includes the ID, the heading and the text. The model shown in Figure 6-4 uses the approach proposed by Soares et al. (2011) and includes the MoSCoW ratings prioritisation as an attribute for each one of the specific requirements. Developing a system that is capable of fulfilling all the user requirements captured is not always feasible. Prioritisation will support the selection of the "Must" and "Should" requirements that will be used in developing a proof of concept system. Having the prioritisation within the SysML requirement diagram will allow, based on the relationships defined, the calculation of risk of a requirement that has not been met as well as the determination of its impact on the whole system. For simplification reasons only a sample of the key priorities are included in the diagram below.

Common Requirements

«Security Requirement»
Supply chain access
Text="The solution shall be able to authorise and control the accessibility of users outside the OEMs network within the supply chain"
ID= REQ41
Priority= "Must"

«Supply Chain Requirement»
Exchange information through the supply chain
Text="The solution shall be able to pack different data formats within a single object and share the information within the supply chain, either with the OEM or sub-suppliers"
ID= REQ25
Priority= "Must"

«Accessibility requirement»
Review the history of a part/sub-system/ system
Text="The solution shall be able to extract the Repairs/1000 KPI and the claims of a part/ Sub-system/system from the warranty system"
ID=REQ3
Priority="Must"

«Administration Requirement»
Login to the system
Text="The solution shall request users to login in order to define a search term"
ID= REQ36
Priority= "Must"

«Administration Requirement»
Silo registration
Text="The solution shall provide the administration the capability to easily define and register additional silos "
ID= REQ39
Priority= "Should"

«Administration Requirement»
Define/Modify workflow
Text="The solution shall allow the administrator to modify/define a new workflow to allow the functionality of the system to be expanded or customised"
ID= REQ40
Priority= "Should"

«Generic Requirement»
Predefine search results
Text="The system should allow users to predefine search results to improve the performance of the system. Therefore if a large number of claims is required for review, the users could provide a list with VIN numbers and the system will prepare the data for the next hour/day"
ID= REQ65
Priority= "Want"

«Generic Requirement»
Save a session for future reference
Text="The solution shall allow the user to save a session with the returned results for future reference. The period that the data will be available needs to be defined from the user. "
ID= REQ30
Priority= "Must"

«Scalability Requirement»
Scalable to multiple visual environments
Text="The solution shall be able to visualise the extracted data into multiple visual environments such as portable devices, desktops and 3D environments."
ID= REQ32
Priority= "Should"

«Accessibility requirement»
Review the cost of a part/sub-system/ system
Text="The solution shall be able to extract the Cost Per Unit (CPU) and the claims of a part/ sub_assembly_code/Function Group_Code from the Warranty system "
ID=REQ8
Priority="Should"

«Accessibility Requirement»
Review the Quality History of a part/sub-system
Text="The user shall be able to review the quality history of a part/sub=system/system using data extracted from the warranty database based on a search term depending on the scope of the FMEA (either Part_ID, sub-system_code)."
ID=REQ5
Priority="Must"

«Use Case» - «Generic requirement»
Collate Quality History to run a robust FMEA
Text="The user shall utilise various information sources to produce a comprehensive list of past concerns/failures and their root causes, based on internal and external data"
ID=REQ27
Priority= "Must"

«Use Case» - «Generic requirement»
Assess returned parts and assign liabilities
Text="The user shall gather all the relevant information pertinent to a claim to review a returned part and assign a liability (CAT1,CAT2,CAT3)"
ID= REQ28
Priority= "Must"

«Generic requirement»
Support in identifying gaps in bulletin and diagnostics
Text="The solution shall be able to support the engineers to review and identify gaps in bulletin and diagnostics provided to the dealer in order to ensure that the dealer had enough information to make a repair"
ID= REQ29
Priority= "Must"

«Accessibility requirement»
Access information provided to the dealers
Text="The user shall be able to review the published Technical Service bulletins, diagnostics and service manuals associated with the searched VIN ton ensure that dealers had enough information to make a repair"
ID=REQ12
Priority="Must"

«Accessibility requirement»
Review the Sufficiency plans
Text="The solution shall be able to extract or re-create the sufficiency plans of a sub-system level or Function group level from the Warranty database"
ID=REQ9
Priority="Should"

«Accessibility requirement»
Filter the returned results
Text="The solution shall be able to filter the returned results using at minimum the Country of origin or the Months-In-Service criteria"
ID=REQ4
Priority="Should"

«Accessibility requirement»
Access PDM/PLM to extract product data
Text="The solution shall be able to extract a light weight CAD representation of the searched term, ideally one parent and all children."
ID=REQ11
Priority="Could"

«Visualisation requirement»
View Product structure
Text="The solution shall provide the user with the ability to hide and view parts from the BOM structure."
ID=REQ51
Priority="Must"

«Accessibility requirement»
Access PDM/PLM to extract product data related to a claim
Text="The solution shall be able to obtain the part number associated with a claim and extract a light weight CAD representation of the searched term, ideally one parent and all children"
ID=REQ14
Priority="Must"

«Accessibility requirement»
Access Quality projects related to a claim
Text="The solution shall be able to extract the description and the status of quality projects related to a selected claim in order to allow the user to assess if fault reviewed is/was addressed from an ongoing or closed project. "
ID=REQ23
Priority="Should"

«Accessibility requirement»
Access Vehicle history (RC)
Text="The solution shall be able the technical verbatim and customer verbatim for each warranty claim, the technical verbatim and country from the breakdown reports and customer verbatim for the surveys associated with the searched VIN."
ID=REQ15
Priority="Must"

«Search requirement»
Search using a VIN number
Text="The solution shall be able to search within the warranty system, the vehicle diagnostics database, the tech. pubs system using the Vehicle IDentification Number (VIN)."
ID=REQ22
Priority="Must"

«Search requirement»
Search using a Part/Sub-system code
Text="The solution shall be able to search within the PLM and the other databases using a Part_ID, sub-assembly_Code "
ID=REQ20
Priority="Must"

«Accessibility requirement»
Access stopped shipments
Text="The solution shall be able to extract past campaigns and stopped shipments related to supplier history on previous programmes in order to understand top priority quality failures"
ID=REQ2
Priority="Want"

«Accessibility requirement»
Access documents related to a part number
Text="The system shall be able to allow the users to access relevant document from PLM systems associated with a part number. These could be either change requests, work orders, issues, concessions or limitations) "
ID=REQ56
Priority="Want"

«Supply Chain requirement»
Access Supplier Test data
Text="The solution shall be able to extract and therefore allow suppliers to integrate their internal systems in order to combine their internal test data with the claims obtained from warranty system. "
ID=REQ24
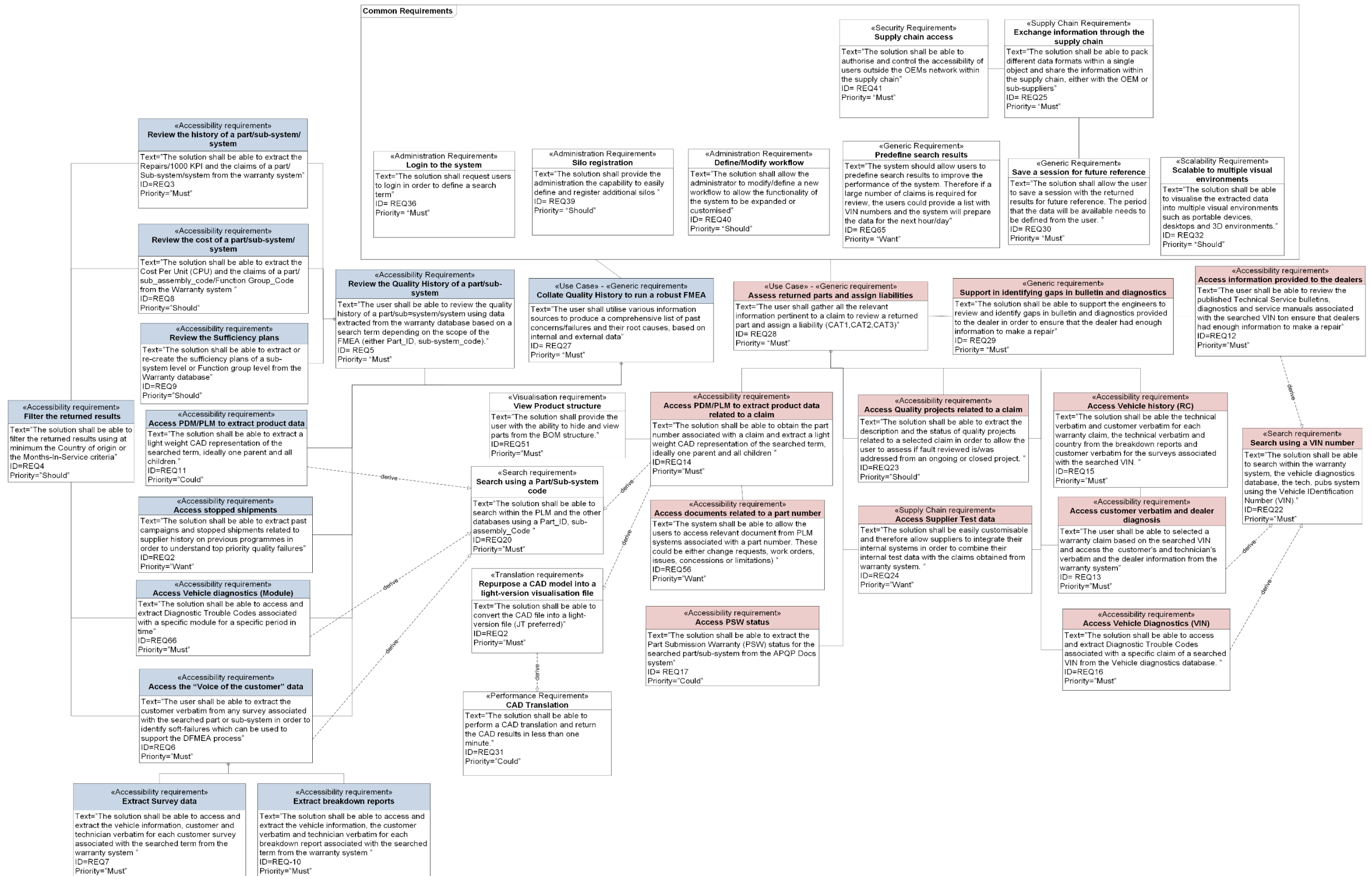Priority="Want"

«Accessibility requirement»
Access customer verbatim and dealer diagnosis
Text="The user shall be able to selected a warranty claim based on the searched VIN and access the customer's and technician's verbatim and the dealer information from the warranty system"
ID= REQ13
Priority="Must"

«Accessibility requirement»
Access Vehicle diagnostics (Module)
Text="The solution shall be able to access and extract Diagnostic Trouble Codes associated with a specific module for a specific period in time"
ID=REQ66
Priority="Must"

«Translation requirement»
Repurpose a CAD model into a light-version visualisation file
Text="The solution shall be able to convert the CAD file into a light-version file (JT preferred)"
ID=REQ2
Priority="Must"

«Accessibility requirement»
Access PSW status
Text="The solution shall be able to extract the Part Submission Warranty (PSW) status for the searched part/sub-system from the APQP Docs system"
ID= REQ17
Priority="Could"

«Accessibility requirement»
Access Vehicle Diagnostics (VIN)
Text="The solution shall be able to access and extract Diagnostic Trouble Codes associated with a specific claim of a searched VIN from the Vehicle diagnostics database. "
ID=REQ16
Priority="Must"

«Accessibility requirement»
Access the "Voice of the customer" data
Text="The user shall be able to extract the customer verbatim from any survey associated with the searched part or sub-system in order to identify soft-failures which can be used to support the DFMEA process"
ID=REQ6
Priority="Must"

«Performance Requirement»
CAD Translation
Text="The solution shall be able to perform a CAD translation and return the CAD results in less than one minute."
ID=REQ31
Priority="Could"

«Accessibility requirement»
Extract Survey data
Text="The solution shall be able to access and extract the vehicle information, customer and technician verbatim for each customer survey associated with the searched term from the warranty system "
ID=REQ7
Priority="Must"

«Accessibility requirement»
Extract breakdown reports
Text="The solution shall be able to access and extract the vehicle information, the customer verbatim and technician verbatim for each breakdown report associated with the searched term from the warranty system "
ID=REQ-10
Priority="Must"

derive

Figure 6-4 SysML Requirements Diagram

During the requirements elicitation process it was highlighted that engineers spend a significant amount of time searching for information while manually accessing multiple silos to extract the required information. In order to improve the root cause analysis, engineers need to be able to integrate the required information in a single and visual environment. The requirements analysis showed that it is critical for engineers to be able to visualise different clusters of data in a single environment and to enable data reuse across the supply chain. Data such as the "voice of the customer" (surveys, breakdown and recovery reports); technical publications (manuals, bulletins and diagnostics); product data (CAD data, specifications and associated documentation), warranty claims and faults recorded from the dealers (customer and technician verbatim), and the "voice of the vehicle" (diagnostic trouble codes) are necessary in order to build a full quality picture. Similarly PD engineers use the quality history obtained to determine the failure modes and prevent re-occurrence through the DFMEA process. By examining the process maps from chapter 5 and by analysing the requirements captured, it was identified that new requirements can be created by derivation. VIN search was created by derivation as warranty engineers need to be able to search via a VIN in order to extract the information required to conduct a root cause analysis of a claim. Part number/sub-system code search was also created by derivation to allow PD engineers to collect the quality history of a part/sub-system. Furthermore, all the domain experts stated that full scale CAD models are not relevant to their processes. Therefore, to improve the performance of the system, CAD translators could be used to repurpose CAD data into a light version CAD representation that is sufficient for engineers to conduct a root cause analysis. Another requirement that was created by derivation is the access to the BOM structure as engineers need to be able to review a part in relation to its sub-assembly.

In terms of the PLM systems used, warranty engineers stated that the solution should allow supplier and OEM engineers to view data extracted from PLM systems without depending on PD engineers to manually send these information. Data extraction must be handled in a secure and controlled way. As warranty engineers are associated with the after sales phase of the product lifecycle, their access to the PLM system is currently restricted. Similarly, for warranty engineers within the supply chain their access is restricted due to the licensing cost involved and the infrastructure required.

6.3. UML Modelling - "Use-case" View

UML modelling techniques are widely used and contribute in transforming user requirements into system behaviour while at the same time offering a shared understanding and enabling more effective communication through a standardised language. Schulz (2001) stated that most UML-based methodologies focus on the solution and define the system functions using use-case diagrams instead of addressing the business-oriented application requirements. To mitigate this risk, the system architecture proposed is developed to support the business challenges identified within the processes that OEM and supplier engineers follow as described in chapter 5. Therefore, the system functionality is developed to support OEM and supplier warranty engineers with steps "ID.5 – Parts assessed by supplier" and "ID.7 – Decisions assessed by the OEM" from the "In-service product failure identification and root cause analysis" process and PD engineers with the "Quality history for DFMEA" process. Konrad and Gall (2008) observes that in many cases stakeholders do not have a clear understanding of requirements as their knowledge and understanding of requirements is usually limited within their own organisation. To mitigate that risk multiple organisations were used to gather requirements. Requirements were then reviewed against the findings from the literature to ensure the novelty of this research.

UML use case diagrams provide a good graphical representation of the functional requirements of a system as they illustrate the different use cases, the actors and their interactions with the system. Actors may include users, systems or any other entity that has a direct or indirect communication with the system (OMG, 2012). Outside the boundaries, the diagram demonstrates two types of actors; the human actors that represent the end users of the system and the system actors that represent the applications that have a direct or indirect communication with the system. A UML sequence diagram is also used to demonstrate sequence of tasks and messages exchanged once a user initiates a search and until the data are presented back to the screen. A sequence diagram was developed for the two key use cases described. Within the "use case" view, the proposed system architecture is treated as a "black box". Events that occur within the proposed system will be described later in this chapter through the "static" and "dynamic" views of the system architecture. Requirements and test cases documented are linked with the use cases to ensure traceability.

Actors may include users, systems or any other entity that has a direct or indirect communication with the system. Figure 6-5 shows an overview of the human and system actors included in the use case diagram.
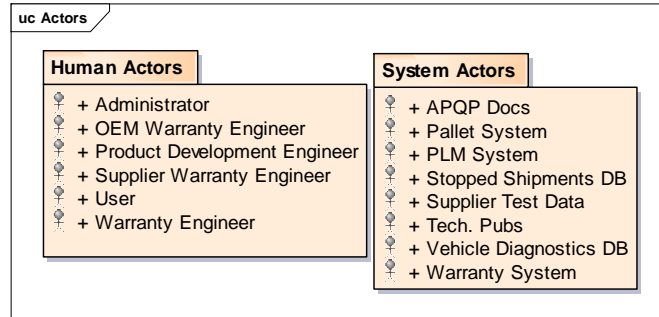

Figure 6-5 Human and System Actors

6.3.1.1. Human Actors

Figure 6-6 shows the relationships among the different human actors which have an interaction with the system. Human actors are also called business actors and represent users outside the modelled system that have an involvement with at least one use case. Table 6-1 provides the definitions for all the human actors that have a direct or indirect communication with the proposed architecture.
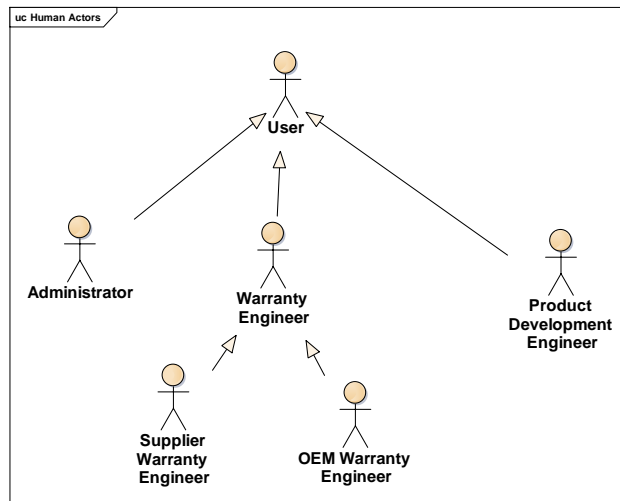

Figure 6-6 Actors grouping

Table 6-1 Human Actors

Administrator	Scope responsibility	Administrators are responsible for maintaining and setting up the system. Two of their primary roles are to register silos and define the workflow that needs to be followed in order to perform a task

User	Scope responsibility	The user actor represents a superclass for every end-user that has access to the system
OEM Warranty Engineer	Scope responsibility	OEM Warranty engineers are responsible for managing and delivering the quality projects raised. They are responsible for overviewing the warranty procedures by assessing suppliers' decisions and ensuring that the dealers are equipped sufficiently to repair the vehicles in the appropriate manner
Supplier Warranty Engineer	Scope responsibility	Supplier Warranty engineers are responsible for delivering the quality projects raised by analysing different types of quality data. They are responsible for assigning liabilities on the faults found and ensuring that the dealers are equipped sufficiently to repair the vehicles in the appropriate manner
PD Engineers	Scope responsibility	In this instance, Product Development engineers are responsible for scoping, detailing and reviewing the DFMEA with the cross-functional teams. PD engineers use various sources to obtain the quality history and as a result define the causes and the effects of potential failures

6.3.1.2. System Actors

Figure 6-7 shows the different segmentation of the system actors used within the use case model. Table 6-2 provides the definitions for all the systems that have a direct or indirect communication with the proposed architecture.
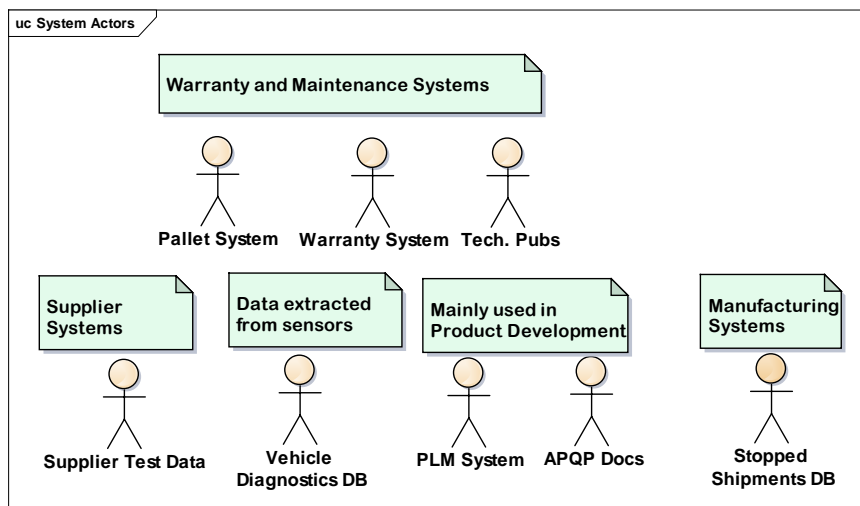

Figure 6-7 Segmentation of System actors

Table 6-2 System Actors

PLM	Scope responsibility	PLM is an enterprise system used to manage engineering data. In this instance, PLM systems will be used to extract CAD data, the Bill-of-Material and any documents associated with the searched part or sub-assembly.
Pallet Recording System	Scope responsibility	For all the parts returned from dealers back to the OEM, the Pallet Recording System is responsible for tracking and maintaining the links between the claims and the part within each pallet. The Pallet Recording System utilises data extracted from the warranty database such as vehicle information, part information and dealer information, which are mandatory in order to start a part assessment. The decision for each one of the parts reviewed will be recorded in this system. The pallet recording system has an in-direct communication with the proposed system architecture.
Tech Pubs	Scope responsibility	Tech Pubs provides access to all the information required to enable dealers to deliver vehicle service and repair for OEM's customers. This includes Special Service Manuals, Electrical Diagrams, Technical Service Bulletins, and Diagnostic Release Notes.
Warranty System	Scope responsibility	This system contains detailed warranty claim information for customer issues that required a repair within the warranty period. All the information related to the fault and the quality history of each vehicle are available within the warranty system. This system allows users to organise claims, breakdown reports and voice of the customer data such as surveys against a quality project which aims to address similar faults identified across multiple vehicles. It also serves as a repository for all the quality projects raised.
Vehicle Diagnostics database	Scope responsibility	Vehicle Diagnostics database collates diagnostics from customer vehicles from OEM dealerships from all around the world. Data are collated automatically from the vehicles via the service tool and are automatically send back to the OEM. The data collated covers DTC (Diagnostic Trouble Code), vehicle usage information and battery information.
APQP Documentation	Scope responsibility	Advanced product quality planning is a framework for running and delivering quality products. For the use cases discussed the APQP system is used to extract the Part submission warranty status which demonstrates if a supplier agreed a certain type of quality and is responsible for delivering it.

Supplier Test Data	Scope responsibility	This system actor represents supplier data that needs to be integrated to support root cause analysis. In the quality/service phase, supplier data represent either test data conducted to the returned part or data from quality checks conducted from suppliers prior to shipping the part.
Stopped Shipments DB	Scope responsibility	Stopped Shipments DB is responsible for maintaining all the information regarding quality issues identified from the manufacturing team prior to the shipment of a final product batch.

6.3.2. Use Cases

The use case diagram describes the set of actions that the proposed system should perform in collaboration with one or more external human or system actors. Figure 6-8 shows the generic use cases that need to be completed by every user, the use cases related to the administrator of the system and the business cases that are relevant to the engineers that represent the end users of the proposed solution. Within the boundaries of the use-case diagram an extend relationship was defined between the "conduct root cause analysis" (base) and the "Analyse categorised claims" (extension) use cases. Extend relationships are used to demonstrate that one use case extends the behaviour to another. In UML modelling the extension use case is not meaningful without the base use case (IBM, 2005). The next sub-sections describes each one of the use cases and defines the basic flow required in order to support the processes captured in sections 5.2 and 5.3. Sequence diagrams are also provided to model the sequence of tasks for the two key business cases. Basic flows are provided for the three business use cases. The "Login", the "Register silos" and the "Define workflows" use cases follow the standard IT flow that is used for any system designed.
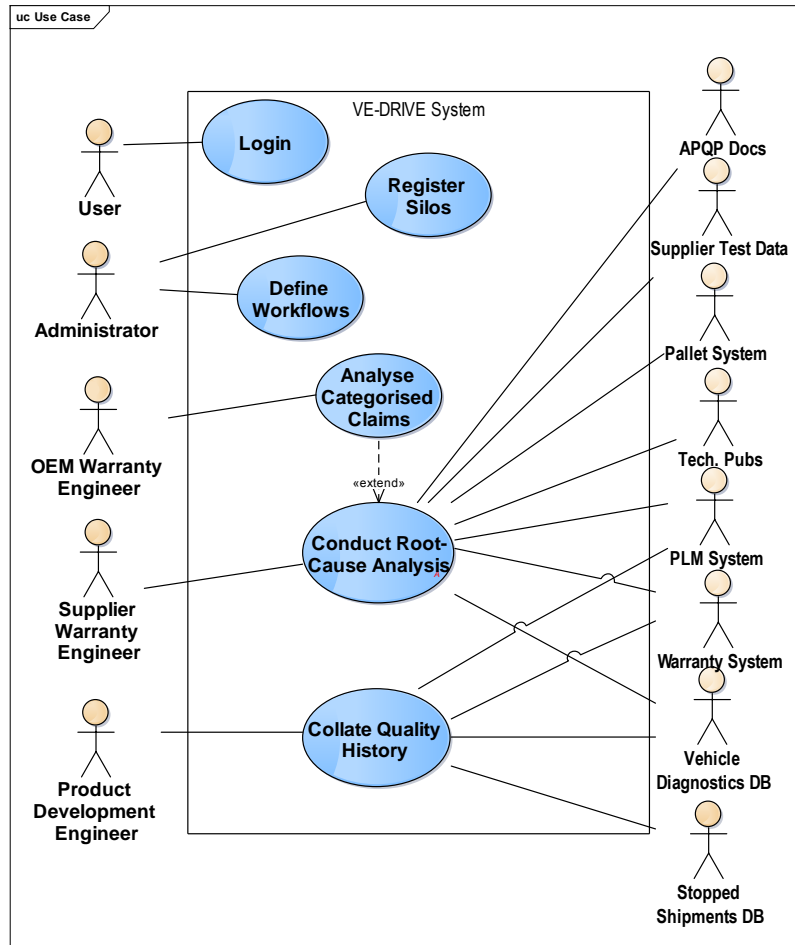
Figure 6-8 Use Case Diagram

6.3.2.1. Conduct Root Cause Analysis
Brief Description

This use case is linked with the ID.5 process step described in section 5.2. This use case is initiated when a component supplier is ready to assess a number of returned parts held in a pallet. Supplier warranty engineers, shall be able to conduct a root cause analysis, assess a returned part and assign a liability by selecting one of the three types of faults (Type1-Supplier fault, Type2-OEM Fault, Type3-NTF). To perform this task, engineers should gather, at minimum the following types of data:

- Vehicle's history
- Vehicle's description
- CAD representation and documents associated with the part
- Customer and technician verbatim
- Diagnostic publications available in OEM dealerships
- Vehicle diagnostics from the time the fault occurred

Moreover, warranty engineers shall be able to identify where gaps in the dealer diagnostic, repair, or root cause analysis procedures exist and as a result close the information gaps, and ultimately reduce the level of NTF warranty returns. The use case is successfully completed when the user has reviewed all the information and assigned a liability against a claim.

