Centre for Innovative and Collaborative Construction Engineering

The Application of Product Service Systems for Hydraulic Excavators

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THE APPLICATION OF PRODUCT SERVICE SYSTEMS FOR HYDRAULIC EXCAVATORS

By
Ka Chun Felix Ng

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

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I would like to dedicate this work to my dad and my uncles, who passed away many years ago. May God rest their souls and look upon me from the kingdom of God above.

ABSTRACT

The concept of Product Service Systems (PSS) was introduced as an alternative business model for Original Equipment Manufacturers (OEMs), who are motivated to shift their traditional manufacturing focus towards the after-sale service, to meet the market demand and gain additional profit and market share. A PSS is a system that integrates product and service as one package at the point of sale. It is increasingly popular because customers are demanding more supplier involvement to prolong and maintain the life of products they purchase and keep them functioning at maximum performance levels. Furthermore, it is also widely accepted within the community that the PSS concepts enhance competitiveness and promote the shift towards sustainable practices and society simultaneously. The flexibility of different PSS models allows OEMs to open new opportunities to improve relationships between customers and suppliers, or better understand the strengths and weaknesses of their own business strategy and products.

Since the introduction of PSS in the 1990s, research communities have contributed greatly to the development of the design methodologies, as well as defining the purpose and benefits of PSS. However, despite such interest, most of their proposals do not have substantial focus on the much needed commercial aspects of PSS product monitoring and data management strategy etc. in business environments. For example, there is a lack of quantitative methods and assessment tools to help OEMs or service providers to understand the prerequisites before implementation and the assessment of a successful PSS application. Furthermore, most PSS research concentrates its implementation on high value products such as Rolls Royce Engines or on products with predictable usage patterns. As a result, OEMs and service providers for medium value products with volatile usage patterns, e.g. the off-highway equipment industry, often struggle to offer more than preventative maintenance, in the most simplistic type of PSS.

This thesis presents a roadmap that has been developed through the assessment of academic and industrial literature and detailed knowledge acquisition and analysis within a commercial capacity. It is aimed at clarifying the required prerequisites such as product usage data, real time monitoring strategy, maintenance strategy etc. that any off-highway equipment OEMs need to determine and validate their readiness level towards the adoption of a use-oriented PSS driven business model. The assessments were conducted to identify the needs and difficulties of a typical off-highway equipment OEM to operate PSS. The roadmap views PSS as a system which consists of the flow and transformation of data, and provides various functions and support in the form of information and knowledge within each individual function within the roadmap.

KEY WORDS

Product Service System, Construction Equipment, Product Monitoring, Data Mining, Knowledge Hub, Condition Based Maintenance

USED ACRONYMS / ABBREVIATIONS

ACS	The Accounts Commission of Scotland
BCD	Bucket Cut Depth
BS	British Standards
BSI	British Standards Institution
CANBUS	Control Area Network Bus
CAT	Caterpillar Incorporated
CBM	Condition Base Maintenance
CEC	Customer Experience Centre
CECE	Committee for European Construction Equipment
CH4	Methane
CICE	Centre for Innovative and Collaborative Construction Engineering
CO2	Carbon Dioxide
CS	Customer Satisfaction
Cu	Copper
DECC	Department of Energy and Climate Change
DEF	Diesel Exhaust Fluid
DEFRA	The Department for Environment Food & Rural Affairs
DM	Data Mining
DPF	Diesel Particular Filter
DTC	Diagnostic Trouble Code
ECU	Electronic Control Unit
EIPA	The European Institute of Public Administration
EngD	Engineering Doctorate
EPSRC	The Engineering and Physical Sciences Research Council
Fe	Iron
FMI	Failure Mode Identifier
FTB	Failure Type Byte
GHG	Green House Gas
GPRS	General Packet Radio Service
GPS	Global Positioning System
ICP/OES	Inductively coupled plasma optical emission spectrometry
ISO	International Standard Organisation
JCB	J. C. Bamford Excavators Limited
KH	Knowledge Hub
KOM	Komatsu Limited
MESA	The Maintenance Engineering Society of Australia
MOD	Ministry of Defence
N2O	Nitrous Oxide
NFPC	National Fluid Power Centre
NRMM	Non-Road Mobile Machinery

OBD	On-Board Diagnostic
ODP	Ozone Layer Depletion
OEM	Original Equipment Manufacturer
PAR	Performance Ability Ratio
PGN	Parameter Group Number
PHD	Doctor of Philosophy
PM	Product Monitoring
PPM	Part Per Million
PSS	Product Service System
R&D	Research and Development
RCA	Root Cause Analysis
RE	Research Engineer
ROI	Return on Investment
RPM	Revolutions Per Minute
SA	Source Address
SAE	Society of Automotive Engineers
SOPS	Standard Operation Procedures
SPN	Suspect Parameter Number
SRI	Southwest Research Institute
USAF	United States Air Force

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LIST OF PAPERS

The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research. The first four publications are included in the thesis in the appendix.

PUBLICATION 1 – CONFERENCE PAPER - PUBLISHED (APPENDIX V)

Ng, F., Harding, J. and Rosamond, E., 2012. A Customers' Satisfaction Based Framework for Continuous Development of PSS. *Proceedings of the 4th CIRP International Conference on Industrial Product-Service Systems, Tokyo, Japan, November 8th - 9th, 2012,* pp. 239-244

PUBLICATION 2 – JOURNAL PAPER – PUBLISHED (APPENDIX W)

Ng, F., Harding, J. and Glass, J., 2015. An eco-approach to optimise efficiency and productivity of a hydraulic excavator, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.06.110

PUBLICATION 3 – JOURNAL PAPER – ACCEPTED (APPENDIX X)

Ng, F., Harding, J. and Glass, J., 2016. Improving hydraulic excavator performance through in line hydraulic oil contamination monitoring, The Journal of Mechanical Systems and Signal Processing. 10.1016/j.ymssp.2016.06.006

PUBLICATION 4 – JOURNAL PAPER – AWAITING REVIEWER APPROVAL OF REVISION (APPENDIX Y)

Ng, F., Harding, J. and Glass, J., 2015. Road Map for Developing a Bespoke PSS System for Construction Machines OEMs, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture.

1 INTRODUCTION

This is an Engineering Doctorate (EngD) thesis which represents a piece of academic research that was conducted within an industrial context. The EngD programme provides four years research training, partly-funded by the Engineering and Physical Sciences Research Council (EPSRC). The degree was first introduced nationally in 1992 with the aim to provide a more vocationally oriented doctorate in engineering than the traditional PhD and with a heavier focus on industrial needs. The work included in this thesis was conducted in partnership with an industrial sponsor, J.C.Bamford Excavators Limited, a leading company in the off highway industry.

This chapter provides the background to the research, introducing Product Service Systems (PSS) as the main theme of the thesis, and explaining the current status of this concept in both academic and industrial sectors. The context of the research is also clarified at the end of this chapter.

1.1 BACKGROUND

In recent decades, there has been a significant shift in business strategy towards the inclusion of service elements in the manufacturing industry. There is a growing trend in the demand for support from customers, which is extending within the product's lifecycle. Whilst customer's requirements need to be fulfilled by functionalities provided during the design and manufacture of the product, increasingly, there also exists an expectation of a substantial aftersales service from the Original Equipment Manufacturers (OEMs)/ service provider. Customers want to ensure that the reliability levels of the products they purchase remain as high as possible until or beyond the customer's return on investment (ROI) period. As the number of products being sold into the market has accumulated over the years, the size of the aftermarket will also increase exponentially. For the past 8 years, between 76% and 79% of the nation's GDP comes from the service sector (World Bank Group 2015b), compared to the 10% contribution in GDP by the manufacturing sector (World Bank Group 2015a). In the US, American business and consumers contribute approximately $1 trillion every year into the aftersales market (Cohen, Agrawal et al. 2006b). The service division of Cisco systems, a system data storage manufacturer, saw an increase of revenue of 13% between 2004 and 2006 (Cohen, Agrawal et al. 2006a). Companies are recognising the importance of gaining a significant aftersales market share in order to maintain their competitiveness within the industry (Gallagher, Mitchke et al. 2005). In 2014, IBM derived over $13 billion of its revenue from its service segment, which is over 55% of its total revenue in the same year (IBM 2014). In truth, this shift in emphasis between manufacture and service began back in the 1990s, when companies started to diversify their investment from manufacturing to service capabilities, thus enabling them to offer product service system (PSS) to their customers.