Basic Flow

Figure 6-9 expands on the use case described by showing all the steps followed in order to satisfy the use case. Supplier Warranty Engineer defines the search criteria using a VIN number. The system then requests and presents the vehicle description, "voice of the customer" data and vehicle's claims from the Warranty system (INT1). In addition, the system presents a visual representation of the vehicle highlighting areas where claims occurred. Once the supplier warranty engineer understands the conditions that the car was operating and the history of the car, he/she selects the claim related to the reviewed part. The system extracts a CAD representation of the sub-assembly using the part-number and the sub-assembly code from PLM system, (INT3). In addition the system extracts, the Part Submission Warranty Status using the part number from APQP Docs, (INT4), any test data test data from the linked supplier's systems (INT6) and Diagnostic Trouble Codes (DTC) from the vehicle diagnostics database using the VIN number and the time period (INT8). Finally the system opens the Tech. Pubs application to the appropriate page using the VIN number. (INT7). The system presents all the information and allows the user to interact with the data by selecting the appropriate menu option. In the end of the session, the Supplier Warranty Engineer records actions and notes of the session. These steps can be repeated multiple times until the user has completed the pallet review. The INTerface reference within the brackets refers to a system interface and links to a table that shows the data required to fulfil the step. Appendix D shows the details for each interface linked. Scenario 1 in section 7.2 demonstrates how the proposed solution is used to satisfy this use case.
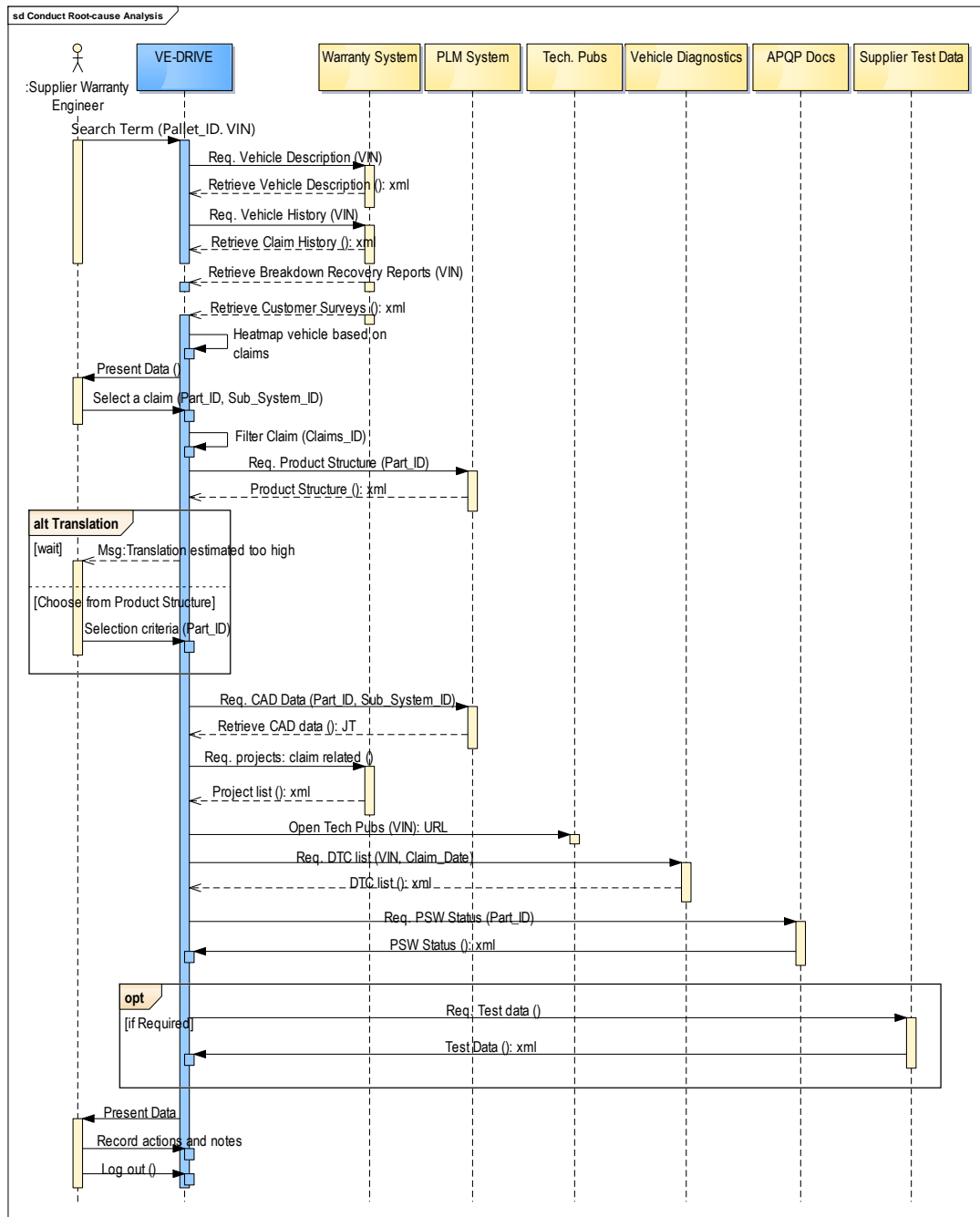
Figure 6-9 UC Realisation - "Collate Quality History to Identify the Root Cause of a Claim"

6.3.2.2. Analyse Categorised Claims

Brief Description

This use case is linked with the ID.7 process step described in section 5.2. The system allows the OEM warranty engineers to review the categorisation of claims by suppliers. Primarily, OEM warranty engineers are looking for suppliers that have high number of NTF claims. Another criteria that OEM engineers track is the amount of warranty spend against the failure occurrence. For example, it might be a small

number of failures responsible for high cost parts (e.g. engines) or a high number of failures responsible for low cost parts (e.g. mirrors). In the use case diagram, this use case is captured as an extension to the "Conduct root cause analysis" use case. This use case is initiated when OEM warranty engineers identify repetitive NTF claims associated with a similar failure effect. To perform this task using the proposed system, OEM warranty engineers utilise a cached version of data that suppliers used to conduct root cause analysis. OEM warranty engineers need to ensure that suppliers were able to:

- replicate the conditions when the part failed
- use test criteria that meet the expected levels
- ensure that the dealers had enough information to make a repair

This use case is successfully completed when the user has reviewed and analysed all the required information and either accepts the supplier's decision or arranges follow up sessions with the supplier.

Basic Flow

The sequence of tasks followed in this use case are the same with the ones described in the "conduct root cause analysis" use case in section 6.3.2.1. Although the steps in terms of system flow are the same, the decision points and the way that data are analysed are different as explained within the process in section 5.2. Scenario 2 in section 7.3 demonstrates how the proposed solution is used to satisfy this use case.

6.3.2.3. Collate Quality History
Brief Description

This use case is linked with the process described in section 5.3. The PD Engineers shall be able to utilise various information sources to produce a comprehensive list of past concerns or failures and their root causes, based on internal and external data. The purpose is to allow engineers to run a robust DFMEA process and as a result prevent recurring of previous faults. This use case is initiated once the scope of the DFMEA is defined. The user needs to obtain the quality history required for the DFMEA prior of designing a part or a sub-system for a new vehicle. This use case is successfully completed once the user has reviewed and analysed all the information required to determine and assess each failure modes.

Figure 6-10 expands on the use case described by showing all the steps followed in order to satisfy the use case.
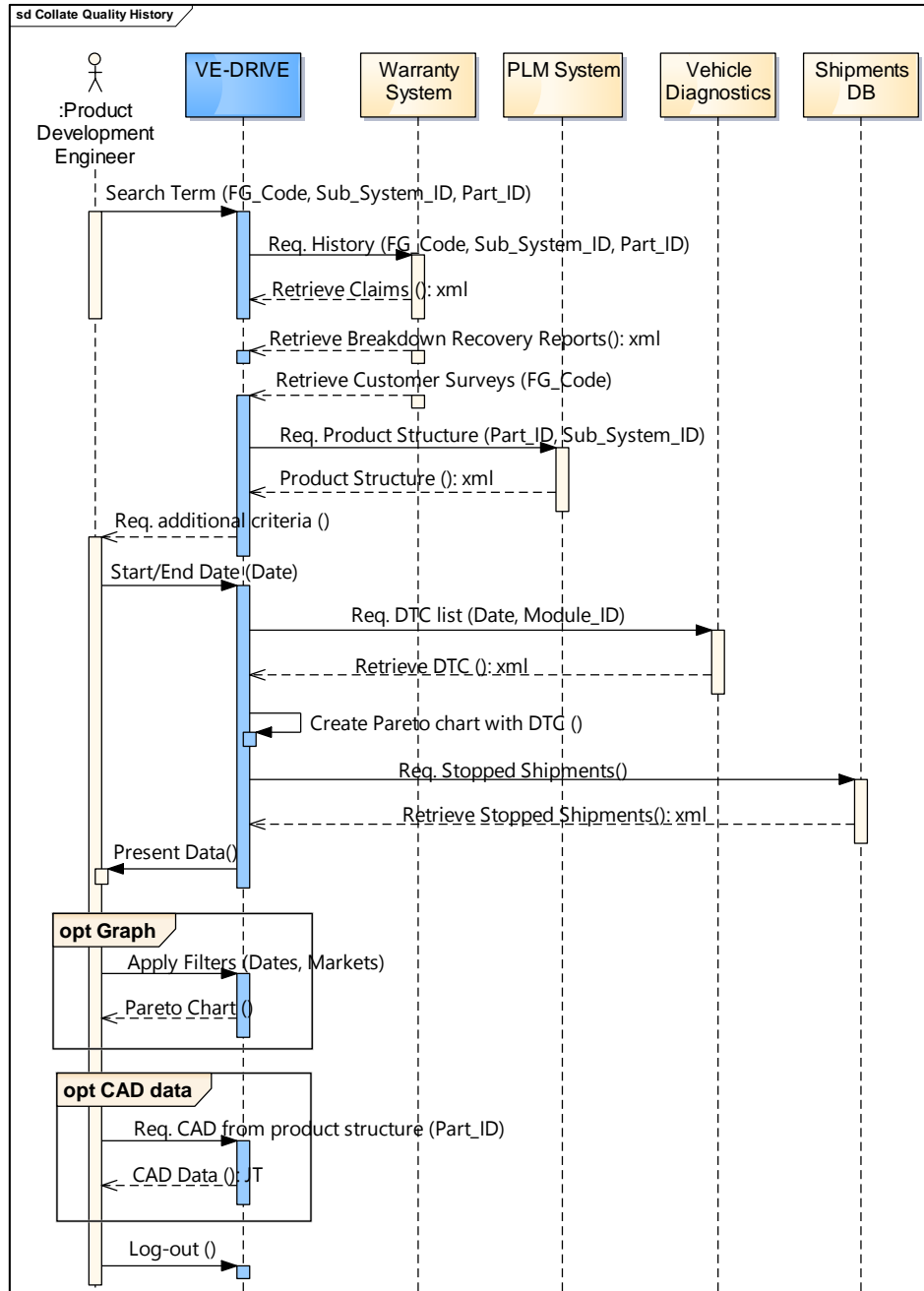
Figure 6-10 Use Case Realisation - "Collate Quality History"

The PD engineer defines search criteria using either the Function Group code, the Sub-assembly_code or the Part_ID. The system requests the product structure from the PLM System (available only for sub-system or part level) and warranty claims, breakdown recovery reports and surveys from the warranty system. To reduce the amount of data returned, the system needs to extract data for both 3 Months-In-

Service (MIS) and 3 Years-In-Service (YIS) vehicles. In addition, the system extracts DTC from Vehicle feedback database using the module_ID and the dates defined, and stopped shipments data associated with the searched programme (INT5). The system presents the returned results and the name of the systems where the data were extracted from. The PD Engineer filters the data based on markets, Months-in-Service or Programmes. The system allows the user to create Pareto charts or hierarchical charts for each one of the data set extracted. The user concludes the use case by recording actions and notes of the session. The INTerface reference within the brackets refers to a system interface and links to a table that shows the data required to fulfil the step. Appendix D shows the details for each interface linked. Scenario 3 in section 7.4 demonstrates how the proposed solution is used to satisfy this use case.

6.3.2.4. Login
<u>Brief Description</u>

User Credentials are passed to the system which are then used to define the level of access permitted for the user in each system integrated. Different users will have different level of access on each individual system. For example, a user may have full access to the warranty system but limited access to the PLM system.

6.3.2.5. Register Silos
<u>Brief Description</u>

The administrator is responsible for registering the silos required to satisfy a use case. The system utilises the silo register in order to determine to what level of detail a query can be effectively executed, by silo and availability. In case there is a need to add a new silo, the administrator is responsible for defining the required information and registering the "new" silo.

6.3.2.6. Define Workflows
<u>Brief Description</u>

The administrator is responsible for defining the workflows required to perform a task. For each use case described the administrator is responsible for designing and maintaining the workflow. The workflow specifies the sequences of data flow, processes and tasks that need to be followed in order to accomplish a task. More details on the workflows are provided later in this chapter in sub-section 6.4.3.

The administrator within the workflow engine can also specify data translations required in order to make the data available in the format required from the presentation layer. For example, in all the use cases described, CAD data were translated from their native format to a light weight JT.

6.3.3. Traceability Matrix

Having the use cases and the actors fully defined, there was a need to be able to trace the requirements against each use case in order to ensure that some of the high priority functional requirements were not missed. Maintaining a traceability matrix allows the linkage between requirements and work products (Hofmann and Lehner, 2001).Traceability matrix is a document used to correlate requirements against use cases, test cases or detailed design documents. In this instance, traceability matrix was used to correlate the requirements against the use cases to ensure that the proposed architecture will provide the appropriate functionality for a use case and as an extent satisfy the requirements captured from stakeholders. Traceability matrix was also used for reviewing which requirements can satisfy more than one use cases. Therefore during the prioritisation process, requirements that satisfy more than one use case can be taken into consideration as they will improve the management of the available resources especially for the two partner companies who were responsible for developing a POC system. Figure 6-11 shows the traceability matrix as extracted from the EA software which was used to model the requirements.

	Use Case::Analyse Categorised Claims	Use Case::Collect Quality History	Use Case::Conduct root cause analysis	Use Case::Define Workflows	Use Case::Login	Use Case::Register Silos
Accessibility::Access the BOM Structure	⇑	⇑	⇑			
Accessibility::REQ10- Extract breakdown reports		⇑				
Accessibility::REQ11- Access PDM/PLM to extract product data		⇑	⇑			
Accessibility::REQ12- Access information provided to the dealers	⇑		⇑			
Accessibility::REQ13- Access customer verbatim and dealer diagnosis	⇑		⇑			
Accessibility::REQ14- Access PDM/PLM to extract product data related to a claim	⇑		⇑			
Accessibility::REQ15- Access Vehicle history (RC)	⇑		⇑			
Accessibility::REQ16- Access Vehicle Diagnostics (VIN)	⇑		⇑			
Accessibility::REQ17- Access PSW status	⇑		⇑			
Accessibility::REQ19- Access the BOM Structure	⇑	⇑	⇑			
Accessibility::REQ2- Access stopped shipments		⇑				
Accessibility::REQ23- Access Quality projects related to a claim	⇑					
Accessibility::REQ3- Review the history of a part/sub-system/system		⇑				
Accessibility::REQ4- Filter the returned results		⇑				
Accessibility::REQ5- Review the Quality History of a part/sub-system		⇑				
Accessibility::REQ56-Access documents related to a part number	⇑	⇑	⇑			
Accessibility::REQ59-Access Vehicle Description	⇑		⇑			
Accessibility::REQ6 - Access the "Voice of the Customer" data (QH)		⇑				
Accessibility::REQ66-Access Vehicle diagnostics (module)		⇑				
Accessibility::REQ7- Extract Survey data		⇑				
Accessibility::REQ8- Review the cost of a part/sub-system/system		⇑				
Accessibility::REQ9- Review the Sufficiency plans		⇑				
Administration::REQ36- Login to the system					⇑	
Administration::REQ37- Error message for login failure					⇑	
Administration::REQ38- Administration Login					⇑	
Administration::REQ39-Silo registration						⇑
Administration::REQ40- Define/Modify workflow				⇑		
Generic::REQ26- Annotate actions	⇑	⇑	⇑			
Generic::REQ27- Collate Quality History to run a robust FMEA		⇑				
Generic::REQ28- Assess returned parts and assign liabilities			⇑			
Generic::REQ29- Support in identifying gaps in bulletin and diagnostics	⇑		⇑			
Generic::REQ30- Save a session for future reference	⇑					
Generic::REQ46- Review categorised claims	⇑					
Generic::REQ55- Generate graphs		⇑				
Generic::REQ58-Package information in a single object	⇑	⇑	⇑			
Generic::REQ60-Follow standards						⇑
Generic::REQ65-Predefine search results			⇑			
Search ::REQ20- Search using a Part/Sub-system code		⇑				
Search ::REQ21- Search using a part/sub-system code related to a claim	⇑		⇑			
Search ::REQ22- Search using a VIN number	⇑		⇑			
Supply Chain::REQ24- Access Supplier Test data	⇑		⇑			
Supply Chain::REQ25- Exchange informaton through the supply chain	⇑	⇑	⇑			
Translation::REQ1- Repurpose the returned results	⇑	⇑	⇑			
Translation::REQ2- Repurpose a CAD model into a light-version visualisation file	⇑	⇑	⇑			
Visualisation::REQ47- Visualise the vehicle description	⇑		⇑			
Visualisation::REQ48- Visualise the vehicle history	⇑		⇑			
Visualisation::REQ49-Visualise a Vehicle representation	⇑		⇑			
Visualisation::REQ50-Generate heatmap on a CAD model		⇑				
Visualisation::REQ51- View Product structure		⇑				
Visualisation::REQ53- View the data sources		⇑				
Visualisation::REQ54- Visualise graphs		⇑				
Visualisation::REQ61-User Interaction	⇑	⇑	⇑			
Visualisation::REQ62-Visualise the CAD representation	⇑	⇑	⇑			
Visualisation::REQ64-Multiple platforms	⇑	⇑	⇑	⇑	⇑	⇑

Figure 6-11 Traceability Matrix – Requirements Against Use Cases

6.4. UML Modelling – Static View

Static analysis demonstrates the structure of the proposed system by decomposing the high-level architecture into layers and packages. The static view creates a baseline in which the dynamic view will expand to include the dynamic behaviour of the system over time. Package diagrams and class diagrams are widely used to demonstrate the static view of a system architecture. Each layer and each package of the system architecture is defined in this sub-section. In addition a class diagram that shows the relationships among the different data sets is used to demonstrate how the functionality is delivered to the end users.

6.4.1. System Architecture Structure

The literature review has shown that within a company, when the task or problem exploration area follows predefined paths within a fixed internal data landscape then the requested data flow and access to information works as intended. It is when the task or problem resolution necessitates accessing data sources outside the norm that issues start to appear. The proposed system architecture will extend the current level of data source integration which will then enable the value of data to be accessed through collaboration within the supply chain. In order to achieve this, a system architecture is proposed for inter-organisation data sharing that can cross organisations and enable data silos to be shared in a controlled manner. The subset of the data silos identified covers a continuum of data types from complex PLM systems through electronic technical publications to vehicle diagnostics and warranty systems.

Figure 6-12 shows the high level architecture divided into three layers: presentation, integration and domain. The core of the solution architecture is based on the premise that discrete silos of information can be made available via web-services. Central to the system architecture is an aggregator that assembles the selected data and initiates translation services whenever required to improve the performance and meet the needs of the presentation layer. System adapters were developed to communicate the integration layer with data extracted from the domain layer. Web Services were selected as a method of communication between the integration and the domain layer, due to their ability to support interoperable machine-to-machine interaction and to manage the transfer of data securely. Data retrieved can be presented in multiple visual environments such as immersive environments, desktops and tablets.
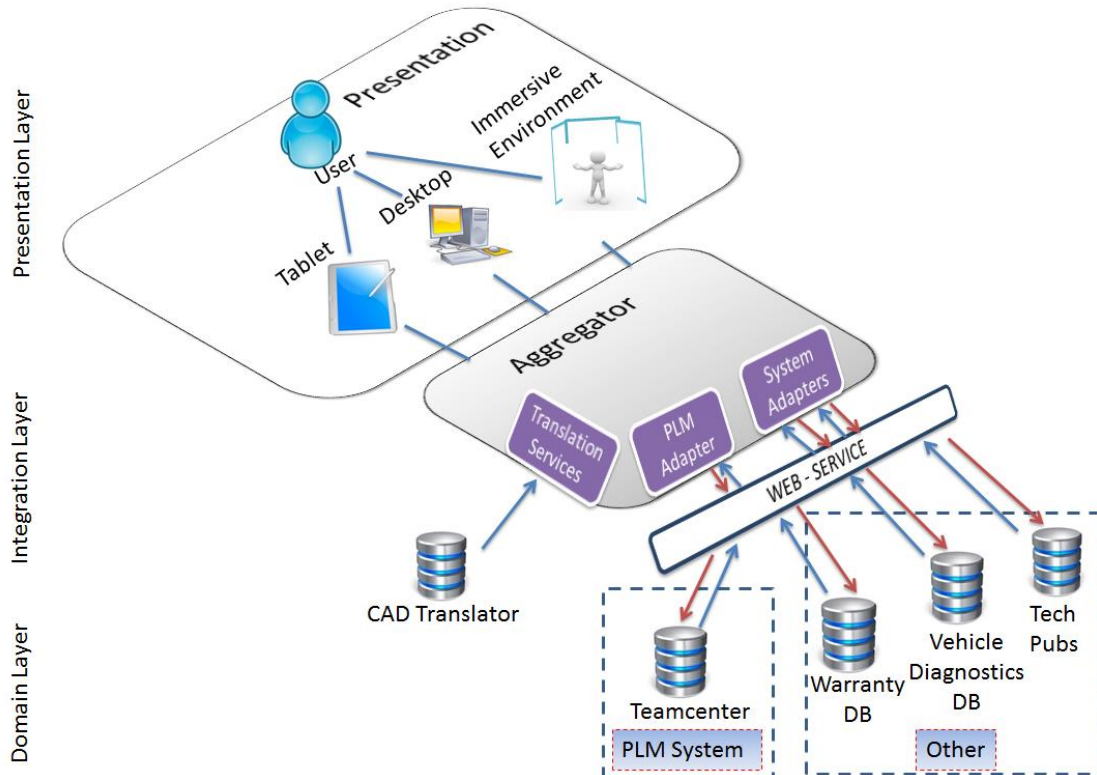
Figure 6-12 High Level System Architecture

Each one of the layers presented in these figures is autonomous and can be implemented as a physically separated component. This aspect is very important as it allows the re-usability and agility of the system. Each layer can be developed separately and then linked with the layer below. Packages presented in Figure 6-13 were developed as generic as possible to support more use cases from the automotive sector as well as use cases from other sectors. However, elements developed to satisfy specific requirements and as a result support specific processes are not meant to be reusable. More insights on the reusability of the architecture is provided in section 8.2 when the system is tested against a use case from the Defence sector.

Once a user initiates a search the aggregator is responsible for making the connections among the different primary keys, decompose and execute the queries and finally cache the returned results. The visualisation engine, which can work in multiple platforms, uses the cached data to present the outcome and construct the menu options. Figure 6-13 reveals the packages held within each one of the layers. Definitions for each one of the packages are provided in this section.
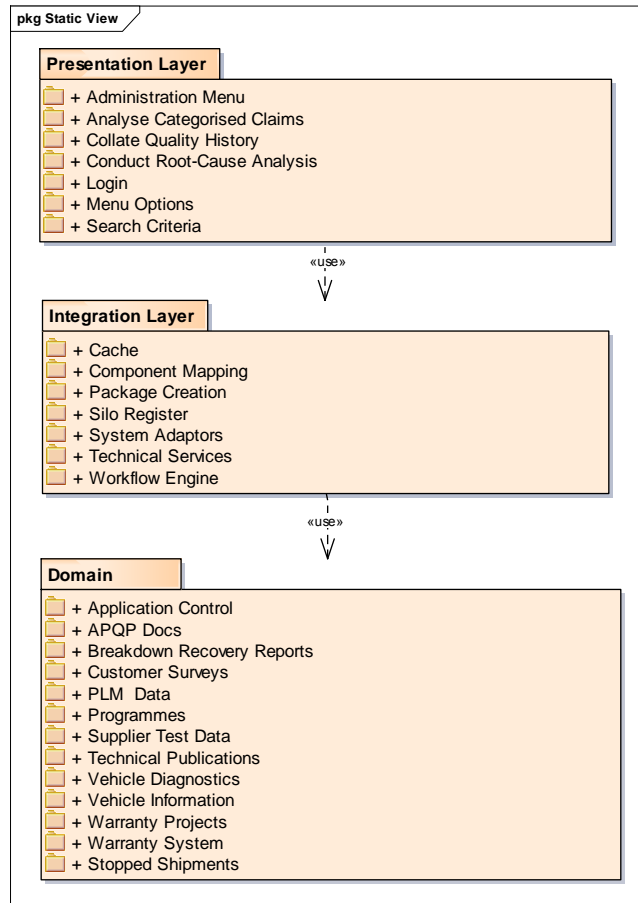
Figure 6-13 High Level Package View

Figure 6-14 demonstrates how the different layers and packages are connected. "Use" arrows show that one package is using another package as an input to perform a task. Arrows without a label show a dependency with another package. Key aspect of the layer segmentation is to separate the domain layer which represents the business logic with the other layers that represent the technology required to extract and visualise the data. As a result, depending on the circumstances, this approach allows either the technology to be improved over time or the domain layer to be expanded whenever a new requirement is identified.
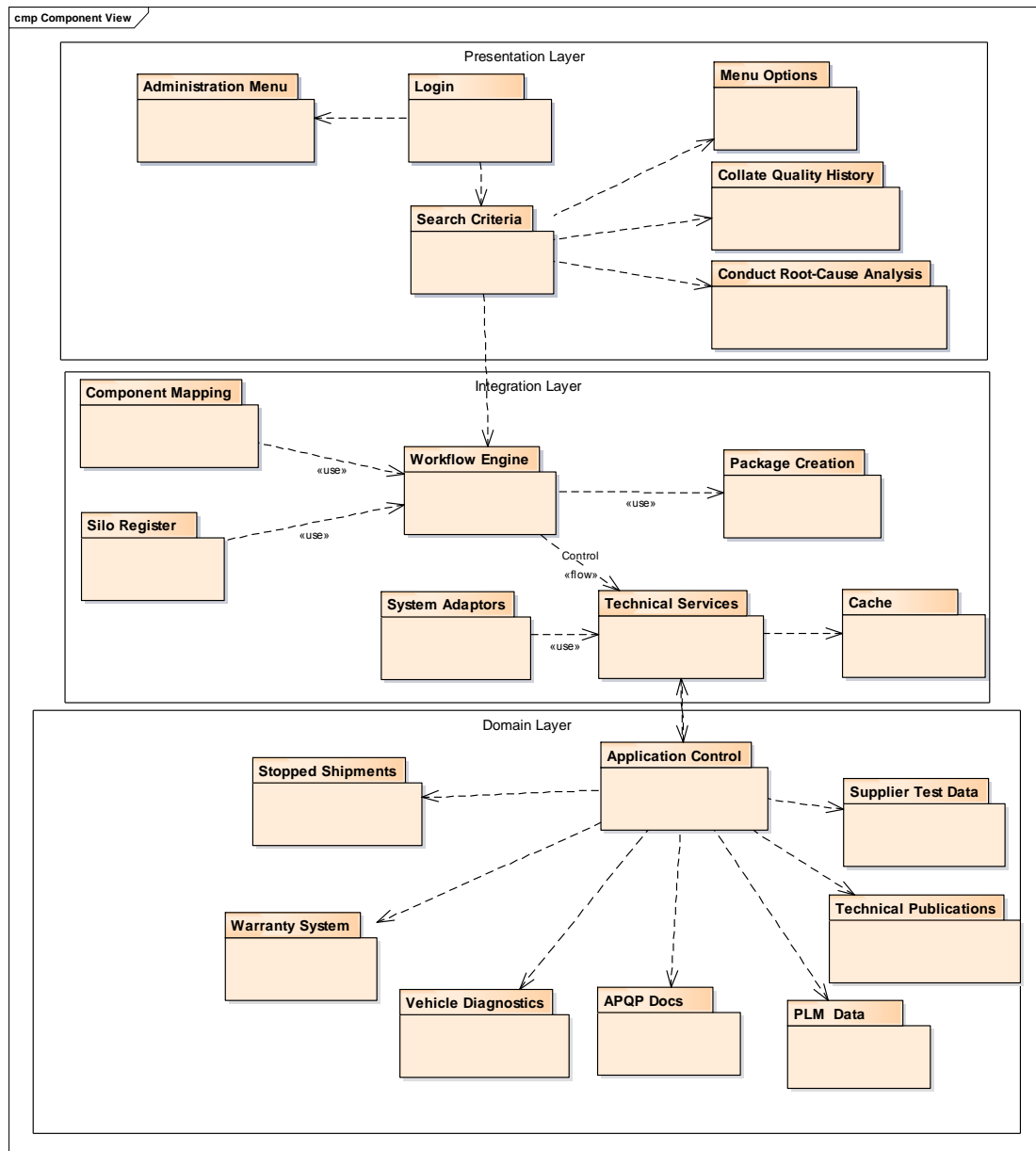
Figure 6-14 System Architecture Static View

6.4.2. Presentation Layer

The presentation layer consists of all the packages that construct the User Interface (UI) and all the controls for user input and display selection. Within the presentation layer there are seven packages that define the UI. The "menu options" package includes the different set of UI controls. Figure 6-15 shows an example of how each package could be modelled in a JAVA environment using WIN32 dialog boxes to deliver the required functionality. Developing a complete UI is considered out of scope in this research. Third party companies have developed two UI (desktop and immersive environment) based on the aggregated data. Scenarios that demonstrate example UI outcome are discussed in chapter 7.
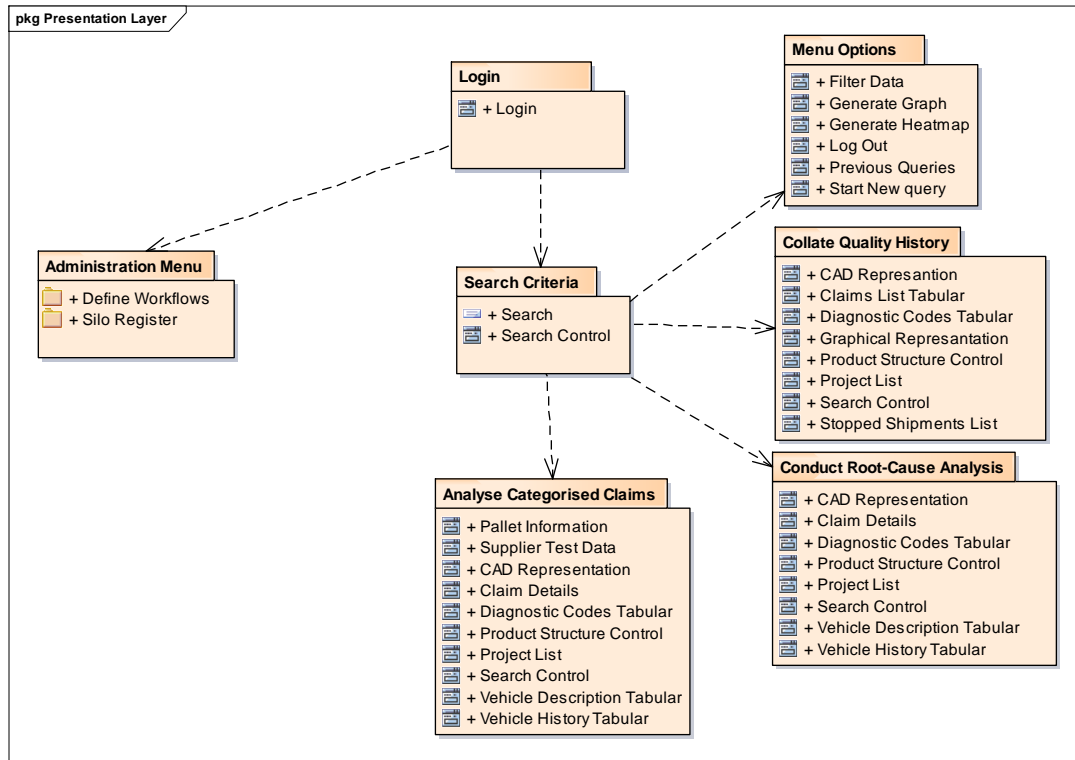
Figure 6-15 Presentation Layer

1. Login: The login package represents a common login interface that requests the user to provide a username and a password in order to access the system.

2. Search Criteria: This component represents the input to the system where the end user will define the search criteria. The search could either be a VIN number, a part number and a sub-assembly code. The input to the search element could be either through the use of a keyboard or through QR code scanned from a portable device.

3. Menu Options: This package includes the different set of UI controls. This set of options allow the users to navigate easily through the different functions of the system.

4. Use Case Views (Analyse categorised claims, Conduct root cause analysis, Collate quality history): Each one of the three packages represents a UI that needs to be designed to support each use case. Although each package utilise common elements there needs to be a separation of each use case to allow the users to view large amount of data in the most effective manner.

5. Administrator Menu is a package that includes the UI and the controls that administrators requires in order to define the workflow for each use case as well as register a new silo. In this instance all the administration options are controlled within Sharepoint 2010 environment.

6.4.3. Integration Layer

The integration layer can be characterised as the "glue" between the domain and the presentation layer (Figure 6-16). The integration layer is used to enable and manage the communication among different systems. The purpose of the integration layer is to automate the business processes involved and provide a unified access to information spread across discrete silos of information. The integration layer utilises web services to communicate and extract data from the domain layer. Kim et al. (2010) highlights that web services are platform independent and allow data to be easily passed through firewalls. As it was identified in the literature review, a service-oriented integration layer allows companies to access the system through heterogeneous IT infrastructures. The application exposes some of its functionality as a service without revealing any implementation details to the outside world (Trowbridge et al., 2003). Service interfaces are developed using XML Web services. The aggregator used for the POC system was developed on a Sharepoint 2010 platform by Theorem Solutions.
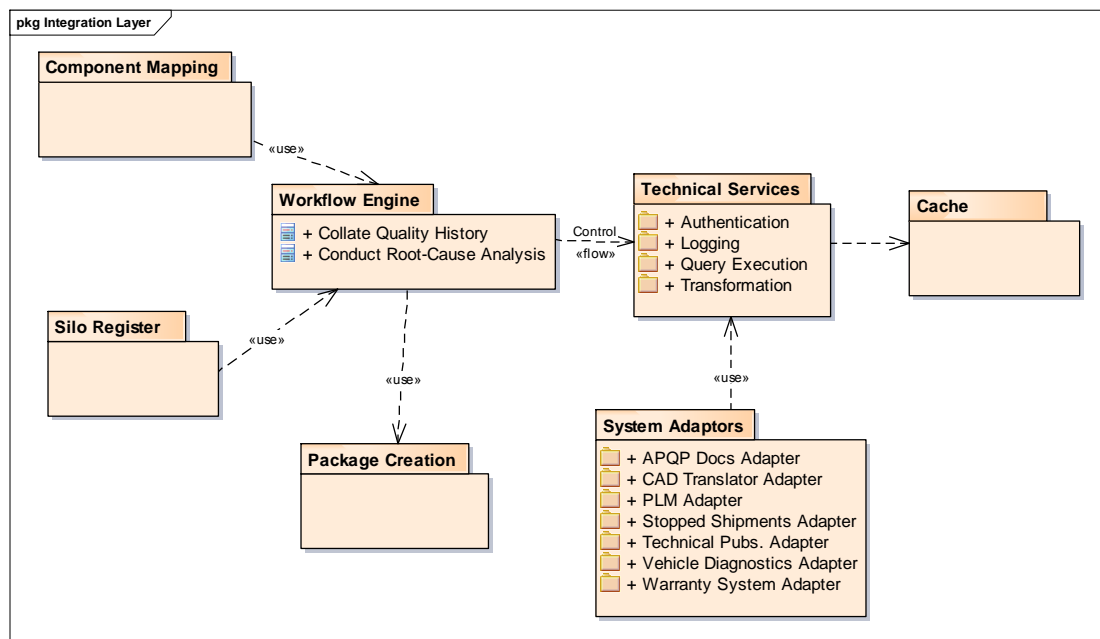
Figure 6-16 Integration Layer

1. *Workflow Engine:* The workflow engine holds the logic behind the system as it is responsible for defining the sequence of tasks required to perform a use case. The search criteria and the login credentials determine the most appropriate workflow for the user. The workflow engine is responsible for executing the sequence of tasks required to satisfy each one of the three main use cases defined. For delivering the

expected functionality, three workflows need to be developed to support the use cases discussed in section 4.3.2.

2. Silo Register is a database that provides an input to the workflow engine with all the available and registered silos. In case there is a need to add a new silo, the administrator is responsible for defining the required information and registering the "new" silo.

3. Component Mapping which can either be provided as a service or linked as a database specifies the relationships among different primary keys and provides an input to the workflow engine. The purpose of this element is to provide a clear definition of each primary key used within the systems integrated and to specify the relationships among the different data sets used. For example, for one of the use cases analysed, the component mapping enables the primary key that defines a claim to be related to the relevant engineering part number and then to the associated diagnostics extracted from the sensors. In addition, the component mapping can be defined to allow a OEMs engineering part number to be linked with the supplier's engineering part number. The component mapping is specific to each company and needs to be customised during the implementation of the system.

4. Technical Services: Technical services are responsible for a variety of tasks. Most importantly they are responsible for analysing, decomposing and executing the queries in order to retrieve data from the domain layer. The system utilises a web service called "GetContent" which was developed by Theorem solutions. Essentially whenever a user hits the search button the system makes a call through the technical services to extract the appropriate files. A web service is defined by the WSDL file. The WSDL describes the web service that runs an exposed method available - QUERY, GETCONTENT. The query for the vehicle description for example is constructed as:

```
SELECT `Issue Id`, `VIN`, `Production Date`, `CTRY Sold`, `Status`, `Mileage`, `Part number (causal)` FROM warranty_system.claims WHERE `VIN` LIKE '%test%';
```

The aggregator processes the results in order to save the file and then write information to the screen. The function returned from the web service is an XML file (created from a C# DataSet object). If a non-XML file was requested the binary information of the file is packaged within an XML file and returned.

Translation services are also enabled whenever required from the technical services and are responsible for translating CAD files from their native source to a light-weight visualisation format. For the proposed architecture, JT (ISO 14306:2012) was chosen as it is probably one of the most widely used visualisation formats. Whenever the

searched CAD model is not available in a JT format within the PLM system, the workflow engine initiates a translation service to convert a native CAD format into JT. Finally, technical services are responsible for maintaining and passing the login credential through the web service to enable the right security rights for each user.

5. *System Adapters* provide an input to the Technical services and are used as a bridge between the technical services and the API provided from each system. Due to the lack of integration capability and standardisation from the maintenance system involved in the automotive sector, system adapters are proposed to avoid the development of direct API calls that restrict the generality of the system. System adapters reduce the amount of effort required, when the system is implemented in a different domain. However connecting to a new warranty system would still require some effort to customise the service depending on the API provided from the application. For enterprise systems such as PLM and ERP systems there are adapters already available from each PLM and ERP vendor.

6. *Cache:* Once the workflow is completed, data retrieved are cached to allow the manipulation of data from the presentation layer. A cache option was implemented to improve the performance of the visualisation engine and to reduce the performance impact that a continuous query response process might have to the systems integrated.

7. *Package Creation:* Allows the user to compress the data obtained into a single object which can then be accessed either from a different visualisation platform or from a different company such as a suppliers and OEMs. The package creation element satisfies the "exchange information across the supply chain" requirement.

6.4.4. Domain Layer

The domain layer represents the business rules and the actual systems that will be used to extract data. It is critical that the domain layer to be designed in isolation so it cannot be affected by the technology used. In order to achieve the level of integration required, system APIs are utilised to allow the communication among the layers and as a result the exchange of information.

Figure 6-17 shows the domain layer and can be divided in two core sections: the application layer and the business layer. i) The application layer is responsible for translating messages (queries, login credentials) back and forth between the aggregator and the domain layer. Some software developers prefer to model the application layer separately while others choose to include it within the domain layer. ii) The business layer shows the relationships among the different packages that are

held within multiple silos. More importantly, it shows the types of data that the service needs to expose to the end users. These data sets are available from extraction from the service and can be served up to the end user whenever the right UI menu selection is applied. Any data manipulation such as the creation of Pareto charts will be handled either from the integration layer or the presentation layer once the data are cached within the aggregator. Definitions for each one of the packages described within the domain layer can be found on the system actors in section 6.3.1.
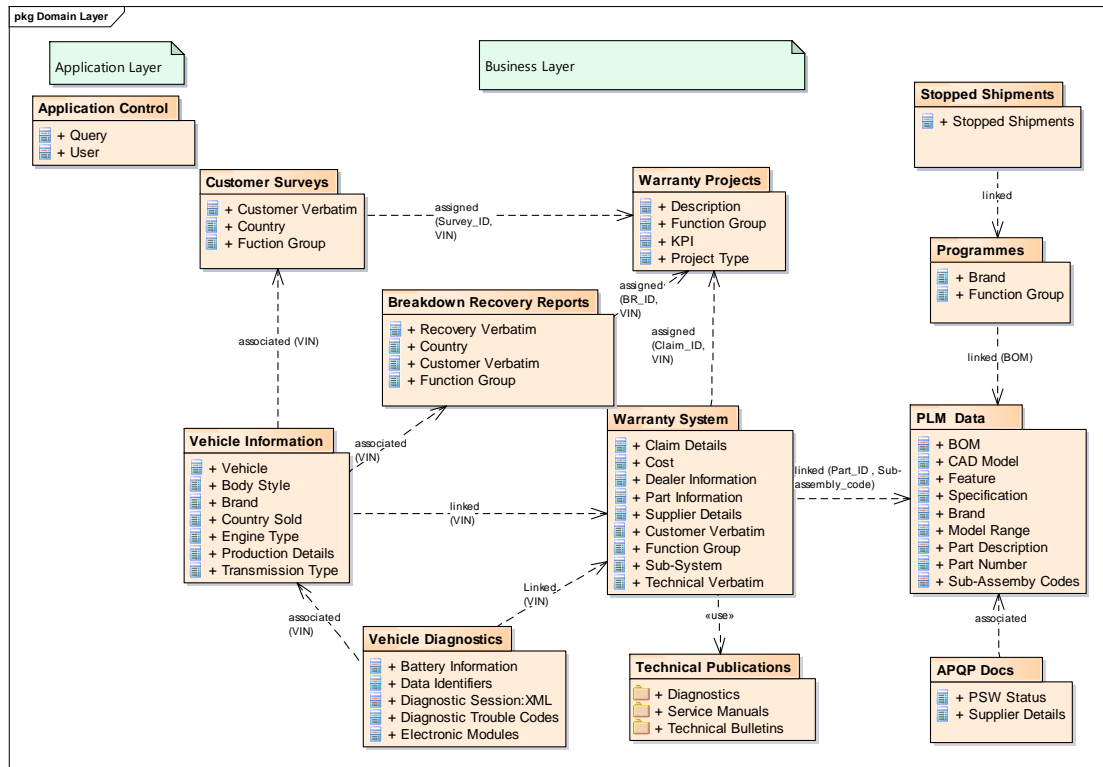
Figure 6-17 Domain Layer

Each application integrated from the aggregator has a different set of primary keys that can cause lack of communication among the different systems used. Therefore the logic within the class diagram shown in Figure 6-18 must be implemented within the component mapping service to specify the links among the different clusters of data. For the "conduct root cause analysis" use case, a warranty claim can be used to map the multiple components across the different systems. A warranty claim consists of a part_ID that can be used to link to the BOM structure and the CAD models within the PLM system as well as the vehicle programmes and the APQP documentation. A VIN in relation to a claim_ID can be used from the system to extract vehicle diagnostics, technical publications, breakdown recovery reports and surveys.
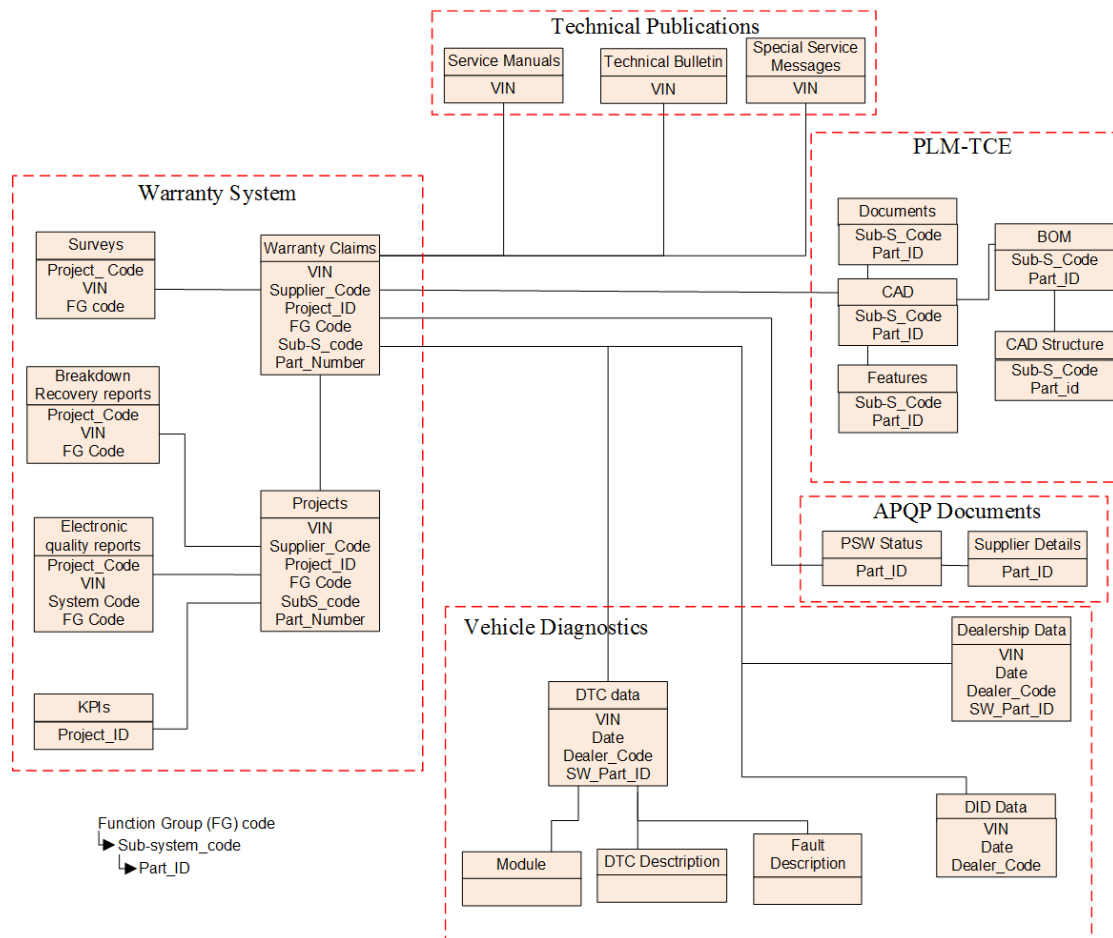
Figure 6-18 Data Relationship Diagram

6.5. UML Modelling – Dynamic View

The main goal of the dynamic analysis is to model the dynamic behaviour of the system over time. Moreover dynamic diagrams allow designers to verify the completeness and consistency of use cases (Cui et al., 2008). Sequence and activity diagrams are widely used to model the dynamic view.

In the two sequence diagrams presented in the "use case" view in Figure 6-9 and Figure 6-10, the proposed system appeared as a "black box". These two diagrams showed that a search term provides an input to the proposed system which then utilises the search terms to extract the required data from all the systems integrated. Figure 6-19 shows the sequence of tasks and the messages exchanged within the proposed system once a search term is received from the user and until the results are presented back to the user. Once the user logs in the system and defines the search criteria, the logic credentials and the search terms are passed to the workflow engine. The workflow engine will receive an input from the silo register to obtain the silo information. The workflow engine based on the search criteria and the login

credentials chooses the most appropriate workflow. Therefore the quality history for DFMEA and the root cause analysis will follow different sequence of tasks within the system. The workflow engine obtains an input from the component mapping database with the correct primary keys which is used to identify the relationships between the search criteria and the primary keys within each system. If additional information required, for example for the vehicle diagnostics database there might be a requirement to define a period of dates to reduce the number of results, then the user is asked to fill additional search criteria. Otherwise the workflow engine controls the technical services and executes the queries to the systems.
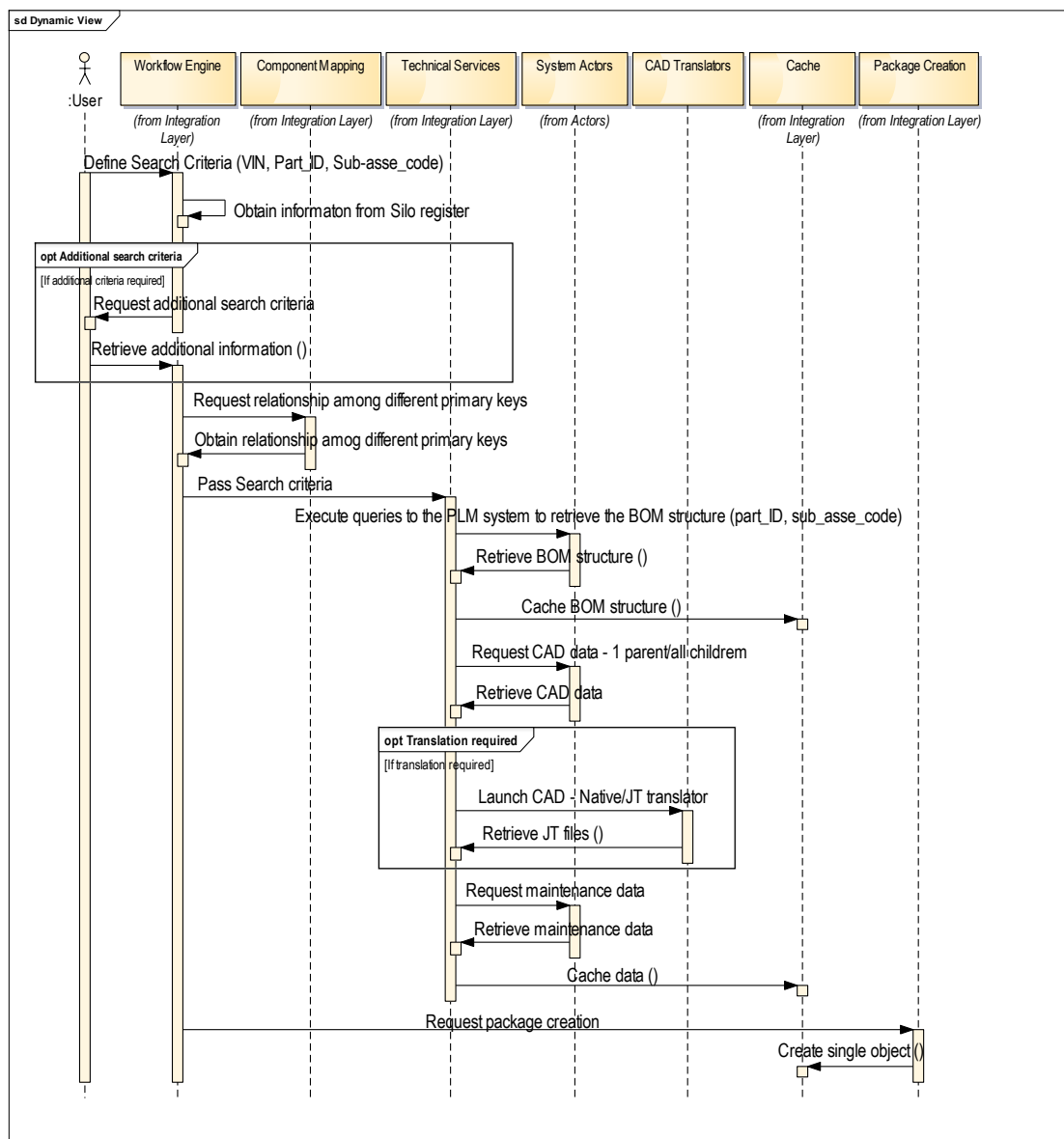
Figure 6-19 System Architecture Dynamic View

The system initially requests the product structure from the PLM system which is returned in an XML format based on the part_ID and the sub_assembly_code

defined within the search terms or extracted from the component mapping. Once the product structure is decomposed based on one parent an all children the workflow engine requests through the technical services the extraction of all the data associated with the product structure and the other search terms (e.g. VIN). CAD models returned to the aggregator are translated into a JT format while all the other meta-data remain in an XML format. All the data are cached against a query number. In addition the workflow engine was predefined to create a single object with all the extracted information which can be used for future reference or shared among suppliers and OEMs.