PSS can be defined as a marketable set of products and services capable of jointly fulfilling a user's need (Mont 2002a). The United Nations Environmental Programme (UNEP) considers PSS as an opportunity to assist in re-orienting current unsustainable trends of production and consumption practices (Manzini, Vezzoli 2002). The basic concept of PSS is simple, products are sold with service/maintenance agreements to the customers, the ownership of a product does not have to be transferred, throughout the life of a product, the customer may pay a small fee to the OEMs or dedicated service providers to maintain or even improve the product by upgrading with the latest available technologies. As a result, OEMs or service providers will generate revenue not only from product sales but also from aftermarket sales. On the other hand, the customers will enjoy a certain level of back up support from the OEMs to ensure the reliability of the product to conduct the needed tasks throughout the ROI period of its life.

However, there are costs and challenges associated with this change of business strategy. It is often necessary for the OEM to significantly change its organizational structure to effectively implement PSS, and be able to support the product and service delivery to the customers. Service delivery in PSS is often recognised in the form of a maintenance agreement, in which service can be scheduled in periodically based on the either the time period of usage or number of days between services. As a result, the most common form of PSS in most industries is preventive maintenance. In each service the service technicians will follow a standard list of checks and worn parts are replaced to ensure the product continues to run at its peak efficiency, unless further specific investigations or repairs are notified. The data that servicing provides gives a certain level of information to the OEMs enabling them to understand how their products are being used in reality. In addition, to further increase understanding of use, some OEMs such as Caterpillar offer a condition based service, in which the critical aspects of the vehicle, such as engine oil, hydraulic oil contamination etc., are monitored to alert the customers or the dealership of possible problems so that they can schedule in the next available servicing appointment based on the issue's severity (Caterpillar Inc. 2015). Unlike the automotive industry, products from the construction industry have multiple categories of irregular usage patterns known as ***duties***. Therefore it is common for products from the construction industry to require repairs/servicing outside of the pre-scheduled regular maintenance cycles or before their next service is due.

There is a large amount of interest in designing a suitable PSS structure for various organisations (Baines, Lightfoot et al. 2007, Mont 2002a). However, there is little practical guidance for the off highway equipment manufacturers to prepare and assess their individual ability to implement PSS and thereby more successfully achieve the advantages that PSS can offer.

1.2 THE INDUSTRIAL SPONSOR

J.C. Bamford Excavators Ltd. (JCB), a privately owned firm, is the one of the worlds' top three off highway equipment manufacturers, manufacturing a range of over 300 types of products, hereafter referred to as ***machines***, throughout their 22 factories across 4 continents. Backhoe loaders are one of the most popular pieces of construction equipment, and were invented by the founder of JCB, Joseph Cyril Bamford, and were first manufactured in 1953. Over the last 60 years more than half a million JCB backhoe loaders have been manufactured in UK, India and Brazil and sold across the globe, making one out of every two backhoe loaders sold in the world a JCB product. A telescopic handler also known as JCB Loadall was introduced by JCB in 1977, since then one out of every three telescopic handlers sold in the world is a JCB Loadall. In May 2013, JCB marked the production of the company's one millionth machine and this global success helped the company to achieve more than £300 million annual profit in three consecutive years of 2012, 2013 and 2014. JCB offer customised equipment to multiple sectors such as construction, agriculture, waste etc. with a guarantee to ensure around 95% availability of parts being delivered to any part of the world within 24 hours should this be required. JCB employs around 12,000 people on four

Figure 1-1: JCB Backhoe Loader 5CX

Figure 1-2: JCB Loadall 535-125

continents to support the demands globally. JCB also offers a wide range of service packages known as JCB Assetcare, to give customers peace of mind at a minimal cost.

1.2.1 THE ORIGINAL EQUIPMENT MANUFACTURERS AND THEIR DEALERS

Figure 1-3: JCB Dealer Visit at JCB World HQ

Similar to most OEMs in the off-highway equipment industry, JCB does not sell their machines directly to the customers, but through 2,000 authorised dealer depots situated around the world responding to the demands from 150 countries. These dedicated dealers have to comply with certain requirements from the OEMs, before each individual dealer becomes an official dealer for the OEM. The duties and responsibilities of dealers differ from OEM to OEM depending on their business strategy, most OEMs allow dealers to sell machines, parts, after-sales support or even hold auctions of second-hand machines. In return, OEMs offer necessary training to ensure that the dealers are equipped with the right equipment, skills and knowledge to ensure customers are fully supported through the machines' life. The usual perception within the automotive industry is that a customer is also the end user of the product however this is not necessarily true within the construction industry. In particular within the construction industry, the customers tend to be companies and ownerships are exchanged in auctions throughout the first three years of the product's life. These companies operate in a similar manner to Hertz, Enterprise, and Europcar from the automotive industry, where machines are being rented to various end-users who exhibit different use profiles. Most construction companies will have regular maintenance service agreements with the dealers, until the machines are sold back to the dealership within the first 3- 5 years of the product's life.

Figure 1-4 describes the relationship between the OEMs, dealers and the customers. As stated in the figure OEMs mostly rely on feedback from their dealers, in order to understand the market demand. The dealers are equally reliant on the OEM's support regarding aftersales support. Little or no direct interaction exists between the OEM, and most customers and end-users, and this is very common in industries, unless the customers are one of the OEMs' major customers. As a result, OEMs often may not fully understand the product lifecycle of their machines, yet this understanding is critical when determining a service strategy.

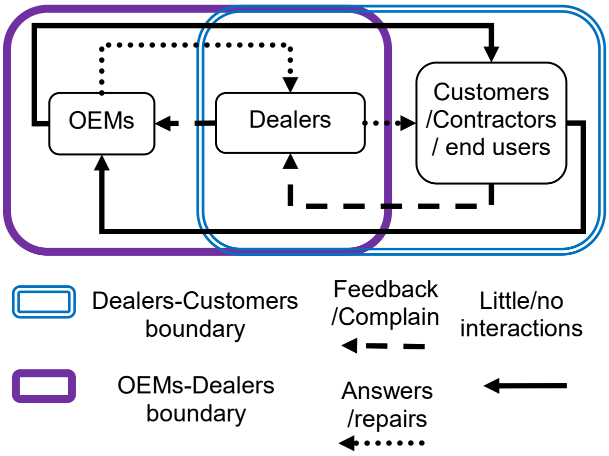

Figure 1-4: Typical OEMs, dealers and customers relationship.

1.2.2 IMPLEMENTING PRODUCT SERVICE SYSTEM

The nature of PSS is not new within the off-highway equipment market, OEMs have been offering various types of PSS through their dealers to customers for over a decade. These PSS offerings are commonly delivered in the form of a service agreement, providing preventative maintenance at a fixed interval usually based on the accumulated engine hours. Unlike motor vehicles or even an aircraft engine, which are designed to primarily perform one or two types of functions, some off-highway equipment is designed to perform more than fifteen types of primary functions. Such dynamic use profiles simply cannot be adequately sustained by regular preventive maintenance schedules. In the off highway industry therefore

PSS need to understand the condition of the product in real time, to allow the OEMs or service providers to offer services at the right time and level. Little real time usage data are currently being collected from the machines by construction OEMs and service providers, and the data collected are not necessarily rich enough to define the duties that the machines have been involved in. Hence, although marketed as condition based maintenance (CBM), many of these programs may not be fit to satisfy the true purpose of CBM for PSS.

1.3 THE CONTEXT OF THE RESEARCH

The context of this research was specified by the Research Engineer (RE) and the JCB director for advanced engineering and research, Mr. Peter Jowett in 2010. A need was identified from the company's five year plan to utilize and develop JCB's telemetry system to increase the responsiveness of JCB's PSS, as well as changing the culture within JCB's service agreements from passive to a proactive approach. The structure and policy setting for JCB's PSS has been primarily driven by historical information such as service and warranty records etc. The main barrier to the transformation of their PSS is the lack of dynamic product data and empirical accounts of product usage. With the emerging telemetry technologies, more real time data could be extracted to support the transition from the current passive PSS to proactive PSS.

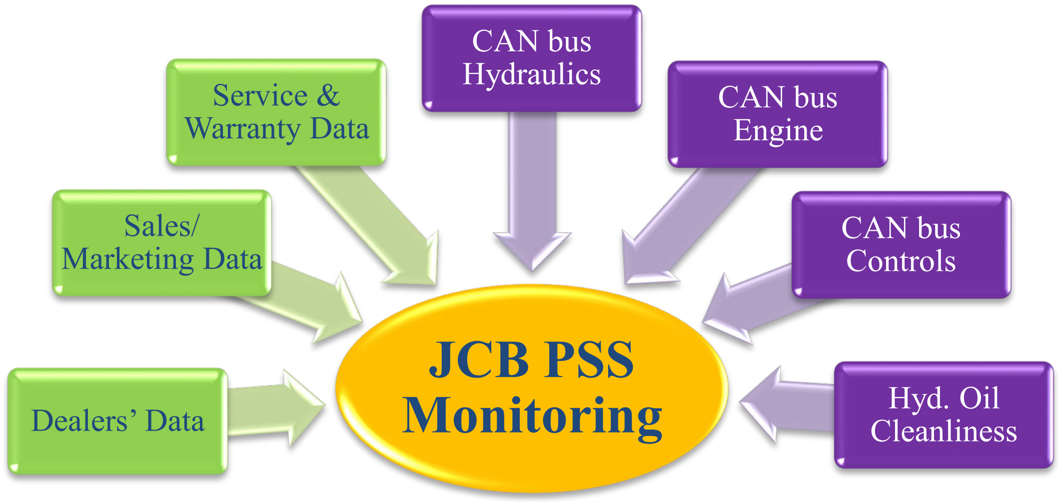

Figure 1-5: Context of Research

Figure 1-5 shows the context for the new JCB PSS system. As shown in Figure 1-5, the data sources that drive the JCB PSS will increase from three (green) to seven sources by introducing telemetry data (purple). The records from service, warranty, sales and dealers are currently used to provide the historical aspects of machines' usage profiles. Such profiles provide a basic view of the expected life expectancy before a component is required to be replaced under both intended and unintended working environment and usage style. Most of this information is being used to determine the service intervals and service protocols within the service agreement. However the root causes of product and component failures were very difficult to determine or predict without the support of real time data. Such data could be provided if full records of the components' deterioration rates or abnormal operating behaviours of the machines etc. were available. JCB telemetry was officially launched in 2011, and has been extracting simple information to support the customers and help them to manage their fleets. The raw data is extracted from the machines' controller area network (CAN bus), an internal communications network that interconnects device such as sensors and

Engine Control Units (ECUs) together, which cover the main elements of modern off-highway equipment.

There is an increasing expectation from the market that real time data will be available, and the perception that its utilization will provide better aftersales market support. As a result, this research focuses on the use of telematics as an additional input for PSS, as well as creating practical PSS guidance for OEMs to increase their utilisation of detailed knowledge for the implementation and improvement of their PSS offerings.

1.4 AIM AND OBJECTIVES

1.4.1 OVERARCHING AIM AND OBJECTIVES

The overarching aim of this thesis is:

To design a PSS implementation roadmap for off highway original equipment manufacturers

In order to achieve the primary aim, four objectives were defined and a plan made for how they would relate to the publications required as part of this research.

Objective 1: To assess the readiness of the sponsor company's telemetry system, in respect of the telemetry system infrastructure, data types and machine coverage that could be used to support PSS.

Objective 2: To investigate the infrastructure regarding the generation of dynamic data within the CAN Bus network on products and assess the data's values towards improving the PSS

Objective 3: Conduct an empirical investigation on the feasibility and suitability of the recommended dynamic data for product monitoring in PSS

Objective 4: To create a roadmap that clarifies the required data and structure prerequisites, for OEMs to determine and validate their readiness level in respect of the adoption of a PSS driven business model.

As shown in Figure 1-6, the four objectives in this thesis have been split into four work packages, each with a specific objective and planned tasks. Clarification and validation of the research focus would be conducted in work package one, whereas work packages 2 and 3 would focus on the core experimental research. Finally, work package four delivers the roadmap that clarifies the prerequisites for the adoption of a PSS driven business model.