6.6. Chapter Summary

This chapter showed the requirements analysis and the modelling approaches followed to design a novel system architecture for integrating PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise cross supply chain data in a single environment across the supply chain. Requirements gathered from multiple OEM and supplier stakeholders were analysed, grouped and prioritised prior to the design of the system. A SysML requirements diagram was created to analyse and visualise the dependencies between non-functional and functional requirements as well as create new requirements based on derivation. The outcome of the requirements analysis showed **what** the engineers require from the proposed system. It showed that engineers need to be able to search, view and share multiple data across the supply chain. The subset of the data silos identified cover a continuum of data types, from complex PLM systems through electronic technical publications to vehicle diagnostics and warranty systems. The requirements captured were then used to model the functionality using UML use case and sequence diagrams. The use case diagram captured six use cases, three of which were developed to support the processes presented in Chapter 5. The "conduct root cause analysis" use case showed that the proposed architecture offers warranty engineers the functionality to search via a VIN and through the selection of a claim, all the information required to assess a returned part will be obtained. The "analyse categorise claims" use case extends the functionality described above as it allows OEM warranty engineers to re-use data and ensure that the root cause analysis followed by the supplier warranty engineers meets the expected criteria. Finally, the "collate quality history" use case supports PD engineers in extracting the quality history required to run a robust DFMEA and as a result prevent recurring faults.

Furthermore, in this chapter multiple views of the proposed system architecture were presented to demonstrate **<u>how</u>** the functionality is delivered to the end-users. The high-level architecture was decomposed into three layers (presentation, integration, and domain). Each layer was defined and decomposed further into packages to demonstrate the static view of the system architecture. Each one of the layers presented in the system architecture is autonomous and can be implemented as a physically separate component. This aspect is important as it allows the re-usability and agility of the whole system. Furthermore, the static view was used as a baseline for the dynamic view that shows the dynamic behaviour of the system over time. The sequences of tasks, the messages exchanged and the process followed within the system were described through the dynamic view. Chapter 7 demonstrates how the proposed architecture is used to support warranty and PD engineers to improve root cause analysis through the use of specific example scenarios.

Demonstrating the Proposed System Architecture Using User Scenarios

The purpose of this chapter is to describe three user scenarios in order to demonstrate how the proposed system architecture could be used to deliver the UML use cases discussed in chapter 6. Three scenarios were captured, one for each key use case. The scenarios demonstrate the flow of the system by examining all the steps followed, starting with the search criteria defined by the user, the interactions with the system throughout the root cause analysis, the example data presented in the User Interface, and finally the outcome of the root cause analysis. Data used in the scenarios are for illustration purposes only and do not necessarily represent real vehicle faults.
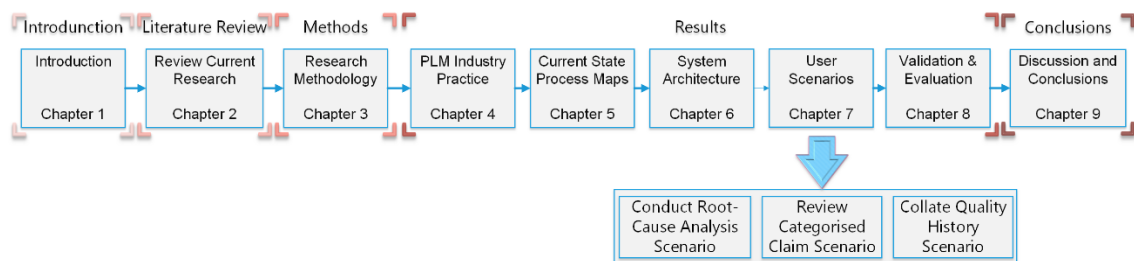
7.1. Introduction

This chapter presents three scenarios that demonstrate how the proposed system architecture supports the root cause analysis by allowing engineers to visualise data in a single environment across the supply chain. The first scenario is based on the "conduct root cause analysis" use case and as an extent to the ID.5 process step of the current state process maps. This scenario demonstrates how a supply chain engineer utilises data extracted from the OEM's domain to conduct a root cause analysis and document the outcome against one of the three types of faults (Type1-

Supplier's liability, Type2-OEM's liability or Type3-NTF). The second scenario is based on the "analyse categorised claims" use case and as an extent to the ID.7 process step of the current state maps. This scenario demonstrates how OEM engineers can use the system to assess the decision that supply chain engineers made, review the test criteria that suppliers followed as well as ensure that dealers had enough information to make a repair. The third scenario describes how the system can support PD engineers to collect the quality history required prior to run an FMEA. This scenario is based on the "collect quality history" use case and as an extent to the "Quality history for DFMEA" process map.

Considering that this research is part of larger project called VE-DRIVE, aspects of the scenarios explained were tested using the POC system. As this system was developed to test the system architecture and its applicability, it was limited in terms of data and systems integrated. Therefore, it was deemed inevitable to fully test the scenarios using the POC system. Therefore, scenarios will be explained using a combination of screen shots captured from the POC system developed by Theorem Solutions and Holovis International and example raw data. Data presented in a form of table show the raw data as they are structured within each database. All data were modified to protect company's anonymity and confidentiality. Figures used in this chapter are used for illustration purposes only and are not tightly linked with real vehicle faults. What these scenarios aim to achieve is to demonstrate that by integrating product-data from PLM systems with warranty claims, vehicle diagnostics and technical publications, engineers were able to improve the root cause analysis and close the information gaps.

7.2. Scenario 1: Conduct Root Cause Analysis

Scenario one is triggered when a pallet is ready for assessment in the warranty centre. Pallets consist of parts returned from dealers and are associated with each supplier. Therefore parts are separated based on supplier's responsibility rather than commonality of parts. Once a pallet is available in the warranty centre, suppliers will be notified via an e-mail that they have a certain period of time to assess the parts. Supplier warranty engineers start the process by opening the pallet recording system to review each claim associated with the reviewed pallet.

1. Supplier warranty engineer opens the Pallet recording system to review the pallet information. Table 7-1 shows an example of the information that suppliers are looking for. Supplier warranty engineers choose to assess the first claim in the table, highlighted in red.

Table 7-1 Pallet information as Extracted from the Pallet information System

Pallet ID	Part ID	Part Description	Mileage	Vehicle Identification Number	Month of Warranty	Repair Date	Technician Comment	Customer Comment
ADERF	AF3221321DS	regulator-wi	2132	TESTA4323910	36	4/5/13	Faulty driver's window regulator verified customer concern. Replaced faulty window regulator and verified repair	Please assess window. It doesn't operate properly and has a scratching nise. We have lubricated the part once
ADERF	AF3221321DS	regulator-wi	827	TESTA4323982	33	6/5/13	Tested and confirmed customer concern, replaced windows regulator/motor and tested OK	Window bouncing back open when trying to close
ADERF	AF3221321DS	regulator-wi	1124	TESTA4328813	21	6/5/13	Window squeaking - confirmed fault and replaced regulator and tested - now ok	Window squeaking

2. Supplier warranty engineer logs into the system using their username and password. The system uses the username and password to decide to workflow and recognise the appropriate access rights to each individual system. The system verifies the password and visualises the search box. Figure 7-1 shows in red the search box as captured from the POC system.
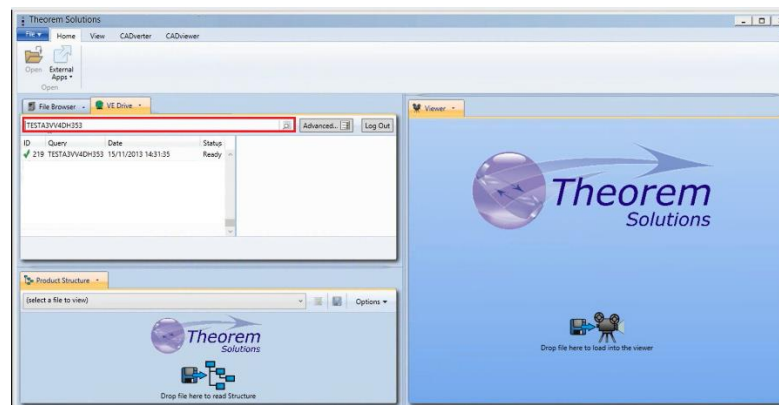
Figure 7-1 Search box (Screen Shot Captured from Desktop UI Developed by Theorem Solutions)

3. Supplier warranty engineer searches the system using the VIN number in order to extract the vehicle's description and the vehicle's history. Input to the proposed system: "TESTA4323910". The system extracts the data from the domain layer utilising the web services as discussed in chapter 6. The system presents a generic visual representation of the vehicle, defined from the brand name and the model type, and allows the user to colour code the vehicle representation based on different criteria such as areas where previous claims occurred for the searched VIN, cost of claims etc. Figure 7-2 shows a visual representation of a vehicle as extracted from the POC system.

Figure 7-2 Highlighted Vehicle Based on Claims Cost (Screen Shot Captured from immersive environment UI Developed by Holovis International)

The system also presents a vehicle description of the searched VIN. The vehicle description is extracted from the warranty system using the VIN search criteria. Table 7-2 shows in a raw format, the information required to represent the vehicle's description.

Table 7-2 Scenario 1: Vehicle's Description

VIN	Engine serial Number	Production Month	Plant	Warranty Start	Year	Body Style	Transmission	Engine
TESTA4323910	3289381287T	5/2011	UK	1/8/11	2011	5 Door	6 AUTO	5.0L V8

The system also presents the vehicle's history such as claims, surveys and breakdown recovery reports associated with the searched VIN. Vehicle history is extracted from the warranty system. Vehicle history includes not only the claim that supplier warranty engineers are reviewing but also any previous faults, surveys or breakdown reports that are linked with this specific vehicle. Table 7-3 shows an example of the data required to build the vehicle's history using example data in raw format. The supplier warranty engineer reviews the vehicle's history to understand what the customer complained about, what the technician did to fix the issue and the conditions that the vehicle was operating (miles, country etc.). Moreover, supplier warranty engineers are trying to understand any relationships among previous faults. In this example the same fault occurred twice as shown in Table 7-3. The first time the dealer followed the technical bulletin provided by the OEM to fix the issue. However a few months later the same fault was identified again. Therefore the second time the dealer decided to replace the part to ensure customer satisfaction.

Table 7-3 Scenario 1: Vehicle's History

Category	Customer Comment	Technician Comment	Condition	Mileage	Part Number	Part Description	Sub-Assembly Code	Sub-Assembly Description	Date Captured	Country Repaired	Repair Dealer	Total Cost (£)
Claim	Please assess window. It doesn't operate properly and has a scratching noise. We have lubricated the part once	Faulty driver's window regulator, verified customer concern. Replaced faulty window regulator and verified repair.	Does not operate properly	47321	AF3221 321DS	Window Regulator	321312	Window Mechanisms	04/05/2013	UK	London Dealer	£110
Claim	Please assess window. It doesn't operate properly and has a scratching noise.	Investigated customer concern. Check tech. bulletins & referred to noJ3312. Removed window regulator and greased internal pulleys. Rebuilt and confirmed as being ok & quite	Does not operate properly	43509	AF3221 321DS	Window Regulator	321312	Window Mechanisms	01/02/2013	UK	London Dealer	£75
Survey	Have difficulty inserting a medium or larger plastic or paper cup into holder, also experience difficulties				DF2331 2342ST	Cockpit function	764853	Interior Trim	03/10/2011	UK		

4. The supplier warranty engineer selects a claim to review. The claim selection initiates a new search to the workflow engine utilising the causal part number and the sub-assembly code included in the claim. In this instance, the part_ID called AF3221321DS and the sub-assembly code 321312 are utilised from the proposed system extract the CAD sub-assembly and all the associated data. The system filters the vehicle history and presents only the information related to the claim selected. The system presents a light-version CAD representation in a JT format with an option to extract documentation associated with the part. CAD data are extracted from the PLM system using the web service defined by utilising the part_ID and the sub-assembly code. Any additional documentation can be made available once selected from the main menu. Figure 7-3 shows a representation of a window regulator.

Figure 7-3 Window Regulator Assembly Representation

The system presents the PSW status. The PSW status is extracted from the APQP Docs system. The system utilises the part number and the programme name to extract the correct data. Supplier warranty engineers needs to ensure that a PSW document is in place for this specific part or sub-assembly. Table 7-4 shows the raw data that warranty engineers need to review in this process step.

Table 7-4 PSW Status

Part Description	PSW Status	PSW Signed Date	Supplier Code	Supplier Name
Window Regulator	Complete	3/6/2009	S23123	Supplier X

5. The supplier warranty engineer selects to review vehicle diagnostics from the menu. Figure 7-4 shows a screenshot from the menu selection created within the immersive environment UI. DTCs are extracted using the VIN number and the date that the claim was captured in the warranty system. The system can be customised to extract all diagnostics related to the searched VIN that range from the date that the claim was recorded minus seven days. Stakeholders identified that in most cases dealers would record a claim in the warranty system a few days after the vehicle was plugged in to extract diagnostics. However it is rare that the amount of days will exceed a week.

Figure 7-4 User Selects Vehicle Diagnostics (Screen Shot Captured from Immersive Environment UI Developed by Holovis International)

6. The supplier warranty engineer tests the part to replicate the fault and verifies customer's concern.

7. Supplier warranty engineer selects to open the technical publications system to review if the dealer had enough information to make a repair. The same menu option is used to select the appropriate option. The system will open the technical publications system on the appropriate web page using a web browser as shown in Figure 7-5. The system utilises the VIN search criteria to construct the correct URL address. The reason for opening the system instead of extracting the data are explained in Chapter 8 where the system architecture is validated. The supplier warranty engineer searches the tech. pubs system using

the bulletin_ID,J3312 in this example and identifies the bulletin that the dealer followed. The supplier warranty engineer reviews the documentation provided in the tech pubs system. The workshop manual suggests dealers to apply a lubrication gel in the main axial of the pulley between the rail, the pulley bracket and the pulley. However supplier's previous tests proved that gel lubrication can obstruct the pulley and therefore for new vehicles they suggested that a lubrication spray should be used. The root cause of that claim was identified as the wrong instructions provided to the dealer. The part was mistakenly replaced as it can still operate within the acceptance criteria after properly being lubricated.
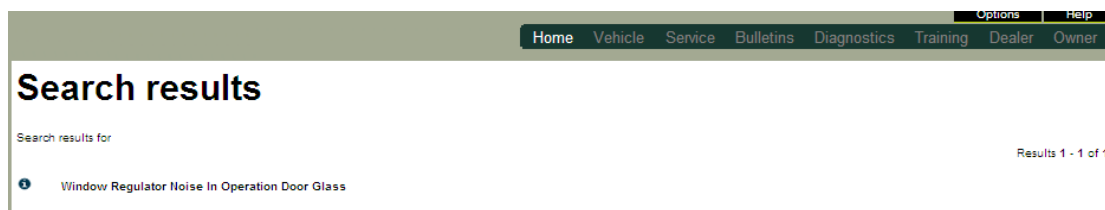
Figure 7-5 Tech Pubs. VIN Search

8. The fault is categorised as a Type2 fault (OEM's liability) as the documentation provided to the dealer was not up to date. The supplier warranty engineer records an action and triggers the process for updating the documentation within the tech. pubs system. The root cause is communicated with the service supplier responsible for updating the documentation and the OEM warranty engineers.

9. The user initiates a new search to review the next part. The system packages the information in a single document. Data are available for a pre-defined period of time.

7.3. Scenario 2: Analyse Categorised Claims

The second scenario examines the "analyse categorised claims" use case which aims to support OEM warranty engineers to analyse a categorised claim in order to ensure that suppliers followed the appropriate testing criteria as well as ensure that dealers had enough information to make a repair. OEMs warranty engineers focus mainly on Type 3-NTF claims which represent faults that supplier warranty engineers could not replicate in a testing environment. This scenario explains how OEM warranty engineers could utilise the functionality of the system to standardise and improve the current process. The analysis of categorised claims allows OEM and supplier engineers to work collaboratively by improving the testing equipment, ensuring the dealers have the appropriate information to make a repair and as a

result ensure customer satisfaction. This scenario is triggered when an OEM warranty engineer identifies a repetition of Type-NTF claims for the same part.

The example scenario in this instance is related to a mirror sub-assembly which was replaced on a few occasions by dealers. When the part was tested from supplier warranty engineers, it was identified that the part was fully functional and therefore there was no reason for replacing the part.

1. The OEM warranty engineer logs in the POC system using the username and password. The system verifies the username and password and shows the UI. The system uses the username and password to decide to workflow and recognise the appropriate access rights to each individual system.

2. The OEM warranty engineer reloads the query that the supplier warranty engineer ran in order to load the data that suppliers used and assess the part. Figure 7-6 shows the list of pre-cached queries within the desktop UI of the POC system developed.
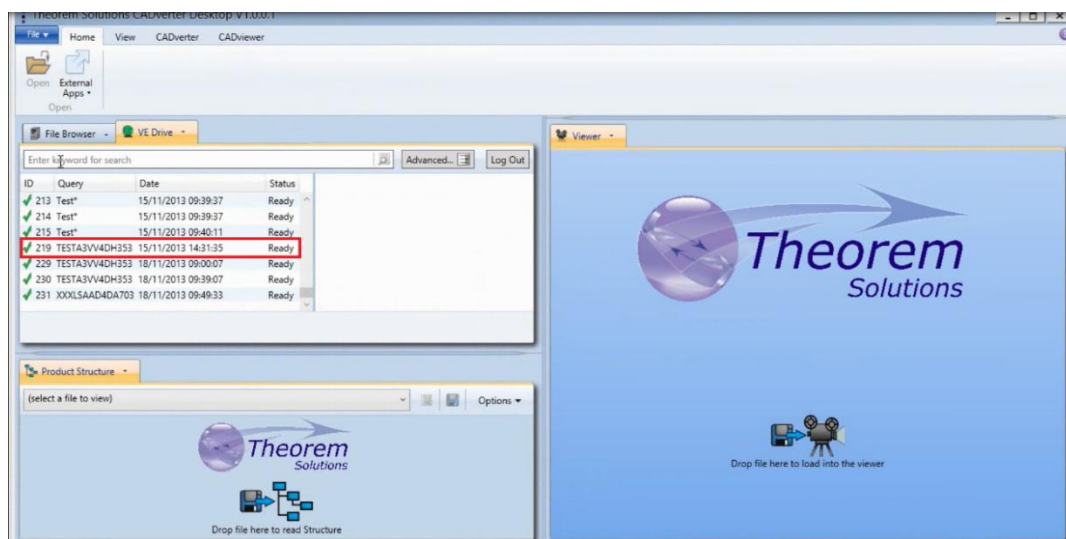
Figure 7-6 Loading a Pre-cached Query (Screen Shot Captured from Desktop UI Developed by Theorem Solutions)

The system presents a generic visual representation of the vehicle and allows the user to colour code the vehicle representation based on different criteria such as areas where previous claims occurred for the searched VIN, cost of claims etc. The system also presents a vehicle description of the search VIN similar to scenario 1. The system also presents the vehicle's history such as claims, surveys and breakdown recovery reports associated with the searched VIN. In this instance there is only one claim associated with the searched VIN. Table 7-5 shows the vehicle's history. The OEM warranty engineer reviews the

vehicle's history to understand what the customer complaint about, what the technician did to fix the issue and the conditions that the vehicle was operating (miles, country etc.). In this example, the customer complaint that the front side mirror is not folding with a key. The dealer check the customer's concern and decided to remove and replace the front mirror side.

Table 7-5 Scenario 2: Vehicle's History

Category	Customer Comment	Technician Comment	Condition	Mileage	Part Number	Part Description	Sub-Assembly Code	Sub-Assembly Description	Date Captured	Country Repaired	Repair Dealer	Total Cost (£)
Claim	Check front side view mirror not folding with remote key	Checked customer concern, found mirror internal fault cause. Removed and replaced miror	Does not operate properly	7365	DF2912 1314TX	Mirror motor electrical connector	23120	Mirror Assembly	05/01/2013	UK	Dealer F	£140

3. The OEM warranty engineer selects to review the data associated with the claim. The claim selection initiates the system to reload the associated data. The system filters the vehicle history and presents only the information for the selected claim. The system presents a light-version CAD representation in a JT format with an option to extract documentation associated with the part as show in Figure 7-7. The system also presents the PSW status which shows that there is an appropriate PSW documentation in place which ensures that suppliers will deliver the expected quality.
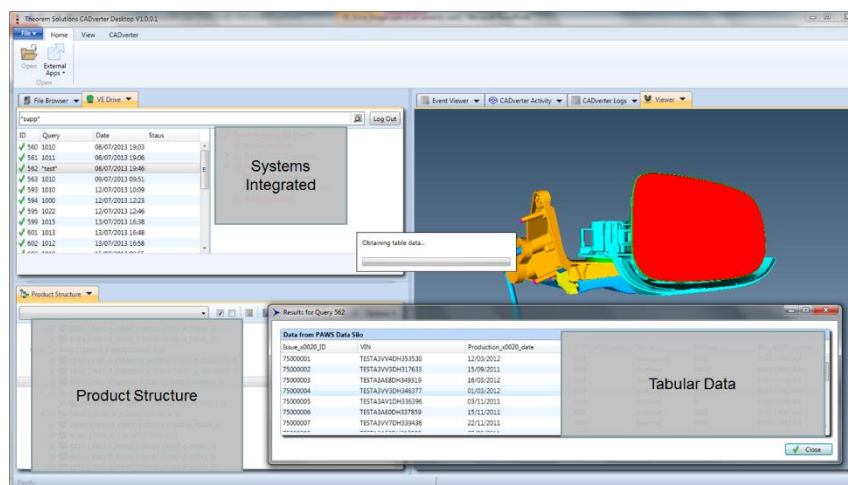
Figure 7-7 Mirror Subassembly Extracted from a PLM System (Screen Shot Captured from Desktop UI Developed from Theorem Solutions)

4. The OEM warranty engineer selects to review vehicle diagnostics from the menu as described in Scenario 1. Figure 7-8 shows how the OEM warranty engineer can obtain a list of diagnostics within the immersive environment user interface. In the example data shown on Figure 7-8, the sensors captured an issue related to the driver folding mirror. Reviewing the diagnostics the OEM warranty

engineer receives a description from the sensor that mirrors were unable to fold either due to "circuit short to battery" or due to an open electronic circuit.
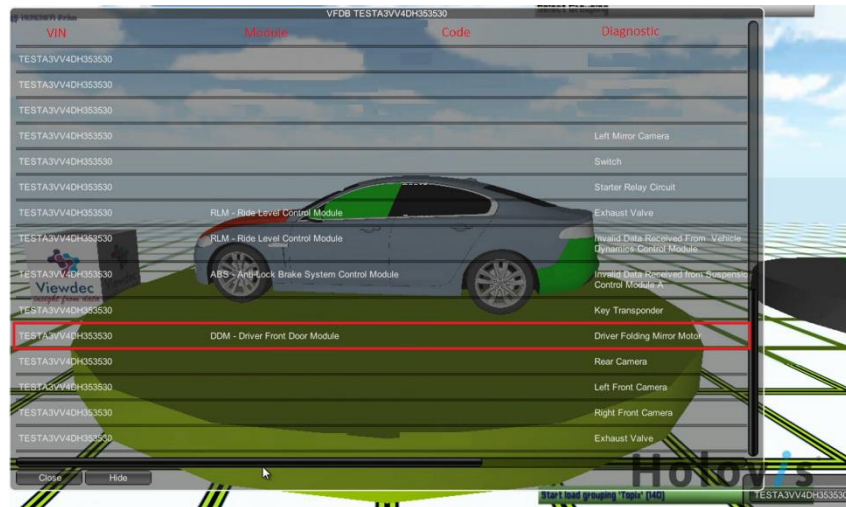
Figure 7-8 Vehicle Diagnostics (Screen Shot Captured from Immersive Environment UI Developed by Holovis International)

5. The OEM warranty engineer reviews the CAD data and the documentation associated with the part to understand the interactions among the mirror and the other sub-systems used. The OEM warranty engineer reviews the tech documentation which suggests that all bulletins are up to date.

6. The OEM warranty engineer requests from the system to review any relevant quality projects associated with the searched part. Projects are extracted from the warranty system using the sub-system examined and the association between the fault type and the project description. The OEM warranty engineer reviews the projects associated with the mirrors but currently there is no project associated with this type of fault.

7. The OEM warranty engineer has an indication that this is probably an engineering issue. The diagnostics and the CAD assessment suggest that the plug within the mirror housing backs out slightly breaking the circuit. Therefore the engineer re-categorises the fault as Type1-Supplier issue. The OEM warranty engineer records the action and passes the data to the OEM engineering team for further investigation as well to Supplier engineers. As an interim action, the OEM warranty engineer communicates the issue with the service supplier responsible for tech publications to issue a special service message to the dealers to ensure that dealers will always check the plug prior to changing the part.

8. The user logs out of the system.

7.4. Scenario 3: Collate Quality History

The third scenario examines the "collect quality history" use case which aims to support PD engineers both in the supply chain and in the OEM domain to determine the failure modes and their causes and effect which are required to run a robust DFMEA. It was highlighted from engineers that whenever a part is carried on a new vehicle, it carries not only its properties but also its history and faults. By automating the "collect quality history process", it is anticipated that tasks can be standardised across departments and suppliers and therefore the same level of granularity in terms of analytics will be followed.

This scenario was considered out of scope for the proof-of-concept system developed from the two partner companies due to its complexity and the project time restrictions. Presenting raw data in this thesis was deemed inappropriate due to confidentiality restrictions when it comes to cumulative data. However the "collect quality history" use case was stated as critical from key stakeholders and the literature as it was identified that knowledge rarely returns back to the PD engineers once the product is on-sale. Therefore, this scenario will provide insights on how the system could be used to support this specific process.

This process is triggered prior to designing a part or a sub-system for a new vehicle. The first step is to define the scope of the DFMEA analysis. In this scenario the scope is defined in a sub-system level using the mirror sub-system as an example.

1. The PD engineer logs in the POC system using the username and password. The system verifies the username and password and shows the UI. The system will use the username and password to choose the appropriate workflow and define the correct permission rights to each individual system.
2. The PD engineer defines the previous programme of interest and initiates a search using the sub-S_code. System input: "23120" (from Table 7-5). The system extracts stopped shipments data from the stopped shipments database using the programme name that the PD engineer selected. The system presents the data. The PD engineer reviews the data to identify any major design issues that obstructed the shipment of a batch.
3. The PD engineer requests claims associated with the searched sub-assembly code to review the hard failures of the sub-system occurred in the previous programme examined. Data are extracted in their raw format. This step is very

similar to the steps described in the other two scenarios. However the outcome of this search is not based on a specific VIN but across VIN numbers which are related to a specific programme. Reviewing raw data would be impossible for engineers, therefore analytics are applied on the raw data to support engineers in identifying failure modes against cost. The presentation layer will be responsible for creating a Pareto chart to demonstrate accumulatively the number of failure modes against cost. Claims can be also related against projects to demonstrate how failure modes were solved through projects. Figure 7-9 shows a graphical representation of projects against claims against KPIs developed by Holovis International. Figure 7-9 shows an example of how data could be visualised to support PD engineers in understanding warranty claims against cost and associated projects.
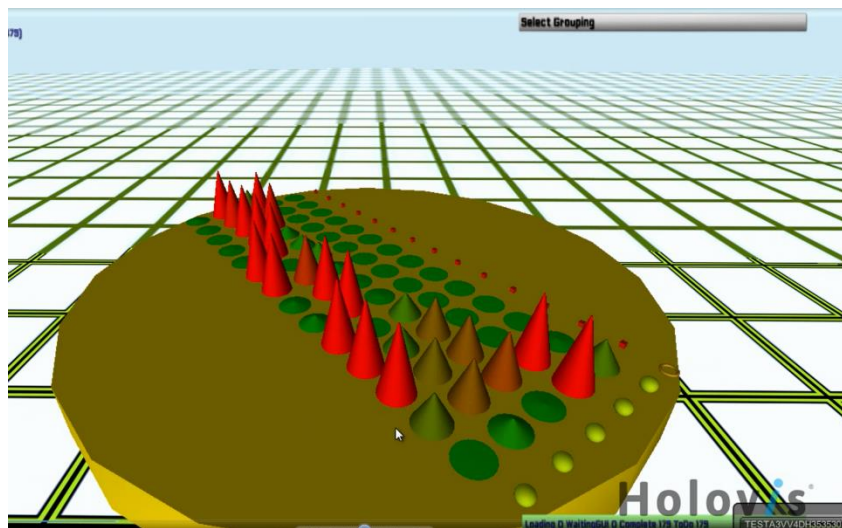
Figure 7-9 Graphical Representation of Accumulative Claims (Screen Shot Captured from immersive Environment UI Developed by Holovis International)

4. The PD engineer filters claims based on cost and the market area and generates Pareto charts based on the selected criteria. This functionality allows engineers to review claims associated with specific markets and cost to ensure that market conditions will be taken into consideration when running a robust DFMEA.

5. The PD engineers request vehicle diagnostics based on the searched programme and the sub-S_code. Vehicle diagnostics are only relevant to electronic parts and sub-systems. Similarly with the previous step, PD engineers are looking for trends and patterns of failure modes and their effects that can be captured in the DFMEA analysis. Vehicle diagnostics provide an objective insight as data provided are captured from the sensors and are not subjective to the dealer's option. Data will be extracted in their raw format and analytics will be

applied from the presentation layer similar to the previous step. Figure 7-10 shows an example of a hierarchical graph with the count number against each diagnostic trouble code. Similarly with the claims, data needs to be filtered against each market to understand market conditions.
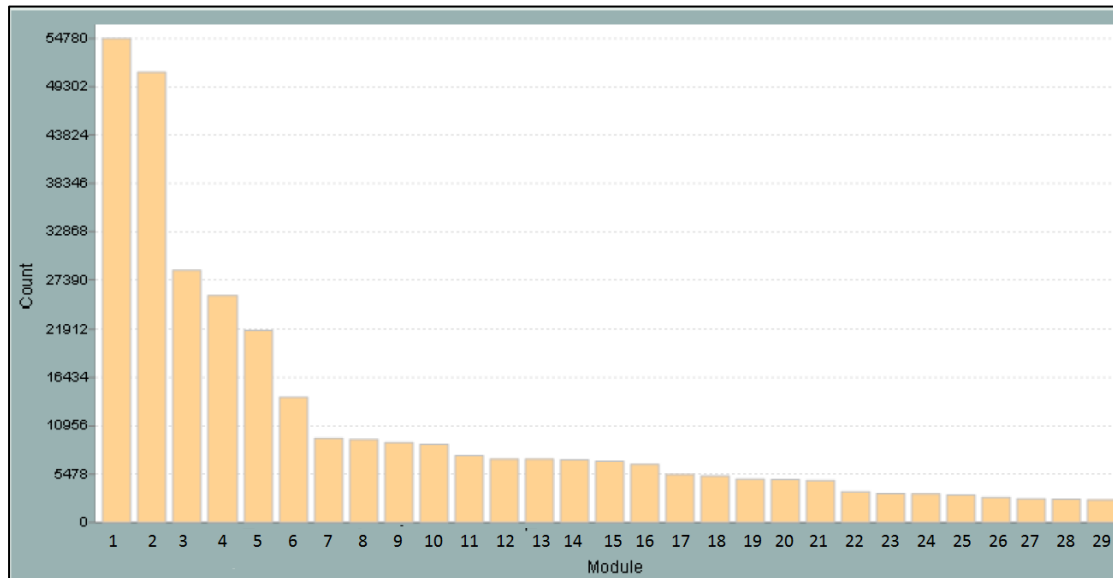
Figure 7-10 Graph Showing a Cumulative View of the Number of Different DTCs

6. The PD engineer selects the menu option to review surveys associated with the searched programme and the sub-System_code. The system presents the information extracted. Similarly with the previous steps, data are extracted in their raw format and Pareto charts are generated based on the raw data. The purpose of this analysis is to allow PD engineers to understand soft failures which represent in many cases parts that operated as intended but still did not meet customers' expected criteria.

7. The PD engineer selects from the menu option data extracted from the PLM system to review alerts and issues associated with the part as well as any documentation associated with the part. Alerts and issues are filtered based on severity prioritisation which is defined within the PLM system. Alerts and issues with severity three to five are more likely to represent issues that are linked with design issues of a part or sub-system.

8. The PD engineer reviews alerts and issues associated with the searched part/sub-system.

9. The PD engineer identifies and captures all the failure modes derived from the quality history collected.

10. The PD engineer logs out of the system. The system packages the information for future reference. Data are stored for a certain period of time. Engineers can reuse the data to support the cross-functional team meetings and justify the prioritisation selection on the DFMEA.

7.5. Discussion

Chapters 6 and 7 demonstrated a novel system architecture that was developed to support the challenges identified within the current state process maps. In addition, the development was based on the requirements captured from automotive experts and included requirements that are not currently satisfied from the existing systems or processes. UML models were used to specify the required system functionality. The system was designed based on a three layer approach that allows the re-usability and agility of the system. As a result, depending on the circumstances, this approach will enable either the technology to be improved over time or the domain layer to be expanded whenever a new requirement is identified. Regarding the functionality and the output, the proposed system architecture:

- Provides an automated way of extracting data from multiple systems, such as the PLM system, the vehicle diagnostics database and the warranty system
- Supports the root cause analysis by delivering the amount of information required, filtering out any unnecessary complexity and data
- Offers a shared environment where OEM and supplier engineers can access data in a secure and controlled way
- Allows warranty and maintenance engineers to have a view access to the PLM system
- Integrates maintenance and warranty information in the context of 3D objects and CAD data extracted from PLM Systems
- Uses the JT format to satisfy the viewing requirements of warranty engineers by allowing them to access and view product data from the PLM system without the need to have a PLM license or view high-resolution native CAD data.
- Provides visual formats to support root cause analysis as graphs and colour-coded 3D models can be developed using data such as claims, cost etc.
- Allows the visualisation layer to be extended if required to include more visual formats that represent data and their relationships
- Allows data to be visualised in different viewing platforms such as desktops, CAVEs and portable devices

- Separates the technology and the domain layers which allows the system to be extended if necessary

The proposed system architecture can be also compared to the supply chain issues related to information sharing and the use of PLM systems identified in section 4.3. The proposed system architecture supports some of the issues in the following categories by:

- *Accessibility*
  - Allowing engineers to access live data by directly querying the actual systems
  - Providing view access to users that do not require full access to PLM systems
- *IS functionality*
  - Allowing OEM engineers to control data sharing
  - Providing BOM access to suppliers if required
- *Information availability*
  - Providing access to all the required information which allows suppliers to reduce on-site(OEM) supplier resources
  - Providing access to the latest version of data as access is retrieved by real-time querying the systems
- *Implementation cost*
  - Reducing the amount of licences required for PLM systems
- *Interoperability issues*
  - Reducing the IT infrastructure required for suppliers
- *Manual systems and data entry*
  - Reducing the manual extraction of data for indirectly connected suppliers by providing a viewing system which allows suppliers to view data in a controlled way

7.6. Chapter Summary

This chapter showed three scenarios that demonstrate how the system architecture proposed could be used to deliver the functionality discussed in chapter 6 and as a result support the processes captured in chapter 5. Although each scenario was linked to a different process it can be observed that all of them aim to allow engineers to integrate data from PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise cross supply chain data in a single

environment. The first scenario demonstrated how the system can be used by suppliers to identify the root cause of a fault that came from a specific vehicle. The second scenario showed how the system is used by OEM engineers to examine faults categorised by suppliers as no-trouble found. Finally, the third scenario is more complex and demonstrates how PD engineers can extract knowledge from data in order to identify the failure modes and their effects and as a result run a robust DFMEA.

Although the scenarios showed how engineers could extract data from PLM and maintenance systems to support the root cause analysis, it is worth mentioning that currently these systems are not integrated and they operate as individual silos. Warranty engineers, especially supplier warranty engineers, have little or no access to the PLM systems and they rely heavily on PD engineers to provide the appropriate data. In many cases decisions are made without having the appropriate amount of information required. The scenarios demonstrated also that it is important not to overload engineers with information. The system should provide the required functionality that allows engineers to go through the different data sets and extract relevant knowledge.

Validating the System Architecture Using the Automotive Case Study and Evaluating its Applicability using the Defence Case Study

The purpose of this chapter is two-fold. Firstly, this chapter validates the outcome of the proposed architecture in the automotive sector through experts' opinion and secondly it evaluates the applicability of the architecture in a different industry sector (Defence). i) For the validation of the architecture, six meetings were arranged in total, three for the "conduct root cause analysis and the "analyse categorised claims" use cases, and three for the "collect quality history" use case. These meetings were held with engineers that represent the domain experts some of who are considered as potential end users of the proposed system architecture. These experts reviewed and validated how the system can support and benefit engineers during the root cause analysis. Technical elements of the architecture were validated from the two partner companies who developed a POC system based on the architecture proposed. In addition, an IT expert from the case-study company was asked to assess the solution from an IT perspective. ii) For the evaluation of the system architecture in a different industry sector a use case was captured and analysed from the defence sector.
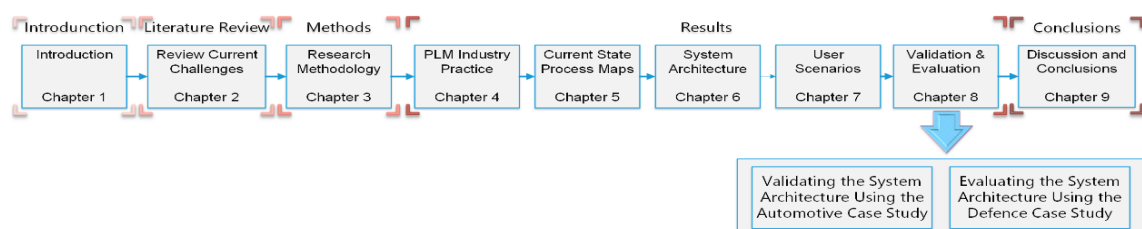
8.1. Validation of the Proposed System Architecture in the Automotive Sector

This section summarises the validation process related to each part of this thesis. An ongoing validation process with the experts responsible for each use case was followed for the current state process maps and the requirements analysis as discussed in chapter five and six. In addition, the outcome of the system architecture in terms of its support to the end users will be also validated. The purpose of this validation is to confirm that by integrating product-data from PLM systems with warranty claims, vehicle diagnostics and technical publications, engineers will be able to improve the root cause analysis and close the information gaps.

8.1.1. Requirements and Process Maps Validation

Current state process maps and requirements were validated from a group of stakeholders responsible for each one of the two use cases. The OEM warranty spend reduction leader and a Supplier Quality manager validated the outcome of the "In-service product failure identification and root cause analysis" process maps while PD team Leader and a Service team leader validated the outcome of the "Quality history for DFMEA" process maps. During each meeting, all interviewees were asked to review the requirements catalogue and validate the functionality proposed. In addition the interviewees were asked to prioritise each requirement using the MoSCow ratings. The outcome of the prioritisation process can be viewed in the SysML diagram presented in Figure 6-4. These validation meetings were held prior to the development of the proposed architecture as the outcome of the validation fed into the development of the system architecture.

8.1.2. Validation Interviews

The outcome of the system architecture in terms of its support to the end users was validated once the system architecture was completed. Two experts from the OEM case study company and one expert from a Tier-1 supplier participated in three individual meetings that were arranged to validate the outcome of the "conduct root cause analysis" and "analyse categorised claims" use cases. All the people interviewed are considered experts in their field as they are highly experienced in maintenance and root cause analysis procedures. The years of experience presented on table 8.1 are related to the number of years that the experts spent in this specific area rather than their overall working experience. For the "collect quality history" use case three experts were chosen from the OEM case study company to validate the outcome of the proposed system architecture. All the experts interviewed

are members of the cross-functional teams that conduct FMEA analysis. In addition, they are responsible for training PD engineers on FMEA analysis. Therefore they have a very good understanding of the challenges that engineers experience as well as the improvements required. Table 8-1 summarises the experts' job roles and their years of experience. Details of the methodology followed in order to validate the system architecture can be found in section 3.2.4.2.

Table 8-1 Validation Interview Details

Name	Job Role	Experience
"Conduct Root Cause Analysis" and "Analyse Categorised Claims" Use Cases		
Expert 1	Warranty Spend reduction Leader	25 years
Expert 2	Senior Quality Manager	15 years
Expert 3	Supplier Quality Manager	28 years
"Collate Quality History" Use Case		
Expert 4	PD Team Leader – Powertrain	18 years
Expert 5	PD Team Leader – Chassis	22 years
Expert 6	Service Team Leader	41 years

8.1.3. Validation Outcome of the System Architecture

All experts validated the research outcome and provided feedback on how the system architecture could be improved. All experts agreed that the system architecture integrates the right amount of information required to conduct root cause analysis and collate the quality history for DFMEA. Moreover, experts identified areas where the system could be improved in terms of information and functionality provided. The "outcome" column in each table summarises the recommendations that experts identified. Some modifications were made in the system architecture to adopt the recommendations such as, changing the interface to the tech. pubs system and restricting the functionality of APQP docs. However some ideas were considered out of scope mainly due to time restrictions. For example, aggregating internet data was recognised as very beneficial for the "collect quality history" use case but very difficult to implement in the time remaining. Therefore these requirements were captured in the requirements catalogue as a "would like to have" and can be considered during future phases of the development. Both the warranty and the PD experts requested to test the POC system and stated that there were not aware of anything similar being developed within their organisation. The details of the validation outcome are presented in Table 8-2 and 8-3.

Table 8-2 Results from "Conduct Root Cause Analysis" and "Analyse Categorised Claims" Use Cases Validation

Question	Warranty Spend Reduction Leader	Senior Quality Manager	Supplier Warranty Engineer	Outcome
Do you agree with the information being aggregated from the proposed system?	Yes definitely. *Tech pubs is a complex system and very difficult to automate. I would prefer if the proposed system opens the tech pubs for us based on the searched VIN and then we can search for the appropriate documentation. **PSW status is a low priority. Therefore the proposed system should only extract the PSW status, nothing more from the APQP docs	Yes. These are the right information for assessing a part	Yes with one more dataset to be included.	*Tech pubs was modified in the system architecture to open the tech pubs system instead of extracting the data ** APQP docs was modified in the architecture to include only the PSW status
Is there anything not covered by the proposed system, in terms of information or functionality?	No. I think that's right Diagnostics are important for electronic parts, not trim parts.	These datasets are correct for this specific process. However I would like to see how the system works when analysing collectively data per part, not per VIN.	*I would like to add our test data on your requirements catalogue. It would be useful for suppliers to have live access to the test data when analysing a claim. Currently we request test data from our factories. Test data are received in excel spreadsheets usually attached on an e-mail.	*Supplier test data were captured in the use case diagram. However, test data were not provided to allow testing the functionality.
How does currently the integration of PLM systems occur?	I have access to the PLM system but I am the only one from my team. Currently product data are not always used in the assessment of the part. I find it useful that the proposed system shows the part in relation to the sub-assembly. Maybe it's worth expanding to include surrounding sub-assemblies not only with the parent.	Very little	We don't have access to the PLM system and even if we did, we don't know how to use it. Therefore we rely on PD engineers to extract the data for us. Currently this is a very manual process. Great idea to represent a part against the sub-assembly. Sometimes you receive a small part and you have no idea where it came from.	

What are the anticipated benefits of the proposed system?	• Improve the root cause analysis by reducing the time spent searching for information • Allow engineers to access more systems that in many cases they didn't have access (training involved) • Other departments could be benefited from this as they use the same tools but not necessarily the same process • In terms of cost maybe time but I don't see less people attending the reviews • It will be very beneficial for younger engineers who are not as familiar as we are with the systems used.	• Reduce searching time • Standardise the process across departments • Create a full quality picture of a part/sub-system • I would be interested to see the cost of implementation compare to the benefits that we can obtain	• Improve the root cause analysis by allowing engineers to link and visualise data • All information are stored in different places. Would be great to link them all together without going manually on each individual system • Would be ideal to have the data in reviews live rather than paper copies from 2 days before. • Having the CAD subassemblies would be very beneficial • Reduce time spend searching for information • Improve collaboration with the OEM	
What would you consider as next steps?	See the system.	Test the system in a lab environment using our data	See the system	Disseminations events will be arranged from the project partners to demonstrate the POC systems
Have you seen anything similar in your organisation?	There is a big programme in place which aims to centralise maintenance data. As far as I know it will not cover technical assessments. I think integration with PLM is out of scope	There is some duplication with a big programme in terms of concept but currently the programme has not delivered something similar to what this research explored	Nothing I am aware of	

Table 8-3 Results from "Collect Quality history" Use Case Validation

Question	PD Engineer - Powertrain	PD Engineer - Chassis	Service Team Lead	Outcome
Do you agree with the information integrated by the proposed system?	Yes the amount of information seems right	• Yes these are the data that we usually review. • Stopped shipments include sensitive data. We need to understand what could be accessed. These issues need to be communicated with the engineers to prevent similar faults happening in the future • Vehicle diagnostics are very important especially for electrical. Probably not so important for Chassis as they are dealing more with mechanical issues	Yes, this is pretty much it. Currently not all the departments use vehicle diagnostics	
Is there anything not covered by the system? (Information, functionality)	• Engineers need to be able to filter each dataset based on the markets. We need to understand how our vehicles operate In countries under different conditions • The proposed system needs to show to the users where the data come from. In case something is missing they can go an search directly to the database	• ***Combining the different datasets would be of interest. Can you generate a graph with diagnostics against claims? • There is a need for an open search using keywords. Users will need to be able to filter data from a system level to a part level. Example discussed: Search for damper and then filtered by model/ programme/ market etc. • Using sub-assembly codes is a good approach as they provide a standardised input and a code to connect multiple systems.	**I would like to see data coming from social media and the internet. Sometimes our customers observes issues before we identify a trend or a pattern. Having a direct input from the customers would be extremely useful	*It was added to the system functionality. The POC system shows the number of returned data for each system. **Internet data were considered out of scope due to the complexity of searching unstructured data. However they will be captured in future directions ***Combining the different datasets is of interest however it was considered out of scope due to time limitations. There are several

				approaches documented in the literature that could be used to automate the workflow engine
How does currently the integration of PLM systems occur?	We have full access to the PLM system.	We use our PLM system on a daily basis	PD engineers have access to the PLM system.	
What are the anticipated benefits of the proposed system?	• Improve our searching capability • Standardise the process as all engineers will utilise at a minimum the same sources of information • Allow engineers to justify the selection and prioritisation of failure modes and effects using historical data	• It will provide a standardised approach that we can use across departments and suppliers. Currently we don't know the level of quality history that suppliers use • Re-use existing knowledge	• Identifying the quality history could be a challenge. We did a test a few weeks ago. We asked several engineers to find the root cause of an old issue. Most of them knew about the fault but they were unable to find the data to support it • Not a standardised process • DFMEAs are usually filled with words that mean different things to different people. Words like too high or too low. What too high means? • This research supports the measuring and prioritisation of failure modes and effects	
What would you consider as next steps?	See a running demo		When can we see the real system?	
Have you seen anything similar in your organisation?	There is some development to improve the DMEA process but not in terms of quality history	Engineers are trained constantly but in terms of systems nothing that I am aware of.	There is some development in the service and maintenance area but the scope is not currently to support PD engineers	

8.1.4. Discussion on Validation – Strengths and Weaknesses

In terms of benefits all the experts recognised that the system architecture supports the root cause analysis by allowing engineers to integrate PLM systems with maintenance information across the supply chain in a single environment. The proposed system architecture allows OEMs and suppliers to integrate and visualise data without the need to acquire multiple licences and without having to invest in building the same level of hardware configuration which is neither practical nor economical. Moreover, experts stated that it reduces the time spent searching for information as well as provide a standardised approach for root cause analysis across departments and suppliers. This is very important considering the number of people involved in this process. It was identified that for the body interior and exterior department only, more than 50 engineers and analysts are involved in the warranty and quality procedures. Therefore standardisation across departments and suppliers is very important as it can provide significant benefits on the root cause analysis process. The expert who represented the Tier-1 supplier highlighted that the proposed system supports engineers to have access to live data in a single environment instead of manually accessing each system or using out-of date printed copies. All the "warranty" experts recognised the importance of integrating PLM systems in their processes and stated the benefits of being able to visualise a part in relation to its sub-assembly. It was mentioned during the interviews that once the vehicle is on-sale, accessing PD documentation associated with a part could be a great challenge as PD engineers concentrate primarily on new vehicles and new programmes.

Regarding the FMEA experts who have access to the PLM system, it was identified that the proposed system will improve the searching capability by allowing engineers to extract graphs instead of exporting raw data from each system and applying analytics manually. Another benefit that was highlighted from the PD engineers is that the proposed system can support engineers to justify their measures against the severity and occurrence of each failure mode and their causes. Moreover the system allows PD engineers to re-use information and knowledge coming back from maintenance and service experts. Standardisation across departments and suppliers was also mentioned as one of the benefits, as an automated system ensures that the minimum level of analysis is conducted from every engineer.

Experts also highlighted area where the system architecture needs to be improved. PD experts highlighted that the system need to have a strong filtering capability to allow engineers to leverage the data and reduce the amount of returned results. In addition, a PD engineer stated that the proposed architecture need to provide analytics that allow engineers to generate graphs that integrate different data sets such as vehicle diagnostics and warranty claims. PD engineers recognised the importance of integrating CAD representations with maintenance information but did not recognise the benefits of aggregating more data from PLM systems as currently they have full access to their PLM system.

Since there were no objections against the proposed architecture and its applicability, the proposed system architecture is considered validated.

8.1.5. Technical Assessment

Through the parent project, a POC system was developed based on the proposed system architecture. Theorem solutions developed an aggregator which was based on Sharepoint 2010 and utilises Theorem's products for translating CAD data from native formats into JT. Test data were exported from the actual systems and were imported into databases that replicated the OEM's environment. Web-services were coded to demonstrate the use of system adapters in extracting data using SOA. Finally a desktop UI was developed by Theorem solutions to visualise product-data from PLM systems against warranty claims, vehicle diagnostics and technical publications as presented in Chapter 7. Holovis International was responsible for developing an immersive environment UI using the Unity3D game engine in order to demonstrate the benefits that can be achieved by utilising a 3D CAVE (Cave automatic virtual environment) and a 3D-Powerwall.

Although the POC system is limited in terms of functionality provided to the end users, due to data and time restrictions, it validates the main elements of the architecture as the POC system was able to deliver at a minimum the required functionality. An IT expert from the OEM case study company tested the POC system and provided valuable feedback. In terms of data aggregation the IT expert stated that maintenance systems currently face many integration challenges posed by legacy systems, security and enterprise maturity. However there are ways to overcome those barriers if companies decide to implement the proposed solution. In terms of the system architecture the IT expert recommended that the application

should be designed to minimise the intervention of IT required to support business change. Solutions should allow the implementation of business rules to be externalised to the core application thus it would be recommended to allow a degree of control to be applied over the system adapters' interface. The use of system adapters and as an extent standard interfaces reinforces interoperability. The more applications that are inter-operable the more likely it is that OEMs can respond flexibly and inexpensively to new user requirements. The IT expert agreed that building a cloud based application was the right choice as most vehicle manufacturers have already started migrating their services to cloud providers (Curtis, 2013)

8.2. Evaluation UML-Use Case from the Defence Sector

This second part of this chapter tests the applicability of the proposed system architecture within a different industry sector. This section will test whether maintenance engineers within the defence sector can be benefited from the functionality described in chapter 6. A company within the defence sector was identified as a good example to further evaluate the proposed system architecture. The defence sector provides a good example of a sector that operates within strict ISO standards and therefore it will stretch the capabilities of the proposed solution and reveal gaps. The use case discussed, although limited in terms of functionality, demonstrates that the system architecture could be applied in the defence sector, highlights areas where modifications are required and reveals gaps among the automotive and the defence sectors.

The methodology described in chapter 4 was followed to capture user requirements. User requirements were then modelled against the system functionality using UML diagrams. A UML use case diagram and a UML sequence diagram were created to model and analyse the requirements in order to identify the areas that need to be customised in the proposed system architecture. In the defence case study, the proposed system architecture supports maintenance engineers to conduct an in-service part failure that occurred on a platform (ship, vehicle). To aid this process, IVHM corrosion data, engineering data from PLM systems, in terms of specifications and CAD for the suspected component as well as electronic publications on how to replace a part need to be integrated to support the root cause analysis. Engineers need to use the performance and corrosion data held in the IVHM database to

validate the design specification and to influence design changes through collaboration along the supply chain.

8.2.1. *UML Modelling – "Use Case" View*

8.2.1.1. Human Actors

Table 8-4 provides the definitions for all the human actors that have a direct or indirect communication with the proposed architecture.

Table 8-4 Human Actors

Maintenance Engineer	Scope responsibility	To optimise maintenance practices and identify options for improving equipment reliability and maintainability that will deliver the agreed service levels and reduce through-life costs of the support solution
PD Engineer	Scope responsibility	In this instance, PD engineers review the outcome of root cause analysis to consider a design change to avoid further occurrences.

8.2.1.2. System Actors

In order to support the root cause analysis it is required to extract the right level of data pertinent to the use case described in this sub-section. Table 8-5 provides the definitions for all the systems that have a direct or indirect communication with the proposed architecture.