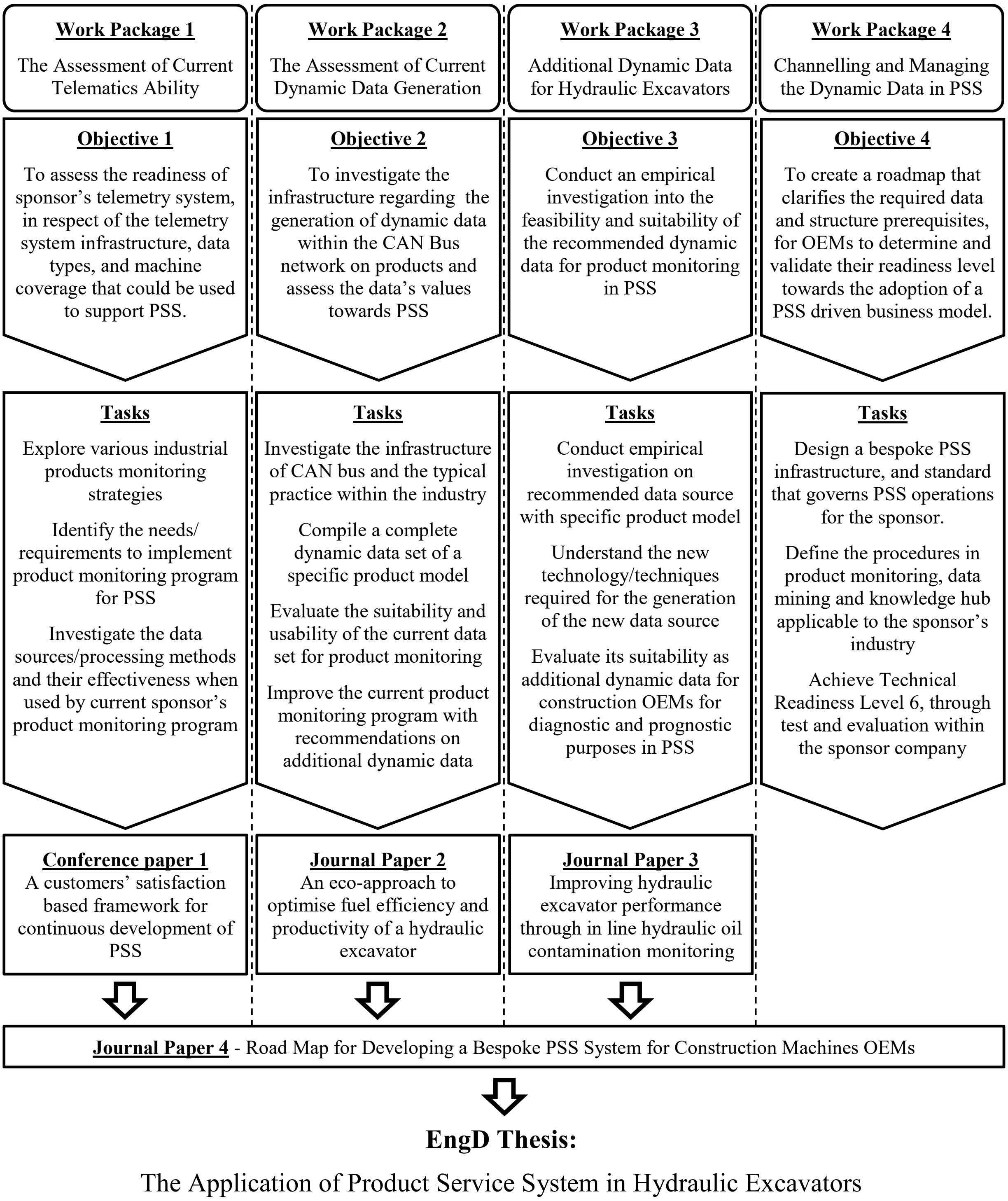

Figure 1-6: Thesis Map

1.4.2 JUSTIFICATION OF THE RESEARCH

In response to the demand for servitization from the market, most OEMs started offering preventative maintenance packages to customers, but underestimated the benefits and importance of proactively analysing the product and service data in order to continuously improve the system. This was also the case for the sponsor company of this thesis. The RE was a sponsored undergraduate in JCB for 5 years before the start of the EngD, and has worked in more than eight different departments in various functions. The RE recognised that the lack of real time product usage data is a common challenge throughout the company. Telematics were introduced into the company in 2011, which provided an incentive for the company to take advantage of the real time data to progress from a passive service model, i.e. to move from a preventative PSS[1], to a proactive service model, using a condition based PSS. As a result, there is a critical demand from the sponsor company for a roadmap on the implementation of PSS using the telemetry system. An initial literature review on the subject also indicates that despite extensive research into PSS design and strategy, there is a research gap within the academic publications regarding the generation, analysis and management of PSS data. This research gap can be seen as a substantial barrier to the implementation of the PSS research into the commercial world. The aim and objectives of this research were approved by the JCB director for advanced engineering and research, Mr Peter Jowett, and confirmed by the CICE Loughborough University, EngD Centre, based on the research's close immediate link to the company's commercial needs as well as an academic need to broaden the research field.

[1] Different types of PSS are defined and explained in the literature review in chapter 3 and in particular in section 3.1.

1.5 THESIS STRUCTURE

The remainder of this thesis is organised into 5 chapters. An overview of each chapter is provided below:

1.5.1 CHAPTER 2 - RESEARCH METHODOLOGY

This chapter explains the research methodology adopted in this research. Due to the nature of the research project, technical experiments were conducted in order to test a number of hypothesises implicit in the objectives. The experiments were designed in accordance with international standards and with the company's knowledge of their customers. This knowledge was gathered through interviews with telematics, electronics and hydraulic experts from the sponsoring company, as well as from experts external to the sponsoring company. The adopted methodologies for each objective are listed and explained with the reasons why they were chosen. In summary this chapter describes and explains the adopted methods for the research, experimental work, data analysis and evaluations.

1.5.2 CHAPTER 3 - LITERATURE REVIEW

This chapter provides the findings of literature reviews that are relevant to the objectives of this thesis. The chapter is split into five sections:

The 1st section covers the fundamentals of PSS within the general and related fields of the thesis, and the research demands from academia. The topics covered include PSS definitions, types, design and applications.

The 2nd section introduces the benefits of real time monitoring, such as on-board monitoring sensors and telemetry, in various maintenance related context. Different types of maintenance and their importance are also explained. It also covers the maintenance type that is suitable for PSS and the role of real time monitoring in the presence of PSS maintenance.

The 3rd section introduces the subject of customer satisfaction, and its usage towards determining the performance of both tangible and intangible offerings such as products and service. The views from both academia and industry were covered.

The 4th section examines productivity and different approaches to its measurement.

Finally the 5th section explores the importance of hydraulic contamination and its effect on productivity and maintenance requirements.

In summary, this chapter consists of five sections of literature review that are used to prepare for the research undertaken in chapter 4, and are supported by the research methods adopted as stated in chapter 2.

1.5.3 CHAPTER 4 - RESEARCH UNDERTAKEN

This chapter is split into three sections. Each section explains one of the individual work packages conducted for this thesis, with the support of the knowledge gathered in chapter 3. The first section explains the research undertaken in the assessment of the sponsor's telemetry system readiness for PSS. The second and third sections cover the two main pieces of experimental work conducted on the topics of productivity and hydraulic oil contaminations. This chapter therefore addresses objectives 2, 3 and 4. All the work mentioned in these sections follows the chosen methodology for each objective explained in the chapter 2. Detailed discussion can also be found in this chapter from planning of the experiments to data analysis and evaluations. This includes assumptions in the experimental planning and design, its contribution and impact to the particular objective as well as the project as a whole, and the predicted outcome of the research based on the research mentioned in chapter 2.

1.5.4 CHAPTER 5 - FINDINGS

This chapter discusses the findings of the work conducted in chapter 4. The results are compared and discussed with the expected outcomes stated in chapter 4, and cross checked with the state of the art knowledge identified in chapter 3. The integrity of the results are also discussed based on the selected methodology stated in chapter 2 and the experiment design in chapter 4. The final conclusions are then drawn and presented as the findings of this thesis.

1.5.5 CHAPTER 6 - IMPLICATIONS AND CONCLUSION

This chapter explains the level of impact this thesis has on the sponsoring company and the related industry. The key benefits are listed and the suggested method of implementation is included for the sponsoring company and the wider industry.

Recommendations for further research include the development of online oil contamination particle counters, and that more parameters should be monitored to create a clearer picture of the machine's components deterioration rate.

This chapter summarises the impact and the means to re-create the benefits found in this thesis at a commercial level. This chapter also concludes the work conducted in this thesis, as well as providing suggestions to improve PSS based on the experiences gathered.

2 ADOPTED METHODOLOGY

2.1 INTRODUCTION

This chapter gives a brief introduction to the various types of research methodologies and methods that are relevant and appropriate to this type of research project. The development and application of the research methodology and methods that have been adopted to achieve the objectives of this thesis are then outlined and explained in section 1.4. Available research methodologies are discussed and explanations given as to why particular methodologies were selected and used in each of the work packages.

2.2 AVAILABLE RESEARCH METHODOLOGIES

Research methodology is a way to systematically solve the research problem (Kothari 2008). It is defined as a set of techniques implemented to achieve predefined goals (Welke 1983). Furthermore, it also describes the sequence in which different techniques need to be performed and checks their consistencies (van den Heuvel 2002). Research is a structured inquiry that utilises an acceptable scientific methodology to solve problems and create new knowledge that is generally applicable (Kumar 2010). Kerlinger has defined, scientific research as “a systematic, controlled empirical and critical investigation of propositions about the presumed relationship in various phenomena.” (Kerlinger 1973).

Pure research involves testing hypotheses that can address the research gaps identified in the first stage of the result, typically through literature review (Kumar 2010). Various theories would be generated, developed and tested. Researchers aim to tackle the theory and hypotheses that may not have an immediate need nor the existence of an application at the present time or in the foreseeable future. Nevertheless the knowledge produced during the research process will be added into the existing body of research knowledge and methods, hence adding value to an application or other development that may be created as a result of the research in the future (Anderson 2004). Action research is recognised by its in-depth characteristic as a disclosure of theoretical insight (Altrichter, Kemmis et al. 2002) and can be considered as a practical approach to identifying and solving an existing problem (Costello 2003). This could be needed for many reasons, including providing policy information, to develop a business plan or simply just to provide understanding about a root cause of a problem. This type of research is typically found in Universities, where they offer a specific applied research program which is funded by an industrial partner from a relevant field.