Table 8-5 System Actors

PLM System	Scope responsibility	PLM system will be used from the proposed system to extract CAD models, the BOM and all the attributes associated with a part/sub-assembly.
Tech Pubs	Scope responsibility	Tech Pubs provides access to all the information required to enable maintenance engineers to deliver service and repair for OEM's customers. It includes complex Interactive Electronic Technical Publications that supports a rich set of media including PDF and Word documents, video and virtual reality emulations, tutorials and design drawings.

⚥	Scope responsibility	IVHM collates and analyses data from the Health monitoring sensors. In this instance IVHM will be used to extract corrosion data of a system or a sub-system over time in order to identify degradation trends.

IVHM System

8.2.1.3. "Analyse an In-service Product Failure" Use Case

Figure 8-1 shows a UML use case diagram. Within the boundaries of the use-case diagram an extend relationship was defined between the "Analyse an in-service Product Failure" (base) and the "Assess any Design changes" (extension) use cases. The evaluation use case discussed in this thesis focuses primarily in the "Analyse an in-service Product Failure" use case. The outcome of this use case can then be used by PD engineers to consider design changes and as a result avoid further failure occurrences. The latter use case is not described fully in this thesis.
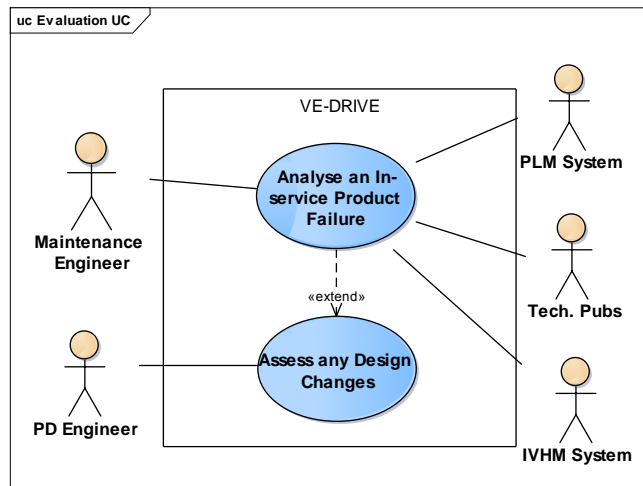
Figure 8-1 Use Case Diagram

Brief Description

The Maintenance Engineer responds to a non-critical issue reported by the operator of a platform. The issue is intermittent and recurring. The Maintenance engineer aims to resolve an in-service part failure that requires short term action together with longer term design changes to prevent re-occurrence. As a device to access information about the components of a subsystem, a portable device is employed by the user. Multiple components are assessed as the user attempts to diagnose the fault and drill-down to information related to the faulty part. This procedure is performed at the platform (ship, vehicle etc.) so that the user can observe the physical components, the data can be referenced and the repair can subsequently be

carried out. The cycle starts with the scoping method which involves the identification of the maintenance task being undertaken, which takes information about the task and the profile of the person (a maintenance engineer). To aid this process, IVHM data as well as design data in terms of specifications and CAD for the components suspected are shared between OEM (Fleet operator) and key suppliers (Tier-1 suppliers). The aim is to use the performance data held in the IVHM database to validate the design specification and to influence the modifications under consideration through collaboration along the supply chain. All these components will be assessed as the user attempts to diagnose the fault, identify the root cause through information relating to the issue.

The use case is successfully completed when the user has reviewed all the required information and is able to identify the root cause of an issue or pass the information for further exploration to the maintenance team

Basic Flow

A component is uniquely identified via a QR code captured via the on-board camera on the portable device. The QR code provides an input to the system using the camera instead of typing a "string" code as described in the use cases explored in the automotive sector. Based on the user's context of location, task and role, the most likely relevant information is recovered from appropriate data sources and displayed in a form most suited to the capabilities of the viewing platform. The QR code is passed to the aggregator. The system requests the user to enter the selection criteria for the IVHM database for the scanned part. The system requests the primary keys related to the scanned QR code from the asset management service using web-services. The system requests the product structure, CAD models and specification from the PLM system using the part_ID provided by the asset management service. The system requests corrosion data using the outportset_ID utilising the IVHM service and document titles from the Tech. Pubs system using the part description. The system prioritises the document titles based on an attribute called "number of hits" which is returned from the web service. The system presents the results to the user. The maintenance engineer utilises the product structure in order to move up and down levels in the CAD representations which are extracted from the PLM system. Using the selected part as the starting item, the system uses "connects to" relations to trace the next part into the next compartment or sub-

assembly. Note that this is not an expansion of the assembly product structure, because these components may be in a different branch of the ship structure. The next cycle links the selected part with the IVHM corrosion data. The user can view a graph with corrosion data over time extracted from the IVHM system. To support the maintenance process the system provides the maintenance engineer with a list of publications relevant to the part scanned prioritised based on the number of URL hits. The user opens the relevant publication within the Tech Pubs system and replaces the faulty part. The system saves a session file and if required shares the details to the PD engineer who can use the information to review the analysis and consider design changes to avoid further occurrences. The basic flow is presented in Figure 8-2.
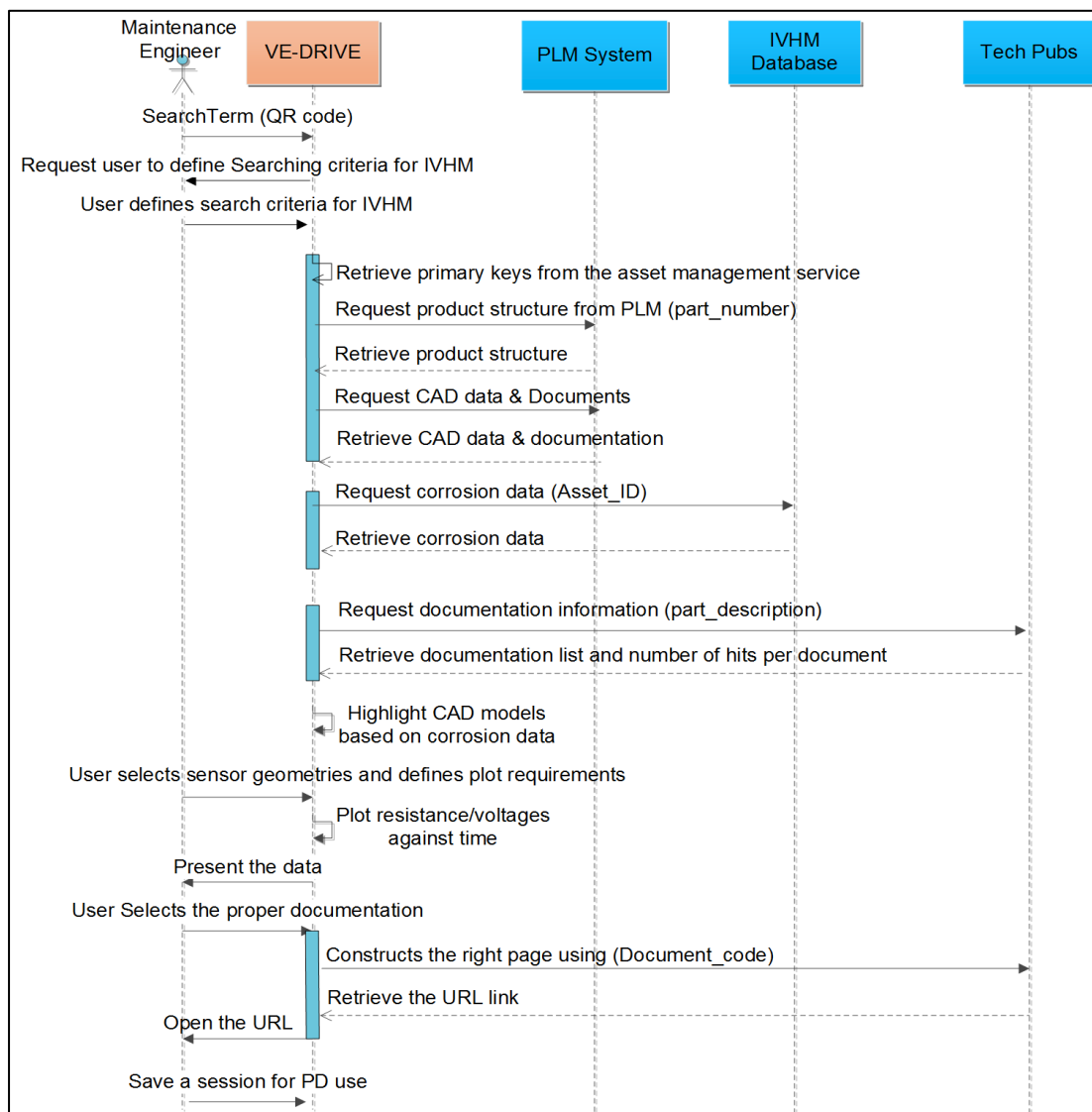
Figure 8-2 Sequence Diagram for Validation Use Case

8.2.2. UML Modelling - Static View

The static view of the system architecture is very similar to the one described section 6.4. However there are some elements that need to be modified to adopt the new systems integrated. In terms of the presentation layer there are no major alterations required. For the integration layer, there are some modifications that need to occur to adopt the new domain layer. Firstly, the administrator has to register each system that has a direct communication with the proposed solution in the silo register. Secondly, the technical services need to be modified to adopt the web-services for each system. In this instance, coding the web-services was deemed easier than in the automotive use case as all the systems integrated provide a comprehensive set of APIs that allow system integration. System adapters were developed from the case study company based on the published standards for each system (OSA-CBM and S1000D). Finally, a new workflow was designed to accommodate the steps required to satisfy the use case. Similarly with the use cases described within the automotive sector the workflow utilises the BOM structure extracted from the PLM system to construct and execute queries to the IVHM and the tech. pubs systems. Figure 8-3 shows the adjustments described in the system architecture highlighting with read the major modifications, with orange the minor modifications and with black lines with no modifications.
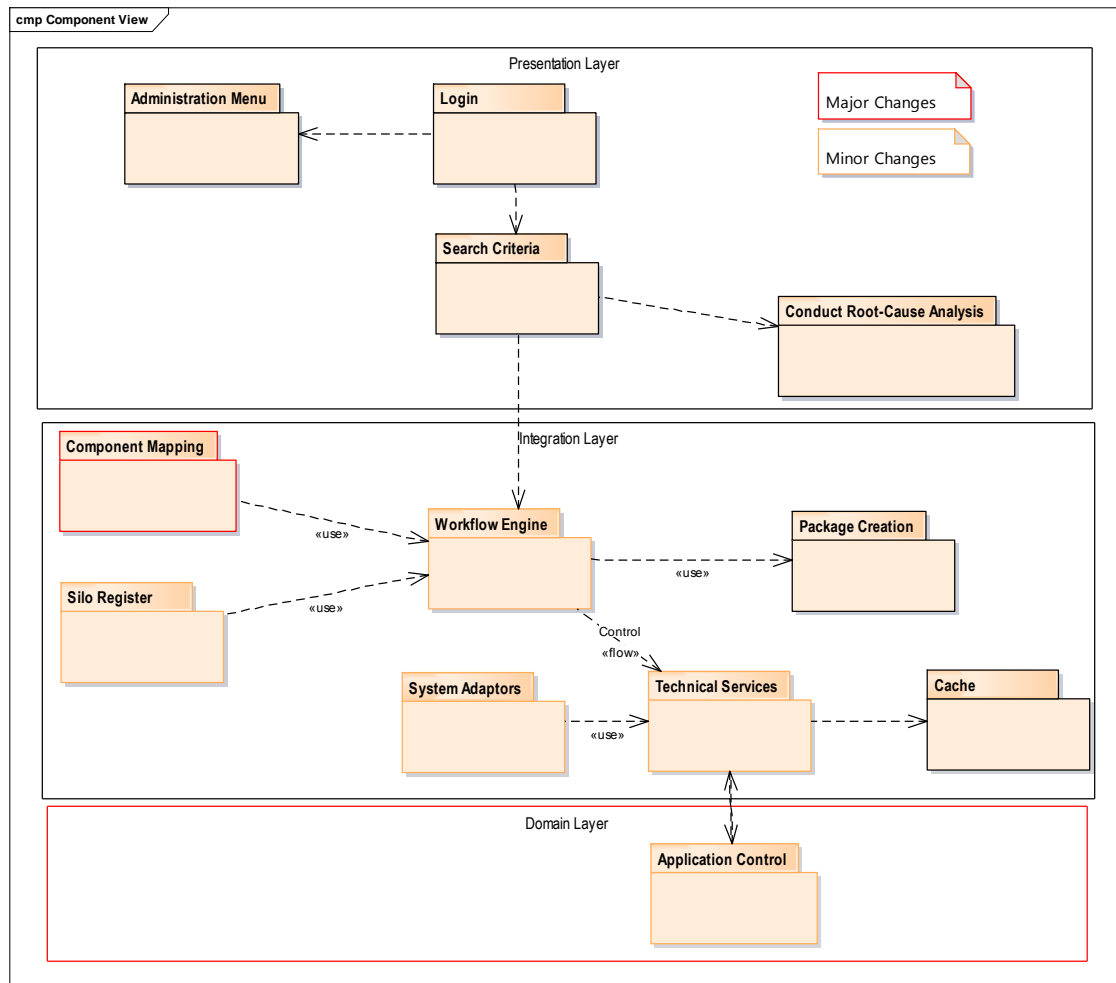
Figure 8-3 System Architecture Adjustments for the Defence Use Case

However as stated in chapter 6 the component mapping database which offers an input to the workflow engine is specific to each domain layer and as an extent to each company. Therefore the case study company was responsible for developing a component mapping database (also called as asset management service) that holds the links among the different systems used in order to enable the proposed system to integrate CAD data extracted from the PLM system with IVHM corrosion data and documentation extracted from the tech. pubs system. Figure 8-4 shows a simplified view of the primary keys utilised in each dataset.
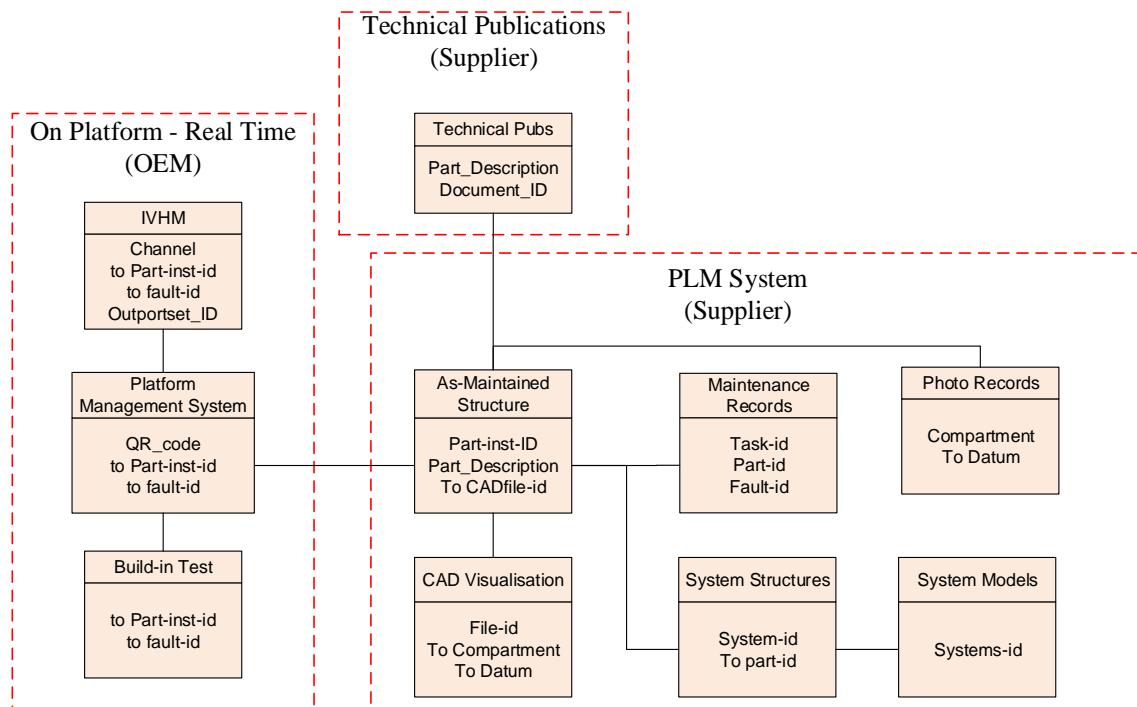
Figure 8-4 Evaluation Case Study - Systems and Primary Keys

The proposed system receives an input from the user which in this instance is in a form of a QR code scanned from the camera of a portable device. The workflow engine utilises the web-services developed in order to request the correct primary keys from the asset management service. The asset management service returns the correct primary keys which can be used from the proposed system to extract the data required to satisfy the use case. Figure 8-5 shows the input and the outputs of the component mapping service. These primary keys are:

- outputset_ID of the attached sensor that can be used from extract data from IVHM
- search terms from part description that the sensor is attached to, that can be used to identify a list of relative publication from the tech. pubs system
- part_ID from the part that the sensor is attached to that can be used to extract CAD data from the PLM system.
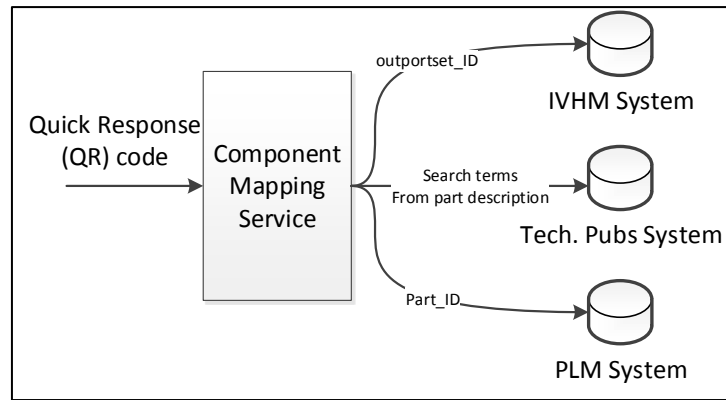
Figure 8-5 Component mapping service output

The following section provide a description of the system interfaces.

PLM System

Similarly with the automotive use cases, Teamcenter was chosen in order to test the PLM system integration. As a system, it provides a well-defined SOA infrastructure that allows the proposed system to connect via web-services and extract data. The API exposes the business logic server to web-services and allows the aggregator to extract the BOM structure and as an extent CAD models with their associated attributes (Siemens PLM Software, 2010)

IVHM System

IVHM system was developed based on the OSA-CBM standard which allows the aggregator to extract and manipulate data using web-services through the well-defined OSA-CBM API. From the six services provided from the OSA-CBM architecture only two layers will be used in this research. The OSA CBM web application provides two SOAP services for accessing corrosion data. The Data Acquisition (DA) service which allows access to a historical store of corrosion data and the State Detection (SD) service which delivers a dataset with state values. The SD service provides a state value of the sensor and an indication of when the corrosion makes the sensor go open circuit. The service returns a dataset containing resistance values recorded by a set of corrosion sensors over a period of time. The other OSA-CBM services described in chapter 2 (Advisory Generation (AG), Prognostics Assessment (PA), Health Assessment (HA) and Data Manipulation (DM)) are not implemented at this time.

Tech Pubs System

The tech pubs system is a powerful system that holds all the required technical information and provides a combined maintenance toolset of technical documentation, fault diagnostics, maintenance management and training information. The Tech pubs system architecture is based on S1000D standard which provides a comprehensive set of API's that allows other systems to "data mine" the technical publications. The service will return only the title of the document, a document_id required to build the URL and the number of hits for each document. Similarly with the automotive use case, it was identified that extracting data from a tech. pubs system is not possible due to the amount of data held in the system. For example, on a Type 45 Destroyer, there are roughly 120,000 pages of information, plus around 17,000 graphics which is counted as 6.8 gigabytes of information (BAE Systems, 2013). Therefore extracting the amount of information required from the users was considered inefficient. The system will construct the URL link using the document_id whenever the user makes a menu selection.

8.2.3. UML Modelling – Dynamic View

The dynamic view demonstrates the dynamic behaviour of the system over time. The dynamic view of the system follows the same steps with those described in section 6.5. During the evaluation UML use case the proposed system receives a QR code as an input. The QR code is then communicated with the asset management service to obtain the primary keys required from the technical services. The system requests the user to fill some additional search criteria, such as defining the maximum and the minimum value of state which defines the data extracted from the IVHM database. Technical services uses the Part_ID provided to run the GetContent() query in order to extract the product structure and through the product structure the CAD data for each part identified within the product structure in a light JT format. The system was customised to apply the same logic on CAD data with the one described in chapter 6 (1 parent-all children). The aggregator then executes the GetContent() query to the IVHM system to extract the corrosion data captured from the sensors. Once the data are extracted, they can be either presented in a form of a heatmap in the CAD model or through a graphical representation. The proposed solution uses the part_description and the search terms provided from the component mapping service to run a query in order to extract a list of relevant publications. The prioritisation is based on the number of user hits per publication. This is an attribute that is returned

from the web-service. Whenever a user selects a technical publication from the list provided, the proposed system constructs the URL and then opens the actual application to the correct web page. Therefore the engineer can relate the diagnostics from IVHM and the CAD data while reviewing the instructions on how to change a part.

8.2.4. Discussion of the Evaluation Case Study

The outcome of the evaluation case study is twofold. Firstly, the use case captured, although limited in terms of functionality, demonstrates that maintenance engineers within the defence sector require the ability to integrate product-data from PLM systems with technical publication and diagnostics captured from the sensors. This system could be of benefit for maintenance engineers as it allows them to minimise the effort of searching for information and it provides the right depth of data for conducting a root cause analysis. Engineers from the case study company stated that currently IVHM and PLM systems are two isolated worlds. Therefore, as it was identified in the literature, the benefits of integrating PLM systems with MRO procedures has not been realised yet. Moreover it was highlighted from the stakeholders that when the task or problem exploration area follows predefined paths within a fixed internal data landscape then the requested data flow and access to information works as intended. It is when the task or problem resolution necessitates accessing data sources outside the norm that issues start to appear. Accessing data across the supply chain can be a challenge. Stakeholders highlighted that it is rare for system admins to allow unregulated direct access to their databases. Therefore to satisfy the access concerns from data source owners, utilising a web service interface where the access is decided at the service interface level would be the most appropriate way of integration. Having an aggregator as an intermediate service to access the database will open the possibility of performing not only access checks but creating value added interpretations that can be configured for the individual user. In terms of the overall system architecture, it was identified that the system does not require major modification to support a new use case. The evaluation case study emphasised the importance of the component mapping element that maintains all the links among the different systems integrated. In order to allow the multiple systems to be linked in a test environment an asset management service was developed from the case study company and holds the links among the different primary keys.

The second part of the evaluation allows the author to capture some interesting findings by comparing the two sectors. One similarity that can be identified among the use cases from the automotive and the defence sector is related to the functionality and systems required to perform a task. The IVHM database is similar to the vehicle feedback database while the technical publications systems in both business cases are applications developed from third party companies which make direct extraction of data a challenge. One of the most important differences among the automotive and the defence sector is the use of standards within the maintenance systems. The IVHM database uses the OCA-CBM standard while the tech. pubs system the S1000D. Systems developed using standards usually have an open API, hence easily able to interface with external systems. As a result of the standard APIs provided, the system was tested through queries to the actual systems in a test environment. Therefore it was identified that this is an area that the automotive sector could be benefited and learn from the defence sector. Developing or adopting standards will allow automotive companies to standardise their maintenance applications and as a result reduce the amount of effort required for integrating multiple systems across the supply chain. Through the literature review a few publications that aim to implement IVHM within the automotive sector were identified. Another area that was captured as different compare to the automotive sector was the perceived importance of security. Although security was out of scope in this research, stakeholders advised that it needs to be taken into consideration moving forward as failure to demonstrate the basic levels of security will make the system unacceptable.

8.3. Chapter Summary

In this chapter, six semi-structured interviews with automotive experts were used to validate the outcome of the proposed system architecture. The validation demonstrated that by integrating product-data from PLM systems with warranty claims, vehicle diagnostics and technical publications, it is expected that engineers will be able to improve the root cause analysis and close the information gaps. The validation also demonstrated the importance of standardising the processes across departments and suppliers. In addition a POC system developed from the two partner companies demonstrated the applicability of the architecture and therefore it validated its technical elements. The POC system was tested from an IT expert who provided independent feedback.

In order to evaluate the applicability of the proposed system architecture in a different industry sector, a UML use case from the defence sector was captured. Similarities and differences among the two sectors were analysed in section 8.2.4 to demonstrate best practices that could be shared. The evaluation case study also demonstrated that without major modifications the system architecture could be used to support the defence sector.

Discussion and Conclusions

The outcome of this thesis is a novel system architecture that integrates PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise the required cross supply chain data in a single environment. This chapter concludes the thesis with a discussion on the key outcomes of this research with respect to the aim and objectives. Furthermore, the contribution to knowledge and the research limitations are discussed in detail. In addition, this chapter provides directions for further research to allow new researchers entering the field to extend this work further. The last section of this chapter compares the achievements of this research against the aim and objectives stated in Chapter 3.
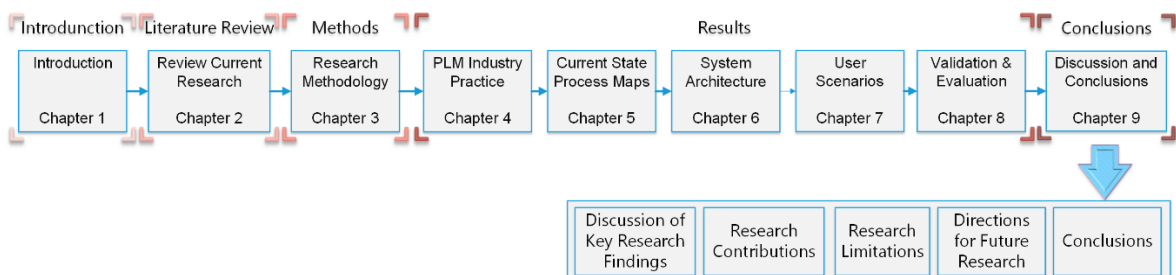
9.1. Discussion on Key Research Findings

This section summarises the key research findings in each of the main phases.

9.1.1. Literature Review

The review in section 2.2 analysed existing literature in the area of information flow in the supply chain across different phases of the product lifecycle by providing a two-

dimensional framework classification based on the phase of the product lifecycle and the type of each publication. The analysis of 132 articles in different phases of the product lifecycle and through cross phase examinations provided insights and highlighted a number of interesting observations which are discussed in detail in sections 2.2.3 and 2.2.4. The main finding of the analysis showed that currently PLM systems are isolated from the maintenance and warranty phase as currently PLM systems focus mainly on the PD phase. Moreover the analysis showed that the majority of studies propose system architectures that either allow data exchange among heterogeneous PLM systems or aim to extend the current functionality of PLM systems beyond the traditional PDM systems. However, system development in the area of maintenance has attracted less attention from researchers compared to the PD phase and the majority of studies still focus in the aerospace sector. The analysis of articles in the maintenance phase of the product lifecyle demonstrated that currently there is a lack of a central repository to manage, maintain and share maintenance data. Until recently organisations have developed multiple internal systems to manage different types of maintenance information and as a result they now face the need to develop standards and integrate those systems. Through cross phase examination it was identified that although individually most of the systems used in each phase of the product lifecycle are well established, further research is required to integrate systems and processes across multiple phases of the lifecycle and across the supply chain.