Descriptive research is an approach in which a problem is described in detail and clearly defined investigation methods are used. The statistical results will tell what it is, while inferential statistics try to determine cause and effect (Krishnaswamy, Sivakumar 2009). Correlational research is a measurement of the relationship between two or more independent variables, and the researcher will attempt to discover or establish some form of link between the aspects of a phenomenon (Schmidt 2013). Explanatory Research focuses on "why" and "how" two or more situations are related together. e.g. research into the crime rate over different countries or the trend over a period of time etc. (DeVaus 2001). Exploratory research explores new territory within the research study and investigates the need and value of its potential. It is often called a feasibility study or pilot research.

A quantitative approach can be construed as a research strategy that emphasizes quantification in the collection and analysis of data (Bryman 2012). Researchers who use this approach tend to reduce the complexity of the problem into a more manageable size (Fellows, Liu 2009). A qualitative approach is known as an inductive strategy of linking data and theory, hence a research strategy which usually emphasizes words rather than quantification in the collection and analysis of data (Bryman, Bell 2007). Triangulation is using more than one type of research method for a single study of social phenomena; it can be used within or across research strategies to allow the researcher to corroborate results between quantitative and qualitative data (Bryman 2009).

2.3 ADOPTED METHODOLOGIES AND JUSTFICIATION

When the research area was identified by the RE and approved by the sponsor, there were considerable areas of uncertainty within the relevant subject areas. As a typical EngD project, it was very industrially focused, inheriting its dynamicity and uncertainty from the industrial context and bringing them into the research environment. Furthermore, the nature of the project requires multiple levels of investigations to explore, validate and improve the current practice of PSS within the sponsor company, wider industry, and extrapolate the findings within the wider academic community. As a result, action research is deemed to be a suitable primary research methodology approach for this thesis. Figure 2-1 is a model of a type of action research defined by O'Leary, which emphasises its experimental learning approach, continuously refining and improving the methods or solutions based on the findings from the previous cycles (O'Leary 2009).

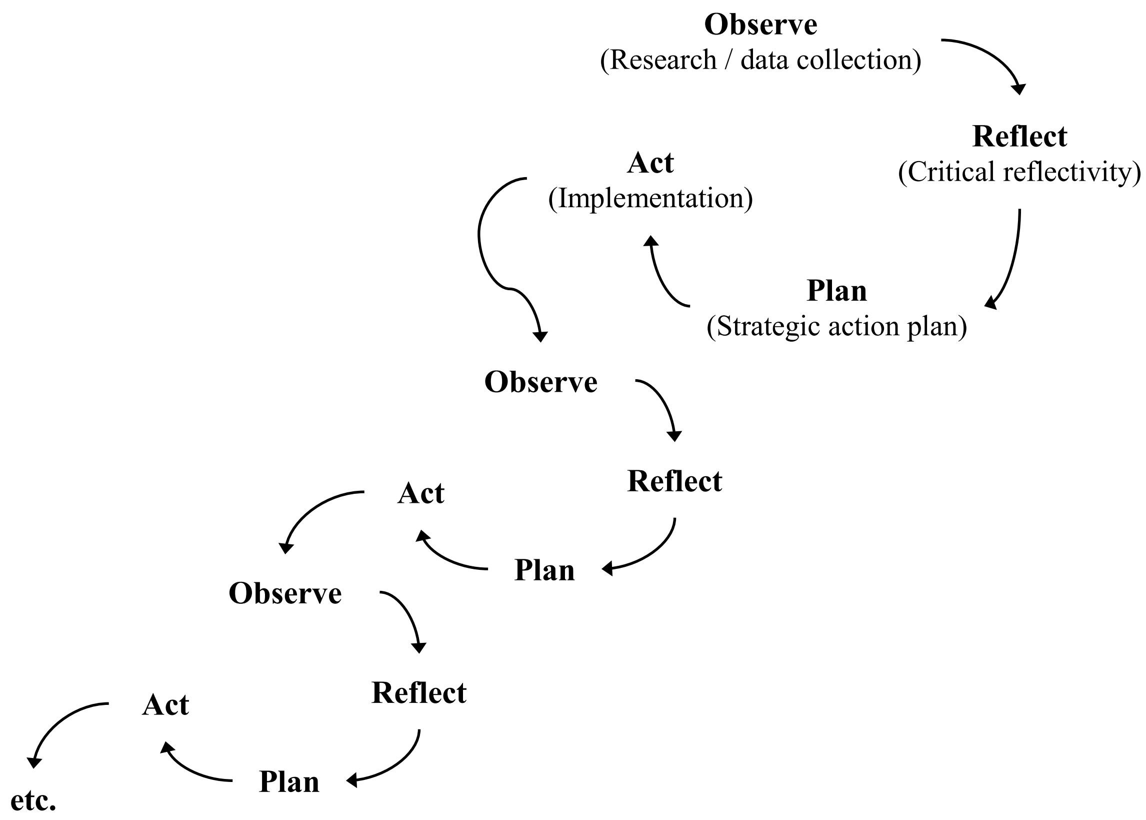

Figure 2-1: O'Leary's Research Cycles

Based on O'Leary's cycles of research, the methodology adopted in this EngD research project was to split the research into four work packages as stated in Table 2-2. Each work package creates knowledge and understanding which will then steer the formation of an aim and objectives for the next work package, ensuring a positive progression within the project and for the sponsor.

2.4 RESEARCH METHODS/TOOLS USED

Table 2-1 shows the chosen methodologies and methods used in this thesis, and Table 2-2 shows how O'Leary's cycles have been applied to each work package in this research. Focused literature reviews were conducted within each of the work packages, including work package 4, to provide background knowledge of the specific research areas of the work package and identify the knowledge gaps that needed to be addressed to fulfil the specific aim and objectives. Literature from both industry and academia were used to ensure that a good balance of practicality and theoretical understanding of the subject was captured.

The Adopted Research Methodologies and Methods		Research Methods		
		Statistical Analysis	Experimental Research	Focus Group
Research Methodologies	Action Research		X	X
	Descriptive Research		X	
	Correlational Research	X		
	Exploratory Research	X	X	X
	Quantitative	X	X	

Table 2-1: Adopted Research Methods and Methodologies

2.4.1 WORK PACKAGE 1

This work package was primarily conducted based on an action research methodology, and the research method was literature review. Being at the early stage of the research project, the RE needed an unbiased fundamental understanding of PSS, in order to fulfil the objectives and the research stages as stated in O'Leary's cycles of research. Observational Descriptive Research was also adopted to allow the RE to assess the level of PSS that the sponsor company was at, although a qualitative research method such as a survey within the company could also potentially provide the same information. However it is likely that such data could contain biased and single minded points of view, which do not add any value but only inaccuracy to the research. The work was conducted at the JCB Customer Experience Centre (CEC), which operates as a first response centre for global JCB machines, by processing captured telemetry data from JCB products. For more information please refer to section 4.2.

2.4.2 WORK PACKAGE 2

The aim of work package 2 was to investigate the infrastructure for the generation of dynamic data within the CAN bus network on the sponsoring company's machines and to assess the data's suitability to dynamically support PSS. A literature review and interviews with telematics, electronics and hydraulic experts from the sponsoring company, as well as from experts external to the sponsoring company were conducted, to assist in the research into all aspects that relate to the CAN bus, hydraulic systems and the system in the chosen excavator which should be focused on. The experts that were involved in the discussion were company's products' experts, who provided answers and suggestions to the origin and purpose of each CAN bus signal from a population of over 3000 individual signals.

The discussions with the experts were designed to identify the building blocks of the entire CAN bus network, and all the background assumptions behind each CAN bus signal, which subsequently allowed the RE to reflect on the ways in which these data can be processed and give any valid values to support the PSS. During the planning stage, hypotheses were put together and tested under experimental conditions to test and validate the reliability of these signals for PSS and other critical parameters such as digging patterns and engine speed levels that have direct and indirect effects on productivity and fuel efficiency. The experiment results helped to draw a conclusion regarding the previously identified research gaps which were relevant to the sponsor company and their PSS offering. More details can be found in section 4.3.

2.4.3 WORK PACKAGE 3

The aim of work package 3 is to conduct a final assessment on the suitability of dynamic data to support the implementation of PSS, with action research being the adopted research methodology. Treating hydraulic oil contamination as dynamic data to assess, an oil sampling system was designed and installed on an excavator that was scheduled to run for 1900hrs, whilst hydraulic contamination data was being collected throughout. Four focus groups were consulted consisting mostly of industrial experts with appropriate experience from within the sponsor company or from five approved suppliers. The discussions within these focus groups ranged from industrial practice on applications to the new product requirements requiring research by the suppliers. The RE communicated with the chosen suppliers 2 to 3 times each week to discuss the feasibility of the available technology from each supplier and the installation locations of the sensors. The discussions often ended with decisions that the RE should gather and process more test data before the next meeting. These discussion outcomes gave the RE evidence to validate the findings from literature as well as enabling the experiments to be designed using the correct method and procedures. As well as choosing the reliable and accurate sensor for the experiment.

Statistical correlation was heavily used in work package 3, where the relationships between several particles were determined in the form of correlations, by using a statistical analysis software package known as statistical package for the social science (SPSS). More details can be found in section 4.4.

2.4.4 WORK PACKAGE 4

The purpose of work package 4 was to field test the concept of the roadmap by underpinning the real-time product monitoring strategy of a high profile project within one of the leading OEMs from the off-highway industry with the involvement of most of the PSS stakeholders, such as the OEM, dealers, customers etc. under typical business conditions across the globe. The roadmap was created to fulfil the research aim stated in chapter 1, by utilising and summarizing the key findings from work packages 1, 2 and 3. Continuous development and improvement of the roadmap and mechanisms created in accordance to the roadmap have ensured that the solution has a high immediate contribution and impact on industry as a well as to academia. Similar to work packages 2 and 3, this work package was conducted primarily in the form of experimental research. With the wealth of understanding and knowledge gathered from all previous work packages, the roadmap, which is the proposed end result that addresses the aim of the research, was used and demonstrated in its intended and relevant environment, i.e. the off-highway equipment industry. Due to the uncertainties that were likely to arise during the process, O'Leary's cycles of research were again adopted, to observe and reflect on the materialisation of any uncertainties, and as a result plan and improve the roadmap's robustness to counter such circumstances.

2.4.5 SUMMARY OF RESEARCH METHOD CYCLES

The research approach adopted for each work package has been to examine the objective to be addressed by the particular work package and then use O'Leary's Research Cycles. The first stage "observe" has been achieved by literature reviews and analysis of current industries. In the second stage the RE has "reflected" on the findings from stage 1 and in particular has identified gaps in understanding and major problem areas that have been reported. The third stage of O'Leary Research Cycles is to "plan" and the RE had therefore determined what data must be collected, how experiments should be carried out, and what other tasks are required and how these should executed. When plans are fully in place the fourth and final stage in O'Leary Research Cycles is to "Act" by carrying out the planned activities. A summary of the particular steps for each work package is presented below in Table 2-2.

	WP1	WP2	WP3	WP4
WPs' Objectives	To assess the readiness of sponsor's telemetry system, in respect of the telemetry system infrastructure, data types, and machine coverage that could be used to support PSS.	To investigate the infrastructure regarding the generation of dynamic data within the CAN Bus network on products and assess the data's values towards PSS.	Conduct an empirical investigation into the feasibility and suitability of the recommended dynamic data for product monitoring in PSS.	To create a roadmap that clarifies the required data and structure prerequisites, for OEMs to determine and validate their readiness level towards the adoption of a PSS driven business model.
Observe	Literature review and identify all data/information that links to any form of telemetry data usage.	Literature review and identify all the current dynamic data from CAN bus network and other related system.	Literature review and focus groups to understand contamination monitoring on excavators.	Literature review, business demand and the nature of machines diagnostic system infrastructure.
Reflect	Data are largely qualitative without the understanding and use	Dynamic data was identified, but not utilised by appropriate	Despite 70% - 90% of hydraulic system failure being attributed	There is a need to support a fleet of production spec.

	of telemetry data.	analytical process.	to hydraulic contamination, yet it is not being monitored.	machines for engineering development and service support
Plan	Prioritise the work to address the lack of understanding of the product data and information that industry collects and possesses.	Plan Experimental work to assess the limits of these dynamic data for the use of PSS, through remote measuring of productivity and idle time.	To gather hydraulic contamination data and asses it's behaviour to be an effective contributor to PSS. To constantly reflect on the procedures and analysis during the experiment.	Create a roadmap to assist in planning the allocation of resources and flow of data / information to ensure uptime maximisation.
Act	Create and implement new customer satisfaction data analysis process.	Conduct experimental work to assess the PSS capability of the dynamic data.	Conduct experiment and draw conclusions regarding PSS value and commercial suitability.	Create mechanisms to achieve the functions stated in the roadmap.

Table 2-2: O'Leary's cycles of research for each work packages

Further details regarding the actual methods, procedures, and mechanisms used in this thesis can be found in section 4, as well as publications within the appendices V, W, X and Y.

3 LITERATURE REVIEW

This chapter provides the literature review conducted at various stages throughout the EngD project in order to gather the vital knowledge and identify the research gaps from both industry and academic publications within the selected scope. The chapter is split into five parts, each focused on a specific topic related to PSS. These topics are also related to the context of the research demanded by the sponsor, which is to utilize and develop its JCB telemetry system to increase the responsiveness of JCB's PSS. Initial findings from the literature review on PSS, indicate that PSS is often seen as a form of maintenance or service agreement between the service providers and the customer, and there is a strong correlation between the ability to perform certain maintenance approaches and the type of PSS implementation. Real time data is the key to providing the critical usage information to drive a more advanced PSS type. Due to the nature of the thesis' close proximity to the industry, it is very unlikely that the sponsor will alter the existing agreement with the current telemetry supplier, nor alter the architecture of their CAN bus network data and hydraulic system, that are key areas for the telemetry system to extract real time data. Therefore the literature reviews for this thesis are mainly focused on PSS, maintenance, customer satisfaction, measuring productivity on excavators and hydraulic oil contaminations rather than on a detailed comparison of telemetry systems. Product Service System (PSS)

In recent decades, there is a growing number of companies shifting their business model from selling products to providing and selling a service related to the initial product (Oliva, Kallenberg 2003). A PSS integrates product and service into a single package at the point of sale. It can be defined as a marketable set of products and services capable of jointly fulfilling a user's need (Mont 2002a). It can also be described as an innovative strategy, that shifts business focus from the design and retail of physical products, to the design and retail of systems of products as well as services, that are jointly capable of fulfilling specific client demands (Manzini, Vezzoli 2003). Goedkoop explained that the balance between the product and service in a PSS can vary, in terms of function fulfilment and economic value (Goedkoop, Van Halen et al. 1999). Nowadays customers tend to demand more supplier involvement to prolong and maintain the life of products they have purchased and keep them functioning at maximum performance levels (Mont 2002b). Furthermore, there is also a significant shift in commerce transactions to Business-to-Business (B2B) from Business-to-Customers (B2C) (Mont 2001). This shift provides incentives for OEMs to incorporate PPS into their business model, increasing competitiveness within the market. PSS is traditionally used for high valued products such as Rolls Royce engines or Alstom trains, where OEMs have either an extensive understanding in the product usage by their customers or have sophisticated sensor systems installed on their product (Akmal, Batres et al. 2013).

There are several different classifications of PSS that can be split into three main categories; Product-oriented, Use-oriented and Result-oriented (Weber, Steinbach et al. 2004). Each of these categories is defined based on the split between of product and service content within the PSS, as shown in Figure 3-1. Each PSS type also can be categorized by their differences in terms of creating, delivering and capturing value (Reim, Parida et al. 2015). Within PSS, a product is a tangible commodity manufactured to be sold. A service is an activity conducted on a product to increase its intangible economic value on a commercial basis (Goedkoop, Van Halen et al. 1999).