In order to ensure that the research scope was covered and no meaningful publications have been missed, the literature in the area of root cause analysis was reviewed further. The detailed discussion of this section is presented in 2.3.1. Literature review showed that the majority of studies analyse either data sets with warranty claims or data sets with vehicle diagnostics in order to identify trends and patterns of reoccurring in-service product failures. However all these studies make the assumption that these data sets are brought together before the algorithm is applied. Furthermore, it was identified that the vast number of systems used to record, maintain and analyse data, offer little or no integration capabilities, which creates a challenge for suppliers who require the ability to access and analyse these data.

Finally, section 2.4 utilises the classification framework to analyse and compare the system architectures proposed within the literature. The outcome of the analysis

allowed the author to choose the most appropriate distributed data sharing architecture and build on the previous work done. The analysis demonstrated that the XML-based data sharing architectures are more suitable for this type of research due to their ability to utilise web services to exchange data among heterogeneous systems as well as their ability to pass messages across firewalls which is critical when exchanging data across the supply chain.

Through the literature analysis and the key findings discussed, research gaps were identified (section 2.5). It is evident from the literature review that the integration of maintenance information to support supply chain collaboration has not received as much attention as supply chain collaboration during the PD phase of the product lifecycle. The literature review showed that there is a need for developing a novel system architecture that integrates a continuum of data types from complex PLM systems through electronic technical publications to diagnostics and warranty systems and share information across the supply chain in order to support root cause analysis.

9.1.2. Industry Survey

In order to identify, measure and prioritise the perceived importance of supply chain issues related to information flow and the use of PLM systems within the automotive industry, empirical data captured from semi-structured interviews with 15 multinational companies was analysed using the Hicks et al. (2006) methodology. The individual issues captured were classified against 14 clusters that represent the core and the fundamental supply chain issues related to information flow and the use of PLM systems. A detailed discussion of the results is presented in section 4.4. The findings reflect the need to develop automated systems that are able to integrate multiple systems and as result share accurate and complete information. Experts agreed that in many cases multinational companies will not acquire licenses or build the infrastructure required to support each one of the PLM systems that their clients choose mainly due to the high implementation and maintenance costs that are associated with these systems. Therefore even if PLM systems were used as a way to manage and store maintenance information, integration issues would still exist. The analysis led the author to the conclusion that the use of SOA could potentially reduce the amount of accessibility issues identified as users would be able to access data extracted from the PLM system without the need to acquire multiple licenses.

9.1.3. Current State Process Maps

Prior to designing a system architecture for integrating PLM systems and cross-supply chain maintenance information to support root cause analysis, a detailed analysis of two key processes, which demonstrate how automotive vehicle manufacturers and component suppliers utilise maintenance data to conduct root cause analysis, was carried out. A simple flowchart was chosen as the most appropriate technique to capture the processes followed, systems used and information required. The current state process maps allowed the researcher to identify current challenges and opportunities in each part of the process in order to scope the requirements analysis and define the functionality required. The current state process maps captured more information than the proposed solution could achieve but demonstrated focus areas for the proposed system architecture. A detailed view of the challenges identified are presented in sections 5.1 and 5.2. Through the analysis it was identified that access to all the systems involved is manual and time consuming. Usually the amount of information used in part assessment depends on the experience of engineers involved. Moreover it was identified that currently warranty and supplier engineers have limited access to the PLM system and usually rely on PD engineers to provide the data. Usually the data provided are specific to the part which restricts engineers from seeing the interactions of the part with the other systems (sub-assemblies etc.). As a result the lack of the right amount of data can lead to a lack of in-depth quality history which can cause misinterpretations when prioritising failures modes and effects. Another challenge identified is the lack of standardisation within the processes and the systems used across the supply chain.

The outcome of the analysis enhances the findings from literature confirming that currently there is no centralised location for warranty and maintenance information. Most of the warranty and maintenance systems used in the automotive sector provide little or no integration capabilities. Moreover the findings of this research expand on the Centre of Research-CAR (2005) processes as the process maps include the systems used, information utilised and the decision points that engineers follow within the root cause analysis.

9.1.4. System Architecture Proposed and Scenarios

Centred on the need to allow engineers to integrate PLM systems with cross supply chain maintenance information such as warranty claims, vehicle diagnostics and

technical publications a novel system architecture was proposed to support root cause analysis.

Prior to modelling the functionality required, a requirements analysis was carried out. Requirements were analysed, grouped and then prioritised using the MoSCoW approach. Requirements analysis showed that it is critical for engineers to be able to visualise different clusters of data in a single environment and to enable data reuse across the supply chain. Data such as the "voice of the customer" (surveys, breakdown and recovery reports); technical publications (manuals, bulletins and diagnostics); product data (CAD data, specifications and associated documentation), warranty claims and faults recorded from the dealers (customer and technician verbatim), and the "voice of the vehicle" (diagnostic trouble codes) are necessary in order to build a full quality picture. Similarly PD engineers could use the same clusters of information during the design process of a new part or sub-system to determine the failure modes and their effects and to prevent recurring product failures. These requirements are presented in detail in section 6.2. The requirements analysis through prioritisation revealed not only the functionality that needs to be developed but also provided interesting areas for further research.

Once the requirements catalogues were completed, UML diagrams, such as a use case diagram, sequence diagrams and package diagrams, were created to transform user requirements into system functionality. The models were developed to demonstrate three UML modelling views (use case, static, and dynamic) which represent the "design blueprints" of a system that allow engineers to integrate maintenance data extracted from multiple systems which are then visualised in a single environment. The system architecture was developed using a three-layer (presentation, integration, and domain) approach to allow the re-usability and agility of the system. Depending on the circumstances, this approach will enable either the technology to be improved over time or the domain layer to be expanded whenever a new requirement is identified.

9.1.5. Scenarios

The scenarios presented in chapter 7 demonstrate the flow of information within the system by examining all the steps followed, starting with the search criteria defined by the user, the interactions with the system throughout the root cause analysis, the example data presented in the UI, and finally the outcome of the root cause analysis.

The scenarios demonstrate clearly how the system is used across the supply chain to support root cause analysis. The scenarios demonstrate how the system integrates maintenance and warranty information in the context of 3D objects and CAD data extracted from PLM systems by creating a sharing environment where OEM and supplier engineers can access cross supply chain data.

9.1.6. Validation & Evaluation

Validation Using the Automotive Case Study

Six meetings were arranged in total to validate the system architecture, three for the "conduct root cause analysis and the "analyse categorised claims" use cases, and three for the "collate quality history" use case. These meetings were held with engineers who represent domain experts, some of whom are also considered as potential end users in regards to the proposed system architecture. All experts validated the research outcome and provided feedback on how the system architecture could be improved. As a result some of the recommendations were taken into consideration and were used to modify and improve the proposed system architecture. Furthermore, experts provided their view on some of the anticipated outcomes when using the proposed system architecture. All the experts agreed that the system architecture proposed will reduce the time spent searching for information as well as provide a standardised approach for root cause analysis across departments and suppliers. All the "warranty" experts recognised the importance of integrating PLM systems in their processes and agreed on the importance of having a visual representation of a part in relation to its sub-assembly.

In addition, technical elements of the architecture were validated from the two partner companies who developed a POC system based on the architecture proposed. An IT expert from the OEM case-study company provided independent feedback on the system architecture, its context and design principles, constraints and patterns.

Evaluation using the Defence Case Study

This thesis also evaluated the system architecture in a different industry sector using a case study from the defence sector. The first objective of the evaluation case study was to examine whether maintenance engineers within the defence sector require the ability to integrate product-data from PLM systems with technical publications and diagnostics captured from the sensors. The outcome of the requirements analysis showed that the system proposed could be of benefit for maintenance engineers as it

allows them to minimise the effort of searching for information and to obtain the right amount of data for conducting a root cause analysis. In addition, the evaluation case study allowed the author to capture new findings by comparing the use cases between the automotive and the defence sector. The most important similarity among the use cases from the automotive and the defence sector is related to the functionality and the systems required to perform root cause analysis. The most important difference observed among the two use cases is related to the use of standards within the defence sector. The use of standards within the defence sector reduces the cost of creating new or propriety architectures whenever a new application is developed and allows the standardisation of information exchange. The automotive sector could be benefited by adopting the well-defined standards both for vehicle diagnostics using the OSA-CBM and for technical publications using the S1000D standard.

9.2. Research Contributions

The main outcome of this research is a novel system architecture for integrating PLM systems with cross supply chain maintenance information to support root cause analysis. The proposed solution was developed to support not only OEM and supplier warranty engineers to identify the root cause of an in-service product failure but also PD engineers who use the system to review the quality history of a part and ensure that previous failures will not reoccur to new product parts. The development of the system architecture was based on a structured methodology followed in order to identify the research gaps in relation to the current challenges that automotive engineers encounter. The key contributions are summarised as follows:

9.2.1. Current Research and Practice

The literature review carried out in this thesis both in the area of information flow across the supply chain and in the area of root cause analysis revealed several research gaps and provided directions for further research. The literature review presented in this thesis offers three main contributions. The first part provides a framework that serves as an organising structure for clustering articles based on two key elements, the phase of the product lifecycle and the type of the article. The proposed framework summarises and analyses the literature in each phase of the product lifecycle and through cross-phase examinations and can be used by new researchers entering the field as a starting point of their research or by experienced researchers in order to identify research gaps and future opportunities. The second

part of this review, presented in section 2.3, offers a comprehensive review of representative articles in the areas of warranty analysis, on board fault diagnostics and prognostics, and FMEA analysis. An important emergent theme of this part of literature is the importance of taking a holistic and systematic view of root cause analysis as most of the review articles examine each area individually. Finally, the third part of literature review summarises the advantages and the disadvantages of the two main distributed data sharing architectures used which can be beneficial for all new researchers interested in developing data exchange systems.

The analysis of supply chain issues related to information flow and the use of PLM systems provided a classification of the core and fundamental issues. The findings demonstrated a series of challenges that currently suppliers encounter and provided directions for further research. The outcome of the analysis not only enhances Hicks et al. (2006) analysis but also demonstrates supply chain issues related to information flow and the use of PLM systems. The findings of this study could be used to establish a roadmap that links each cluster of issues against the systems required.

The current state process maps captured with semi-structured interviews with automotive experts demonstrated the processes followed, the systems used, the information required and the decisions points in order to perform a root cause analysis. The current state process maps were critical for the development of the system architecture as they were used to define the functionality required. In addition, they provide a contribution to knowledge as this study is only one of the few that demonstrate the systems, the information and the decision points that engineers use during root cause analysis. The "in-service product failure identification" map demonstrates that PLM systems could be used to support warranty and maintenance procedures. This enhances Lee et al. (2008) statement that the potential of PLM systems within MRO procedures has not been realised yet. In addition, the "quality history for DFMEA" map enhances the Kiritsis et al. (2003) view that the amount of information returned back to PD engineers is usually fragmented. This process map clearly shows that structuring the data returned from customers, vehicles and dealers could be used to form the right amount of quality history required in order to run a robust FMEA.

9.2.2. Proposed System Architecture

The main contribution of this research is a novel system architecture for integrating PLM systems with cross supply chain maintenance information to support root cause analysis. The architecture was designed based on a three layer approach that allows the re-usability and agility of the system. As a result, depending on the circumstances, this approach enables either the technology to be improved over time or the domain layer to be extended whenever a new requirement is identified.

The proposed system architecture allows OEMs and their suppliers to integrate and visualise data without the need to acquire multiple software licences or to invest in building the same level of hardware configuration for all users. All experts recognised the importance of integrating PLM systems with maintenance information and agreed that by reducing time and effort in analysing warranty claims and vehicle diagnostics, significant benefits can be achieved. This research also demonstrated evidence of the benefits that can be achieved through the integration of service manuals, engineering documents, warranty claims and vehicle diagnostics which was an area that other researchers such as Chougule et al. (2011) have recommended to extend their work into. The outcome of this research extends the findings of Lee et al. (2008) further, not only by showing the potential of PLM systems within the maintenance procedures but also by demonstrating that through the integration of PLM systems with maintenance information, both PD engineers and warranty engineers could be benefited. Experts recognised that the proposed solution provides a standardised approach for root cause analysis across departments and suppliers. The proposed solution does not aim to replace the existing PLM and maintenance systems in companies but rather to provide a visualisation tool that enables OEMs and their supply chain to integrate and share accurate and complete information. This is one of the main contributions of this research as most of the systems proposed from researchers in the maintenance phase of the lifecycle have a very internal and OEM focus. Finally this research proposes a solution that integrates disparate silos of data where data mining techniques could be applied later supporting the outcome of Buddhakulsomsiri et al. (2006) study. This research also demonstrated that information and knowledge coming back from maintenance experts and aggregated through the proposed system can also be used by PD engineers to prevent failures from recurring on new designed parts.

Three scenarios demonstrated the applicability of the system architecture and the functionality provided. These scenarios provide a contribution to knowledge as they clearly describe the functionality required by warranty and PD engineers in order to improve the root cause analysis and prevent fault reoccurrence. Moreover the scenarios showed the importance of not only aggregating the required data but also the importance of visualisation.

This research provides a web-based architecture that treats network as a virtual warehouse, removing the need to create centralised locations for managing maintenance data. The development of the proposed system architecture also highlighted the importance of standards that can be used to improve system interoperability and reduce integration complexity. The evaluation use case discussed in the next section highlights some of these benefits.

9.2.3. *Validation and Evaluation*

The proposed system architecture has been validated using the automotive case study and its applicability has been evaluated in the defence sector. The evaluation case study showed that the defence sector has benefited from the OSA-CBM and S1000D standards by being able to easily interface maintenance systems with external systems. Currently maintenance and warranty systems used within the automotive sector are not developed based on similar standards. Recent studies discuss the importance of developing an IVHM system that utilises the OSA-CBM standard within the automotive sector (Benedettini et al., 2009; Holland 2008). However, the few articles identified within literature do not expand on these concepts further. By comparing the automotive and the defence case studies, this research identified that further research is required to examine the applicability of the defence standards, such as the OSA-CBM and the S1000D standards, within the automotive sector. The adoption of these standards from the automotive sector could potentially result in reducing the cost of system development as well as improve the standardisation of information exchange.

9.3. Limitations of Research

Although the system architecture was developed as generic as possible with data collection achieved through multiple experts, the author recognises the limitations of this research. This section discusses the limitations identified and the mitigation measures taken to ensure the quality and validity of the research.

9.3.1. Selected Methods

The first limitation is related to the potential bias when conducting semi-structured interviews. By adopting interviews as a data collection method there is always a risk that responses may be influenced by the interviewees' aspirations to present their organisations in a positive way. Although the measures used for this research were rigorously tested and experts were carefully selected, a broader selection of automotive experts could be used to verify the validity of the data collection outcome. Anonymity was also guaranteed for both interviewees and their companies, thus reducing the impact of the aforementioned challenge.

9.3.2. System Testing and Technical Limitations

The actual testing of the system architecture encountered a few challenges. The first limitation is related to the difficulty in testing the applicability of the system architecture by integrating the real systems used within the automotive sector. It was identified that most of these systems offer little integration capability as in most cases there was no API available to use. To address this limitation, a subset of data was extracted from the company's systems, such as vehicle diagnostics, warranty claims, technical publications and CAD data. Each one of the subset of data extracted was then imported into a test environment that represented the OEM's infrastructure, including Teamcenter PLM for the CAD data. As a result the system architecture was tested against the simulated systems in a test environment which was indicative of the real infrastructure. Regarding the evaluation UML use case in the Defence sector, due to the standard APIs provided, the system architecture was tested by querying the actual systems within a lab environment. Therefore, the service allowed the aggregator to extract a limited number of test data. The system is currently undergoing further testing before being implemented in a real production environment. A larger amount of data is required in order to test the performance of the system and ensure that there are no performance interruptions to the systems integrated.

The second limitation is related to the number of tests that the author could run. As the coding of workflows requires modifications within the aggregator's infrastructure, the author was only able to test two out of the three use cases discussed. Therefore, the "collate quality history" for DFMEA use case was not included in the system testing. However the system was rigorously tested against the other two use cases.

9.3.3. Generality of Research

Another limitation of this research is related to the number of validation interviews conducted. To address this limitation, the outcome of this research was validated through semi-structured interviews with experts from four departments (chassis, powertrain, body interior and exterior, and electrical) within a vehicle manufacturer and an expert from an automotive Tier-1 supplier. A larger number of semi-structured interviews with experts from more vehicle manufacturers could further validate the outcome of this research. The evaluation use case from the defence sector mitigated this limitation further by allowing the system architecture to be tested against a case study from a different industry sector.

9.4. Directions for Future Research

This research is proposing a system architecture for integrating PLM systems with cross supply chain maintenance information to support root cause analysis. Despite an in-depth literature review and extensive data collection from experts within the automotive sector there are some areas within the proposed system architecture that require further research and could potentially extend this work further.

9.4.1. Data Analysis & Visualisation:

Currently the analytics and the graphs produced from the visualisation layer of the system architecture are only applied to each individual data set. For example logic was applied within the system to produce graphs for either warranty claims or vehicle diagnostics. Further research is required to develop algorithms that allow the system to combine vehicle diagnostics and warranty claims. The author was unable to identify any existing work that proposes a model or algorithm that analyses warranty claims in relation to vehicle diagnostics. This is key for root cause analysis, considering that the amount of electronic parts in vehicles is continuously increasing. This work can be extended further to include design specifications from PLM systems and suppliers' test data.

The system was developed based on the analysis of current state process maps and the requirements captured through semi-structured interviews. This work can be extended further to allow the proposed system architecture to support other areas of the automotive supply chain that utilise maintenance data.

9.4.2. System Integration

Automotive experts highlighted the importance of capturing and monitoring data from the web and social media. Experts recognised the importance of reviewing customer feedback instantly as currently customer surveys can take a significant amount of time and are limited in terms of numbers, country of origin etc. Although this requirement was captured within the requirements catalogue, it was considered out of scope due to time constraints and technical limitations. Further research is required to develop ways of structuring and analysing unstructured data from the web and social media. Abrahams et al. (2012) study evaluated a new process and decision support system for automotive defect identification and prioritisation and provided some great insights into how social media analytics can improve automotive quality management. This area opens a new potential for the warranty root cause analysis as customer feedback from the web and social media can be received instantly providing engineers a vast amount of data such as pictures, videos and verbal descriptions of the fault.

The concept of ontologies could be used as a method for navigation within the complex data landscape. During the research and design into the proposed architecture, it became apparent that the concept of linking information sources starting with PLM systems through to technical publications and IVHM systems would make the ability to navigate through the complex series of data very challenging. The use of ontologies could potentially answer the above challenge by allowing users to utilise the ontology maps to aid the navigation process. The ontologies of data sources can be visualised as classification methods and provide a way to simplify the data selection process. As each data source is utilised, the initial handshake should respond with an ontological description of the data contained within the service. This response would show the major classes within the service together with descriptors for the links between those classes, attributes within the classes or attributes within external classes.

9.4.3. Role of Standards:

Although individually most of the systems are well established, further research is required to integrate systems and processes across multiple phases of lifecycle. To achieve this, standardisation of data is becoming essential. The use of SOAP and XML seems common across all the systems proposed across the product lifecycle due to their ability to overcome firewall restrictions and their integration scalability

and flexibility. What this study showed is the importance of developing standards that not only cope with the existing CAD formats but also support the standardisation of PLM, PDM and ERP systems. Further research is required to extend the standardisation of enterprise systems which will improve collaboration among OEMs, suppliers and customers and as a result reduce the cost of implementing and maintaining multiple systems.

An area that the automotive sector could benefited and learn from is the defence sector's use of standards used within the maintenance systems. Through the literature review a few publications that aim to implement IVHM systems within the automotive sector, using the OSA-CBM standard, were identified. Developing or adopting existing standards would allow automotive companies to standardise their maintenance applications and as a result reduce the amount of effort required in integrating multiple systems across the supply chain. Further research is required to allow automotive manufacturers realise the benefits of adopting or developing an IVHM equivalent for the automotive sector.

9.5. Conclusions

The purpose of this section is to compare the achievements of this research against the aim and objectives stated in Chapter 3. This section will provide a clear justification of how the research objectives have been satisfied. The aim of this research was "**to develop a system architecture for integrating PLM systems with maintenance information to support root cause analysis** by allowing engineers to visualise **cross supply chain data** in a single environment. By integrating product-data from PLM systems with warranty claims, vehicle diagnostics and technical publications, it is expected that engineers will be able to improve the root cause analysis and close the information gaps". The following discussion analyses each research objective individually:

1. *Review current challenges associated with information sharing in supply chain during multiple phases of the produce lifecycle including maintenance*

    This research carried out a structured literature review in the area of information sharing in supply chain during multiple phases of the product lifecycle. The classification framework helped in assessing existing literature, identifying research gaps and providing directions for further research. In addition, the area of

root cause analysis was also reviewed to ensure that no meaningful publications have been missed.

2. *Capture industry practice and challenges related to information flow and the use of PLM systems in supply chain*

As part of this research, an industry survey was carried out in order to identify and capture the current challenges related to information flow and the use of PLM systems in supply chain. The findings of this survey reflected the need to develop automated information management systems that are able to integrate multiple systems and as result share more accurate and complete information. The outcome of this survey fed into the design of the proposed system architecture, as the functionality of the proposed solution was designed to address some of the challenges that were identified through this survey.

3. *Capture current state process maps to demonstrate the flow and use of maintenance information using an automotive case study*

This objective demonstrated through the current state process maps how automotive vehicle manufacturers and component suppliers utilise maintenance data to conduct root cause analysis. The process maps represent the as-is state and allowed the researcher to capture current challenges and identify opportunities which were then used in defining the scope of the system architecture. The current state maps demonstrate the focus areas for the system architecture.

4. *Develop a system architecture for integrating PLM systems with maintenance information across the supply chain to support root cause analysis*

The outcome of this research was developed through an in-depth requirements elicitation and analysis which ensured that the system developed satisfies the business needs and addresses the research gaps identified. The three architectural views (use case, static, dynamic) demonstrated the i) the interactions among the end users and the proposed system, ii) the structure and dependencies between the different elements of the proposed system, iii) and the sequence of tasks that occur within the proposed system over time.

This research proposes a novel system architecture that integrates PLM systems with cross supply chain maintenance information and through the use of two case

studies shows the benefits that can be achieved in root cause analysis. This research extends the findings of Lee et al. (2008) further, not only by showing the potential of PLM systems within the maintenance procedures but also by demonstrating evidence of the benefits that can be achieved through the integration of service manuals, engineering documents, warranty claims and vehicle diagnostics. The proposed solution provides all the required information to warranty engineers in order to identify the root cause of an issue and close the information gaps. This research also demonstrated that information and knowledge coming back from maintenance experts and aggregated through the proposed system can support PD engineers to eliminate recurring issues on new product parts. The system architecture could potentially be extended further to include other areas of the automotive sector where the integration of PLM systems and maintenance information could bring benefits.

5. *Develop scenarios to demonstrate the usability of the system architecture in terms of its support to root cause analysis using an automotive case study*

Three scenarios were developed to demonstrate the applicability of the system architecture. These scenarios determine the flow of the system by examining all the steps followed, starting with the search criteria defined by the user, the interactions with the system throughout the root cause analysis, the example data presented in the UI, and finally the outcome of the root cause analysis.

6. *Validate the system architecture using an automotive case study and evaluate the applicability of the architecture using a defence case study*

The system architecture was validated using six semi-structured interviews with experts from the automotive sector. All experts assessed the system architecture and recognised the benefits that could be achieved and its contribution to the root cause analysis. Experts stated that the proposed solution allows engineers to integrate the required amount of information by reducing the time searching for information and by providing a standardised platform across departments and suppliers. Through the proposed solution, engineers will be able to identify information gaps within the technical documentation and as a result improve the root-cause analysis.

In addition, the system architecture was evaluated using a case study from the defence sector. This case study demonstrates that the proposed solution could support both the automotive and the defence sectors. The outcome of the evaluation case study highlighted also some important similarities and differences between the two sectors and revealed opportunities for further research. The automotive sector could potentially benefited by adopting the well-defined standards used in the defence sector (e.g. OSA-CBM for vehicle diagnostics and S1000D standard for structuring the automotive technical documentations.)

In summary, the thesis has achieved the stated aim and objectives by developing a system architecture for integrating PLM systems with maintenance information to support root cause analysis by allowing engineers to visualise cross supply chain data in a single environment. In this way, this research has proposed a fully tested and validated system architecture that supports case studies from both the automotive and the defence sectors.

This research addressed the research gaps by demonstrating that:

1. A system architecture can be developed to integrate PLM systems with maintenance information to allow the utilisation of knowledge and data across the product lifecycle
2. Network can be treated as a virtual warehouse where maintenance data are integrated and shared within the supply chain
3. Product data can be utilised in conjunction with maintenance information to support warranty and PD engineers
4. Disparate pieces of data can be integrated where later data mining techniques could potentially be applied.

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Appendix A: Methodology Selection for Analysing Supply Chain Issues Related to Information Flow and the Use of PLM Systems

The literature review was conducted in order to identify, measure and prioritise the perceived importance of supply chain issues related to information flow and the use of PLM systems within the automotive industry.

The first stream of research utilised structured questionnaires to weight and prioritise issues identified within the literature using statistical methods, with data collected from practitioners. This approach allowed researchers to collect a wider sample of primary data and as a result have a stronger prioritisation outcome. Fawcett et al. (2008) analysed data collected both from the literature and a mail survey and demonstrates benefits, barriers and bridges to a successful collaboration in strategic SCM. Fawcett et al. (2008) identified that although technology and information are major barriers, people issues are more significant as they are also the key bridge to successful collaboration. However, it is worth mentioning that inadequate information systems were highlighted as the single greatest barrier in this study. Pujara et al. (2011) analysed barriers identified in the literature through Interpretive Structural Modelling (ISM) methodology and classified them in four categories based on their drivers and their dependence power. Pujara et al. (2011) concluded that lack of top management commitment and the poor understanding of SCM concepts are the most important barriers. Similarly, Jharkharia and Shankar (2005) used ISM methodology to demonstrate the mutual influences among the barriers within the IT-enabled supply chain. Jharkharia and Shankar (2005) results indicated that lack of awareness about use of IT in supply chains, disparity in trading partners' capabilities, lack of funds and poor IT infrastructure are significant barriers and should be taken as high priority. Archer et al. (2008) analysed data collected in telephone interviews in order to identify issues and barriers to the adoption of internet business procurement and supply chain solutions. Archer et al. (2008) demonstrated that SMEs cannot justify the investment in complete interoperable systems due to the low level of data transactions. Therefore SMEs await for more standardised and easier to implement solutions.