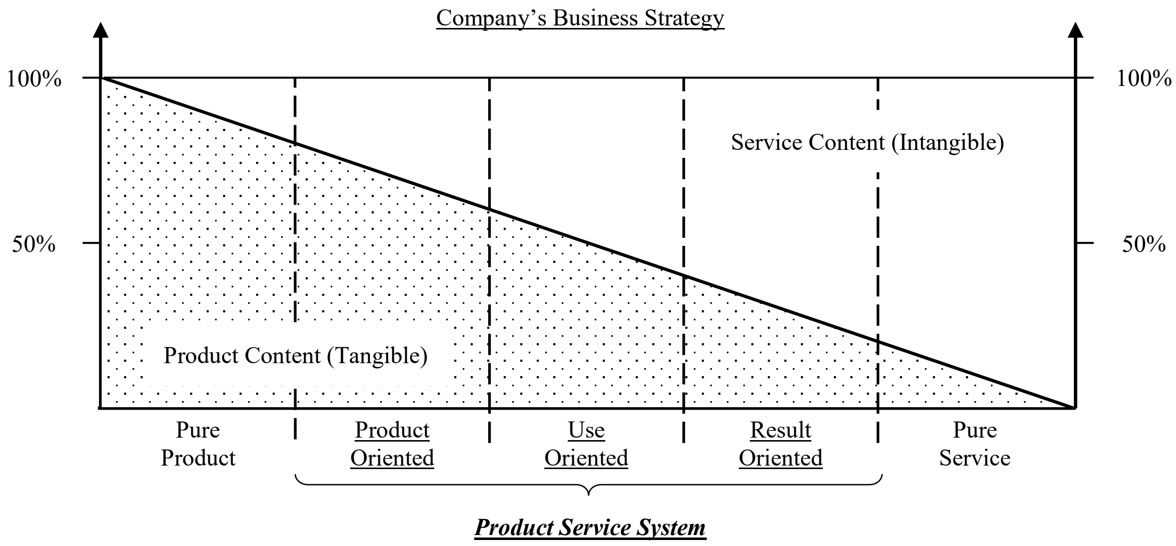

Figure 3-1: PSS Classfications

Product-oriented PSS usually focuses on maintenance support of the product after it is sold to the customers and usually in a context where there is a complete transfer of product ownership from OEMs to the customers, when both parties agree on the terms and conditions regarding to the product and service agreements. The contract will include the total price of the product and the service agreement for the product (Meier, Roy et al. 2010). These service agreements are likely to be delivered in the form of preventive maintenance, carried out by dedicated dealers or service operators at fixed intervals based on product's usage level (Endrenyi, Allan et al. 2001). Andy Wilhelm, senior product manager of Equipment Data Associates (EDA) stated that the sales of service provide the highest gross margin area of the dealerships' business of 54.6% (Wilhelm 2013).

The main difference between a product-oriented PSS with the other two PSS categories is the transfer of ownership. A product-oriented PSS allows customers to enjoy the sense of ownership of the product, whilst taking advantage of experts, [usually the OEMs of the product] to maintain and upgrade the product through warranty and maintenance contracts (Cook, Bhamra et al. 2006). Furthermore, the customers can choose whether to take the advice and services (Rese, Strotmann et al. 2009). Product-oriented PSS can also be considered to be an upgrade from an old business model in which OEMs (often from heavy manufacturing) can gain extra revenue from the service market, without the need for capital investment and major reorganisation of the company structure.

Use-oriented PSS usually refers to the leasing or sharing of products to customers without the transfer of ownership from the dealer or OEMs (Neely 2008). The dealers or OEMs will be responsible to carry out regular service maintenance to ensure the availability of the product to the customer, within the leasing period. Depending on the complexity or value of the product, some OEMs will invest technology to enable remote collection of real time data to determine the time of the next required service and the maintenance work that should be carried out. This approach is also known as condition based maintenance (CBM) (Yam, Tse et al. 2001). If the product fails unexpectedly, the OEMs will often guarantee a minimal period of disturbance before the product is repaired or replaced and the customers can resume their daily routine. Therefore a successful use-oriented PSS often requires the OEMs to have an in-depth understanding of their products, such as failure modes under various usage patterns, as well as the ability to monitor the product's real time condition (Yang, Moore et al. 2009). Without these prerequisites, it is difficult for OEMs to determine whether this type of PSS is achievable, let alone whether it can operate profitably.

A result-oriented PSS usually refers to the sale of product functions to customers without either the transfer of ownership of the product, or the physical existence of the products (Lujing Yang, Ke Xing et al. 2010). It has the highest level of servicing content among the three PSS types, hence the majority of revenue will come from servicing (Tukker 2004). The OEMs have full responsibility for the product and any maintenance that is required for the product. Customers pay a set price to receive a pre-agreed amount of results (end products) from the OEMs. Result-oriented PSS are widely adopted within the chemical management service (Yang, Xing et al. 2010). One example of a result-oriented PSS would be a supplier sign an agreement with the occupants of a building to supply certain pre-agreed level of warmth comfort for a fixed period. The supplier will also be responsible in controlling any relevant factors to provide the agreed thermal outcome (Ostaeyen 2014). The heavy focus on service content makes this solution popular for companies who wish to outsource part of their activities to a third party, who tends to be an expert in a particular activity.

The true strength of PSS lies within the shift of focus on the final need, demand, or function that needs to be fulfilled, by moving away from traditional product concepts (Tukker, Tischner 2006). Baines suggests one of the key barriers to adoption and implementation of PSS is the lack of well-developed tools and methodologies for OEMs (Baines, Lightfoot et al. 2007). Mont urged the research community to explore the needs for PSS design, and to develop a methodological basis for their development, practical implementation and evaluation based on economic, environmental and social consequences (Mont 2002a). Sofia suggests that companies have problems providing a PSS due to their internal inability to successfully design implement such business model (Päivärinne, Lindahl 2016).

3.1 MAINTENANCE

Maintenance can be described as a process that ensures the intended level of reliability and safety of a system is achieved throughout its use phase (Kinnison 2004). The goal of maintenance is to reduce down time by improving product reliability by capturing and analysing any relevant product data (Viles, Puente et al. 2007). British Standards define maintenance as: “The combination of all technical and administrative *actions,* including *supervision actions*, intended to retain an *item* in, or restore it to, a state in which it can perform a required function”, (BSI 1993). The Maintenance Engineering Society of Australia (MESA) states that “Maintenance is the engineering decisions and associated actions necessary and sufficient for the optimization of specified capabilities" (Tsang 1998). In this definition, "the optimization of specified capabilities" implies that the product's functionality should be delivered at a high level of performance and reliability. Tsang stated that the primary objective of maintenance is to preserve system functionality in a cost-effective manner (Tsang 1995), yet maintenance has been described as an expensive and daunting element of support required throughout the product lifecycle of any given system (Jardine, Tsang 2006). Kelly went even further by suggesting that maintenance should achieve the agreed output level and operating pattern at a minimum resource cost within the constraints of the system's condition and safety (Kelly 1989). In summary, maintenance must ensure the required reliability, availability, efficiency, and capability of the physical product (Kumar, Galar et al. 2013).