The second stream in which this work falls into uses the outcome from the literature to support interviews but the supply chain issues and barriers captured are open to the interviewees. This approach allows the researchers to capture issues and

barriers that come directly from industry without limiting the outcome to a certain number of predetermined issues. Childerhouse et al. (2003) demonstrate the barriers of information flow in SCM by using the Cardiff process change model that clusters issues into four key areas: technological, cultural, financial and organisational. Childerhouse et al. (2003) state that "sharing" culture is key in order to improve supply chain collaboration even by using existing technology. Similarly, Cheikhrouhou et al. (2012) highlight that human factors such as trust, power, competence and equity are crucial for any successful collaborative network. Evgeniou and Cartwright (2005) focus on a particular area of Information Management (IM), that of market research data and propose a framework that categorises barriers within information intelligence into three categories: behavioural, process and organisational. Garengo and Panizzolo (2013) propose an integrated product development (IPD) framework which consists of three groups of integration enablers such as organisational, technological and methodology. Tsinopoulos and Bell (2010) analyse case studies from three small UK ETO companies and conclude that the three key barriers to supply chain integration are: management awareness of the benefits of these systems, the perceived risk to the business and to information security and the intensity of skills needed for their successful implementation. Garengo and Parizzolo (2013) validate their framework through interviews with 22 Italian SMEs and proved that innovative technological tools are essential in supporting the supplier involvement in IPD. Sheriff et al. (2012) analysed data captured through semi-structured interviews in order to understand the nature of Information Management in Architecture and Engineering (A&E) organizations operating in the UK construction industry. Sheriff et al. (2012) highlights the importance of developing holistically aligned strategies for IM, better tools to improve the data exchange and appropriate measurement criteria for determining the effectiveness of IM strategies. Hicks et al. (2006) analyse issues collected from engineering SMEs in the Advanced Engineering sector to explore the dependencies and the causalities between core issues in order to gain understanding and support the development of future information management strategies. Hicks et al. (2006) concluded that over two-third of the issues are caused by inadequate information systems or their implementation.

It is worth saying that both streams have advantages and limitations and the selection depends on the purpose and the resources of each research study. One of

the main drawbacks for the first stream of methodology is that questionnaires used to prioritise the issues, were largely based on predetermined options identified from literature, which did not allow for the capture of issues directly from industry. Although most of the studies identified in the literature examine holistically the area of issues in supply chain information exchange, the majority of examples mentioned concerning types of information exchanged and enterprise systems used, are outside the scope of PD. Another finding from the literature is that the majority of studies aim to provide strategic directions and therefore most of the issues captured where kept high level. For example the issue of inadequate information systems was highlighted extensively without though providing guidance on what needs to be addressed technically or strategically moving forward.

Appendix B: Data Collection Question Sheet

B.1 Current State Process Maps Questions

Process

1. How many people are involved in the process?
2. Is the same process followed from every department within the business? (Chassis, Powertrain, Body Engineering, Electrical etc.)
3. When are suppliers involved in the process?
4. What are the inputs/outputs of each task within the process?
5. How do you cluster the different types of claims?
6. What are the current targets for each claim category? (CAT 1,2,3)
7. How often do you review the suppliers' decisions recorded in the warranty system?
8. What type of questions do you aim to answer during the root cause analysis?
9. (For Suppliers) How often do you receive a pallet in the warranty center?
10. (For Suppliers) How do you analyse data for parts outside UK and US and who is responsible for covering the cost?

Information

1. What Information do you required in order to identify the root cause of an issue?
    a. What are the issues associated with the information involved
2. How often do you find that decisions were made without the right level of information?
3. What type of information would you like to utilise from the PLM system?
4. What types of data would you like to access from suppliers' systems?
5. How do you link an existing quality project raised that is related with a new claim? (Search by VIN, Project Code?)
6. Are vehicle diagnostics utilised in the current process when dealing with electrical claims?
7. Do you utilise vehicle diagnostics in the quality history process for DFMEA?
8. In which part of your area do you think information visibility should be improved?

Systems

1. In which systems do you require access to?
    a. What are the issues associated with the systems involved
2. How do you currently access the systems? (Manually? Each system individually?)
3. How much do you currently utilise PLM systems within the warranty process?
4. Do you have access to the PLM systems?
5. What level of access do key suppliers have?
    a. In warranty systems
    b. In PLM systems
6. Which systems do you currently use in this process? (Quality History for DFMEA/Warranty process)
7. Do you export data from the systems to conduct further analysis?

8. How often do you face problems with the different file formats used?
9. How the part numbering is related to your systems? Do you use a specific part number throughout birth to death?
10. Is the warranty system integrated with the vehicle feedback database?
11. (For Suppliers) How do you currently access the OEMs systems?
12. (For Suppliers) In which systems do you currently have access to within the warranty process?
    a. What level of access do you currently have?

B.2 Future State Questions

To-be

1. Which systems/What information would you like to see in the process that you currently have no access to?
2. What level of integration from a PLM system do you require during the root cause analysis? (Quality History/Warranty procedure)
3. What functionality do you expect from the system?
4. How type of search functionality do you require from the system?
5. Do you require full access to the system integrated?
6. Would you like to be able to open the actual system if further analysis is required?
7. Do you believe that utilising an immersive environment (CAVE, Powerwall) would allow you to make more informed decisions?
8. How do you currently utilise the existing VR tools?

Benefits

1. What types of benefits do you expect using this application?
2. Do you foresee that the number of people involved in the process will be reduced?
3. Do you foresee that the time spent searching for information will be reduced?
4. Do you foresee that the quality of root cause analysis will be improved?
5. Have you seen similar capabilities elsewhere?
6. In which part of your area do you think information visibility will be improved?

Specific to Data/IT Managers

Systems

1. What type of the platform is your system based on (Oracle, PostgreSQL, mySQL)?
    a. Is it based on a relational sequence database?
2. Is there an existing API that the proposed architecture could utilise to interface your system?
3. Are you planning to develop an API in your system to allow the system to be integrated via web-services?
4. What is the current number of users?

Information Linkage

1. What primary keys do you use within your system?
2. If PLM systems utilise a part number and sub-system code how the information within your system could be linked?

Appendix C: Requirements Catalogue

This section provides the full list of functional and non-functional requirements. Each requirements is associated with three key attributes:

- Status – Shows if the requirements was implemented in the POC system or it remained in an approved state,
- Priority – Shows the prioritisation of requirements using the MoSCoW technique
- Difficulty – Shows how difficult is the implementation of each requirement.

C.1 Functional Requirements

Accessibility
REQ10- Extract breakdown reports

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Low
Version: 1.4

The solution shall be able to access and extract the vehicle information, the customer verbatim and technician verbatim for each breakdown report associated with the searched term from the warranty system

REQ11- Access PDM/PLM to extract product data

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium
Version: 1.6

The solution shall be able to extract a light weight CAD representation of the searched term, ideally one parent and all children.

REQ12- Access information provided to the dealers

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* High
Version: 1.2

The user shall be able to review the published Technical Service bulletins, diagnostics and service manuals associated with the searched VIN ton ensure that dealers had enough information to make a repair

REQ13- Access customer verbatim and dealer diagnosis

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Low
Version: 1.4

The user shall be able to selected a warranty claim based on the searched VIN and access the customer's and technician's verbatim and the dealer information from the warranty system

REQ14- Access PDM/PLM to extract product data related to a claim

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium
Version: 1.4

The solution shall be able to obtain the part number associated with a claim and extract a light weight CAD representation of the searched term, ideally one parent and all children

REQ15- Access vehicle history (RC)

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Low
                                   Version: 1.4

The solution shall be able the technical verbatim and customer verbatim for each warranty claim, the technical verbatim and country from the breakdown reports and customer verbatim for the surveys associated with the searched VIN.

REQ16- Access vehicle diagnostics (VIN)

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Medium
                                   Version: 1.4

The solution shall be able to access and extract Diagnostic Trouble Codes associated with a specific claim of a searched VIN from the Vehicle diagnostics database.

REQ17- Access PSW status

«Functional»   *Status:* Approved   *Priority:* Could   *Difficulty:* High
                                   Version: 1.4

The solution shall be able to extract the Part Submission Warranty (PSW) status for the searched part/sub-system from the APQP Docs system

REQ19- Access the BOM structure

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* High
                                   Version: 1.4

The solution shall be able to use the BOM structure in order to allow the user to access different levels of assembly.

REQ2- Access stopped shipments

«Functional»   *Status:* Approved   *Priority:* Want   *Difficulty:* High
                                   Version: 1.4

The solution shall be able to extract past campaigns and stopped shipments related to supplier history on previous programmes in order to understand top priority quality failures

REQ23- Access quality projects related to a claim

«Functional»   *Status:* Approved   *Priority:* Should   *Difficulty:* Medium
                                   Version: 1.4

The solution shall be able to extract the description and the status of quality projects related to a selected claim in order to allow the user to assess if fault reviewed is/was addressed from an ongoing or closed project.

REQ3- Review the history of a part/sub-system/system

«Functional»   *Status:* Approved   *Priority:* Must   *Difficulty:* Medium
                                   Version: 1.4

The solution shall be able to extract the Repairs/1000 KPI and the claims of a part/Sub-system/system from the warranty system

REQ4- Filter the returned results

«Functional» *Status:* Implemented *Priority:* Should *Difficulty:* Medium
Version: 1.4

The solution shall be able to filter the returned results using at minimum the Country of origin or the Months-In-Service criteria

REQ5- Review the quality history of a part/sub-system

«Functional» *Status:* Approved *Priority:* Must *Difficulty:* High
Version: 1.4

The user shall be able to review the quality history of a part/sub=system/system using data extracted from the warranty database based on a search term depending on the scope of the FMEA (Part_ID, sub-system_code)

REQ56-Access documents related to a part number

«Functional» *Status:* Approved *Priority:* Want *Difficulty:* Medium
Version: 1.4

The system shall be able to allow the users to access relevant document from PLM systems associated with a part number. These could be either change requests, work orders, issues, concessions or limitations)

REQ59-Access vehicle description

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Low
Version: 1.4

The solution shall be able to extract the vehicle description based on a VIN such as brand, engine type, transmission type, production year etc.

REQ6 - Access the "Voice of the Customer" data (QH)

«Functional» *Status:* Approved *Priority:* Must *Difficulty:* Medium
Version: 1.4

The user shall be able to extract the customer verbatim from any survey associated with the searched part or sub-system in order to identify soft-failures which can be used to support the DFMEA process

REQ66-Access vehicle diagnostics (module)

«Functional» *Status:* Approved *Priority:* Must *Difficulty:* Medium
Version: 1.4

The solution shall be able to access and extract Diagnostic Trouble Codes associated with a specific module for a specific period in time.

REQ7- Extract survey data

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium
Version: 1.4

The solution shall be able to access and extract the vehicle information, customer and technician verbatim for each customer survey associated with the searched term from the warranty system

REQ8- Review the cost of a part/sub-system/system

«Functional»   *Status:* Approved   *Priority:* Should   *Difficulty:* High
                                          Version: 1.4

The solution shall be able to extract the Cost Per Unit (CPU) and the claims of a part/sub_assembly_code/Function Group_Code from the Warranty system

REQ9- Review the sufficiency plans

«Functional»   *Status:* Approved   *Priority:* Should   *Difficulty:* High
                                          Version: 1.4

The solution shall be able to extract or re-create the sufficiency plans of a sub-system level or Function group level from the Warranty database

Administration

REQ36- Login to the system

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Low
                                            Version: 1.4

The solution shall request users to login in order to define a search term

REQ37- Error message for login failure

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Low
                                            Version: 1.4

In case of a wrong password, the solution shall provide an error message requesting the user to re-enter their username and password again

REQ38- Administration login

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Low
                                            Version: 1.4

The solution shall be able to recognise the administrator based on the username and password before they are allowed to conduct any administrative tasks

REQ39-Silo registration

«Functional»   *Status:* Implemented   *Priority:* Should   *Difficulty:* Low
                                            Version: 1.4

The solution shall provide the administration the capability to easily define and register additional silos

REQ40- Define/Modify workflow

«Functional»   *Status:* Implemented   *Priority:* Should   *Difficulty:* Low
                                            Version: 1.4

The solution shall allow the administrator to modify/define a new workflow to allow the functionality of the system to be expanded or customised

Generic

REQ26- Annotate actions

«Functional»   *Status:* Approved   *Priority:* Could   *Difficulty:* Low
                                          Version: 1.4

The solution shall be able to allow the user to record and store actions and notes for each session.

REQ27- Collate quality history to run a robust FMEA

«Functional» *Status:* Approved *Priority:* Must *Difficulty:* High
Version: 1.4

The user shall utilise various information sources to produce a comprehensive list of past concerns/failures and their root causes, based on internal and external data

REQ28- Assess returned parts and assign liabilities

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* High
Version: 1.4

The user shall gather all the relevant information pertinent to a claim to review a returned part and assign a liability (CAT1,CAT2,CAT3)

REQ29- Support in identifying gaps in bulletin and diagnostics

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium
Version: 1.4

The solution shall be able to support the engineers to review and identify gaps in bulletin and diagnostics provided to the dealer in order to ensure that the dealer had enough information to make a repair

REQ30- Save a session for future reference

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium
Version: 1.4

The solution shall allow the user to save a session with the returned results for future reference. The period that the data will be available needs to be defined from the user.

REQ46- Review categorised claims

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium
Version: 1.4

The solution shall allow OEM warranty engineers to review the session file that suppliers used and any additional testing data in order to ensure that suppliers were able to replicate the actual installation environments and as a result categorise the claim

REQ55- Generate graphs

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* High
Version: 1.4

The solution shall be able to generate Pareto charts for claims and cost data based on the selected criteria (at a minimum: Country of origin, Months in Service)

REQ58-Package information in a single object

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium
Version: 1.4

The solution shall be able to pack the information in a single object which can be shared to suppliers or other OEMs

REQ60-Follow standards

«Functional»   *Status:* Approved   *Priority:* Could   *Difficulty:* High
                                      Version: 1.4

The system should shall allow suppliers to interface the system via published standards (PLCS for PLM, XML for web-services)

REQ65-Predefine search results

«Functional»   *Status:* Approved   *Priority:* Could   *Difficulty:* Low
                                      Version: 1.4

The system should allow users to predefine search results to improve the performance of the system. Therefore if a large number of claims is required for review, the users could provide a list with VIN numbers and the system will prepare the data for the next hour/day.

Search

REQ20- Search using a Part/Sub-system code

«Functional»   *Status:* Approved   *Priority:* Must   *Difficulty:* Medium
                                      Version: 1.4

The solution shall be able to search within the PLM and the other databases using a Part_ID, sub-assembly_Code

REQ21- Search using a part/sub-system code related to a claim

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Medium
                                         Version: 1.4

The solution shall be able to search the PLM and the APQP docs system using a part_ID and a sub-assembly_Code in order to extract product data related to a reviewed claim

REQ22- Search using a VIN number

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Low
                                         Version: 1.4

The solution shall be able to search within the warranty system, the vehicle diagnostics database, the tech. pubs system using the Vehicle Identification Number (VIN).

Translation

REQ1- Repurpose the returned results

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Medium
                                         Version: 1.4

The solution shall be able to filter on the returned tabular results to visualise only the relevant instances

REQ2- Repurpose a CAD model into a light-version visualisation file

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Medium
                                         Version: 1.4

The solution shall be able to convert the CAD file into a light version file (JT preferred)

Visualisation

REQ47- Visualise the vehicle description

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Low

Version: 1.4

The solution shall be able to visualise the vehicle description for the searched VIN as extracted from the warranty database

REQ48- Visualise the vehicle history

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Low

Version: 1.4

The solution shall be able to visualise the vehicle history for the searched VIN (claims, breakdown reports, customer surveys)

REQ49-Visualise a vehicle representation

«Functional» *Status:* Implemented *Priority:* Could *Difficulty:* High

Version: 1.4

The solution shall be able to visualise a vehicle representation in a light format

REQ50-Generate heatmap on a CAD model

«Functional» *Status:* Implemented *Priority:* Should *Difficulty:* High

Version: 1.4

The solution shall be able to generate a heatmap against the CAD representation (either on the vehicle representation or the sub-assembly) based on multiple criteria (claims, cost, country of origin etc)

REQ51- View product structure

«Functional» *Status:* Implemented *Priority:* Must *Difficulty:* Medium

Version: 1.4

The solution shall provide the user with the ability to hide and view parts from the BOM structure.

REQ53- View the data sources

«Functional» *Status:* Implemented *Priority:* Should *Difficulty:* Low

Version: 1.4

The solution shall be able to visualise the sources that the data were extracted from, so the engineers are aware of types of data missing

REQ54- Visualise graphs

«Functional» *Status:* Implemented *Priority:* Should *Difficulty:* Medium

Version: 1.4

The solution shall be able to visualise graphs generated from the raw data extracted

REQ61-User interaction

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Medium
Version: 1.4

The system should allow the user to interact with the information, opening and closing sources, possibly by interactively choosing from the available components and sources and allowing the user to "pin" some information to the display to compare with other information

REQ62-Visualise the CAD representation

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Medium
Version: 1.4

The system should allow the user to visualise a part searched, the parts related to it and go to higher or lower levels using the assembly structure

REQ64-Multiple platforms

«Functional»   *Status:* Implemented   *Priority:* Should   *Difficulty:* High
Version: 1.4

The system should allow the data aggregated to be visualised in multiple formats such as desktops, tablets or even CAVEs

Supply Chain

REQ24- Access supplier test data

«Functional»   *Status:* Approved   *Priority:* Could   *Difficulty:* High
Version: 1.4

The solution shall be easily customisable and therefore allow suppliers to integrate their internal systems in order to combine their internal test data with the claims obtained from warranty system.

REQ25- Exchange information through the supply chain

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Medium
Version: 1.4

The solution shall be able to pack different data formats within a single object and share the information within the supply chain, either with the OEM or sub-suppliers

C.2 Non-Functional Requirements

Performance

REQ31- CAD translation

«Functional»   *Status:* Approved   *Priority:* Could   *Difficulty:* High
Version: 1.4

The solution shall be able to perform a CAD translation and return the CAD results in less than one minute.

REQ33- Lookup performance

«Functional»   *Status:* Approved   *Priority:* Could   *Difficulty:* Medium
                                       Version: 1.4

The feature lookup facility shall respond within 20 seconds for 95% of all queries and 30 seconds for 100% of all queries

REQ34- Raise warnings

«Functional»   *Status:* Approved   *Priority:* Should   *Difficulty:* Medium
                                       Version: 1.4

The system shall notify the user if CAD visualisation or translation will exceed 120 seconds and ask for permission

Scalability

REQ32- Scalable to multiple visual environments

«Functional»   *Status:* Implemented   *Priority:* Want   *Difficulty:* High
                                       Version: 1.4

The solution shall be able to visualise the extracted data into multiple visual environments such as portable devices, desktops and 3D environments.

REQ35-Customisable solution

«Functional»   *Status:* Approved   *Priority:* Should   *Difficulty:* Medium
                                       Version: 1.4

The solution shall be able to be easily customised and therefore increase the number of systems interacted without major modifications in the core engine. Preferably web-services should be used.

REQ57-Query Interfaces

«Functional»   *Status:* Approved   *Priority:* Should   *Difficulty:* High
                                       Version: 1.4

Query interfaces should be generic and include explicit mappings between the interface standard (the queries and keys) to the method and data used to access the data sources

Security

REQ41-Supply Chain access

«Functional»   *Status:* Implemented   *Priority:* Must   *Difficulty:* Low
                                       Version: 1.4

The solution shall be able to authorise and control the accessibility of users outside the OEMs network within the supply chain

REQ42- Authenticate the user

«Functional»   *Status:* Approved   *Priority:* Should   *Difficulty:* Medium
                                       Version: 1.4

The solution shall be able to ensure that user logons are authorised in line with the company's policies.

REQ43- Security standards

«Functional»   *Status:* Approved   *Priority:* Want   *Difficulty:* High
                                        Version: 1.4

The system shall comply with the company's security standards.

REQ44- Limit system access rights

«Functional»   *Status:* Approved   *Priority:* Want   *Difficulty:* High
                                         Version: 1.4

The solution shall limit System Access rights and the ability to modify data to the people with the associated rights only

REQ45- Data encryption

«Functional»   *Status:* Implemented   *Priority:* Could   *Difficulty:* Medium
                                         Version: 1.4

The system shall encrypt client information during all data transmissions using 256-bit AES (Advanced Encryption Standard) encryption.

Appendix D – Application Interfaces

The interfaces described in this appendix will support the development of the web-services. The inputs described in each table define the "questions" that each web-service will need to ask for each system individually and the output represents the expected returned results.

INT1 Obtain VIN Details

ID/Name	INT1/Obtain Vehicle Description, voice of the customer and vehicle's history		
Description	The purpose of this interface is to obtain the Vehicle description the vehicle's history as well as the voice of the customer in order to understand the relationship between the reviewed part and previous faults.		
Level	**Input** parameters	Format	Length
01	Vehicle Identification Number (VIN)	String + Numbers	14-18 characters

Level	**Output** parameters	Format	Formatting Rules/Comments
01	Vehicle Description	SQL DB	
02	Brand		
02	Vehicle Line		
02	Model Year		
02	Plant		
02	Body Style		
02	Drive		
02	Transmission		
02	Engine		
02	Sales Dealer		
02	Production Date		
02	Warranty Start Date		
02	Sold Date		
01	Vehicle Claims	SQL DB	
02	Customer Verbatim		
02	Technical Verbatim		
02	Part Number		
02	Part Description		
02	Repair Date		
02	Country Repaired		
02	Cost of the repair		
01	Voice of the customer	SQL DB	
02	Breakdown Rec reports		
03	DTC Comments		
03	Verbatim Comment		

03	Time in Service		
03	Mileage		
03	Breakdown data		
03	Component Fault		
03	Breakdown Rec. component		
03	Component		
03	Fault Description		
03	Initial Diagnosed fault		
03	Project Ref		
02	Surveys		
03	Category		
03	Associated verbatim		
03	Approximate survey data		
03	Confidence in analysis		
03	Function group		

INT2 Collate quality history and voice of the customer

ID/Name	INT2/Collate quality history and voice of the customer	
Description	The purpose of this interface is to obtain the quality history for the subject system/subsystem/component	
Level	**Input** parameters	Format
03	Function Group (FG)	
04	Sub-system code	

Level	**Output** parameters	Format	Formatting Rules/Comments
01	Vehicle Description	SQL DB	
02	Brand		
02	Vehicle Line		
02	Model Year		
02	Plant		
02	Body Style		
02	Drive		
02	Transmission		
02	Engine		
02	Sales Dealer		
02	Production Date		
02	Warranty Start Date		
02	Sold Date		
01	Claim History	SQL DB	
02	Customer Verbatim		

02	Technical Verbatim		
02	Part Number		
02	Part Description		
02	Repair Date		
02	Country Repaired		
02	Cost of the repair		
01	Voice of the customer	SQL DB	
02	Breakdown recovery reports		
03	Project Ref		
03	Type		
03	Customer Verbatim		
03	Technician Verbatim		
03	Component Fault		
03	Component Name		
03	Fault Description		
02	Surveys		
03	Category		
03	Function Group		
03	Detect Type		
01	Project details	SQL DB	
02	Project ID		
02	Overall Project Status		
02	Project Type		
02	Component fault		
02	Supplier plant name		
02	Vehicle Line		
02	Plant		

PLM Interface
INT3 Obtain CAD 3D model

ID/Name	INT3/Obtain CAD 3D Model		
Description	The purpose of this interface is to obtain a visual representation of a part or/and a sub-assembly		
Level	**Input** parameters	Format	Length
01	Part Number	String + Number	11-16 characters
01	Sub System code	Number	6 numbers

Level	**Output** parameters	Format	Formatting Rules/Comments
01	CAD Model	JT/ CAD native	
01	Part Documentation	pdf	

APQP Docs Interface
INT4 Obtain Part Submission Warranty information

ID/Name		INT4/ Obtain Part Submission Warranty information	
Description		The purpose of this interface is to obtain the Part Submission Warranty status. PSW Is an industry-standard document required for all newly tooled or revised products in which the supplier confirms that inspections and tests on production parts show conformance to customer requirements.	
Level	**Input** parameters	Format	Length
01	Part Number	String + Number	11-16 characters

Level	**Output** parameters	Format	Length
01	Part-Submission Warranty Status	SQL DB	
02	Actual PSW sign-off date		

INT5 Obtain information on stop shipments

ID/Name	INT5 Obtain information on past campaigns and stop shipments			
Description	The purpose of this interface is to obtain information in order to understand stopped shipments on previous programmes			
Level	**Input** parameters	Format	Length	Formatting Rules/Comments
01	Programme			

Level	**Output** parameters	Format	Length	Formatting Rules/Comments
01	Stopped Shipments			

Supplier Data Interface
INT6 Obtain Test data

ID/Name		INT6/ Obtain Supplier Test data		
Description		The purpose of this interface is to review test data captured within the suppliers infrastructure against the part number reviewed		
Level	**Input** parameters	Format	Length	Formatting Rules/Comments
01	Part Number			

Level	**Output** parameters	Format	Length	Formatting Rules/Comments

01	Test Instructions			
01	Acceptance Criteria			

Technical Publications Interface

INT 7 Open technical publications application

ID/Name	INT7/Open Technical publications application
Description	The purpose of this interface is to use the VIN search in order to construct a URL link to obtain published material such as Technical Service Manuals, Electrical Diagrams, Technical Bulletins, and Diagnostic Release Notes in order to ensure that the dealer had all the appropriate information in order to fix an issue.

Level	**Input** parameters	Format	Length
01	VIN number	String + Numbers	14-18 characters

Level	**Output** parameters	Format	Formatting Rules/Comments
01	VIN URL	html	

Vehicle Feedback Database Interface

INT 8 Obtain the voice of the vehicle

ID/Name	INT8/Obtain the voice of the vehicle (telematics)
Description	The purpose of this interface is to collate data DTC (Diagnostic Trouble Code) information from customer vehicles in order to understand what the telematics recorded.

Level	**Input** parameters	Format	Formatting Rules/Comments
01	VIN number	String + Numbers	14-18 characters
01	Module	Numbers	
01	Date	Numbers/Date	

Level	**Output** parameters	Format
01	DTC (Diagnostic Trouble codes) List	tabular
02	Module	
02	Display DTC	
02	DTC Description	
02	Software Part Number	
02	Fault type description	
02	Count	