Scheduled maintenance is one of the most popular types of maintenance within the industry, where specific types of services are carried out to minimise the down time by controlling the rate of deterioration of the product. This maintenance tends to be carried out at a fixed time based on the recommendations from the OEM (Ahmad, Kamaruddin 2012). Yet Labib stated that the same type of machines could be working in different environments, hence different maintenance periods may be required as a result (Labib 2004). Tam also stated that OEM recommendations may not be optimal to fit the actual requirements, due to the lack of the experience from the designers in real life machine failures (Tam, Chan et al. 2006). However, Diego Navarro, the global fleet management solutions manager for John Deere Construction and Forestry Division suggested that the rigidity of such maintenance causes fleet managers only to wait for components to fail, before doing something about it (Skipper 2013). He further suggests that the industry should focus on maximising uptime instead by adopting condition based maintenance (CBM). Condition based maintenance (CBM) is a philosophy for maintaining engineering assets based on non-intrusive measurements of their condition and maintenance logistics (Abdulnour, Dudek et al. 1995). The R & D manager of Southwest Research Institute (SRI), Susan Zubik, stated that the aerospace industry considers CBM to be a maintenance philosophy to actively manage the health condition of assets in order to perform maintenance only when it is needed, and with the least disruption to the equipment's uptime (Zubik 2010). CBM is designed to prevent the onset of a failure (Tsang 1995), hence the equipment condition is assessed by inspection and diagnosis; maintenance actions are only performed when necessary (Wetzer, Cliteur et al. 2000). The United States Air Force (USAF) defines CBM as a set of maintenance processes and capabilities derived from real-time assessment of weapon system conditions obtained from embedded sensors and/or external test and measurements using portable equipment (US Air Force 2010). CBM can also be used to reduce the operation and maintenance costs of wind power generations systems, which monitor data such as vibration, acoustic emission, oil analysis, power voltage and current data (Tian, Jin et al. 2011). Diagnostic and Prognostic are two important aspects in a CBM program, where diagnostic deals with fault detection and prognostic deals with fault and degradation prevention before they occur (Peng, Dong et al. 2010). There are many studies that regard the understanding of machine components, data acquisition from sensors, data extraction, transformation and analysis as vital steps towards prognostic maintenance (Katipamula, Brambley 2005, Jardine, Lin et al. 2006). Maintenance has a key role in delivering performance driven solutions in PSS (Roy, Erkoyuncu et al. 2013), it offers opportunities for OEMs and service providers to provide high value added services during products usage. It is also in the OEMs and service providers' interests to ensure high product performance levels through maintenance at a reasonable cost.

Uncertainties about the current conditions of products operating in the field make it extremely difficult for OEMs to plan maintenance schedules efficiently and cost effectively and therefore result in greater risks of under maintaining products which can lead to failure and longer, unscheduled down-times, which are unacceptable to customers. To reduce these uncertainties, accurate product data, particularly related to product use, need to be acquired and processed to determine the frequency and types of maintenance/service required. Scheidt categorizes the data as static and dynamic life cycle data (Scheidt, Zong 1994). The collection of accurate and useful real time (dynamic) data from a product provides many challenges for most OEMs. When products are designed, particular conditions and methods of use are anticipated and included within the design specification, however, customers (users) may try to stretch or even redefine these boundaries during the product's operational life. To address this problem, OEMs may consider monitoring the real time usage of the product, as is done in the aerospace industry.

Monitoring systems enable CBM as if an abnormal event is detected, maintenance can be scheduled immediately and real time data can be analysed by database software to determine the work and parts that will be required (Heng, Zhang et al. 2009). Bill Sauber, Volvo Construction Equipment North America's manager of remote technologies, stated that OEMs have a tendency to assume that if more dynamic, real time operational data are collected, more information will be captured. However, this data will mostly be just noise. Johnathan Metz, technology application specialist from Caterpillar also suggested that customers are likely to be overwhelmed by the sheer quantity of data, and its irrelevance to the customers' own objectives (Moore 2012). Hence, if there is no system in place to analyse the collected data in a timely manner, only limited value will be gained (Gardiner 2013).

3.2 CUSTOMER SATISFACTION

Baines et al argue that PSS is a competitive proposition, and can directly refer to the need for customer satisfaction (CS) (Baines, Lightfoot et al. 2007). Fornell suggests CS levels can be used to evaluate the overall performance of an OEM's products, rather than singling out an individual experience (Fornell, Johnson et al. 1996). A specification of CS was defined by Eugene who developed a theoretical framework:

$$\text{Profitability}_t = f_3(\text{Satisfaction}_t, \xi_{3t}) \quad (1)$$

$$\text{Satisfaction}_t = f_2(\text{Quality}_t, \text{Price}_t, \text{Expectation}_t, \xi_{2t}) \quad (2)$$

In equation 1 Eugene claimed, profitability at any given time (*t*) is a function of satisfaction (Anderson, Fornell et al. 1994). Satisfaction is a function of three factors: the quality and price of product or service and the customers' expectation at the given time. These equations include vectors of factors (ξ), such as environmental trends or historical dependent variables. Fonseca argues that CS can be viewed as the action of monitoring the quality of service delivered, thus measuring how well the organization is delivering the service (Fonseca 2009). The European Institute of Public Administration (EIPA) also suggests that the main elements in achieving high CS are to understand expectations, i.e. what the customer expects to receive from the service, and perceptions or what the customers think they have received/gained from the services. Expectation can result from personal experience which will vary for different human beings (Staes, Thijs 2008). To satisfy customers, providers should consider contracts from the viewpoint of expectation, rather than only aim to complete the job in the shortest possible time (Shimada, Taira et al. 2011). The accounts commission of Scotland (ACS) stated that the five most common factors that influence the formation of personal expectations from a service are: personal needs, previous experience, word-of-mouth communication, explicit service communication and implicit service communication (Accounts Commission for Scotland 1999). Yap describes service quality as an important driver of behavioural intentions, but its direct effect on behavioural intentions is insignificant compared to its indirect effect through CS (Yap, Kew 2009). Within a PSS, service is generally delivered as a form of after sales service, which can be useful for capturing service feedback from customers. Amon, controller of Fillmore Equipment, suggested that feedback gives opportunities to respond to issues that might otherwise not get resolved and turn bad situations into good (Costin 2007). Morgan, president of Morgan Business Associates, a consulting and training firm, also suggested that the rate of customers moving to competitors should not be neglected, as he estimated that dealers lose about 10% of customers per year, of which 65% left due to CS related reasons (Costin 2007).

As service requirements and product usage vary hugely throughout the machines' life, assessing CS levels in each stage would not only allow OEMs to understand the performance of their product in different conditions, but may also help to improve PSS because the service provider has the incentive to use and maintain equipment properly, increasing both efficiency and effectiveness (Meier, Roy et al. 2010).

3.3 MEASURING PRODUCTIVITY OF OFF HIGHWAY EQUIPMENT

Off-highway equipment OEMs such as Caterpillar Inc., Komatsu Ltd. and J C Bamford Excavators Ltd. manufacture equipment for various industries, such as backhoe loaders, wheeled loaders and hydraulic excavators for handling bulky and heavy materials. A general definition of productivity is given by the association of input(s) and output(s) in the particular context, i.e. productivity = output/input, and this is the common formula adopted within the industry (Park 2006). This is a project-specific model that expressed output in a physical unit such as volume, and the input as cost for labour, equipment, management etc. (Arditi, Mochtar 2000). In the context of excavators, output has often been quantified in terms of the materials handled by machines; e.g. volume of spoil moved per operator-hour (Elazouni, Basha 1996), or volumetric capacity of the bucket (Solazzi 2010). Edwards suggested an alternative approach using the data from machine performance handbooks from OEMs, and estimates excavation cost based on the given cycle time (cycle/h) and productivity (m^3/h) of the excavator (Edwards, Holt 2000). Unlike Elazouni's model (Elazouni, Basha 1996), the cycle times were derived from OEM performance handbooks (notwithstanding criticisms of the accuracy of such data) (Lambropoulos, Manolopoulos et al. 1996), and a multiple regression equation was used.

$$Y=\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n \quad (1)$$

Y is the cycle time under the influence of β

β is the partial regression coefficient, which varies with x

x is the particular independent variable

A usual industrial perception is that the highest productivity will be achieved, if the maximum volumetric fill of the bucket is always achieved, yet others disagree suggesting that to minimise cycle time operators tend to fill the bucket to only 80% of capacity which results in more passes than would be required if the bucket was always filled to 100% (Fiscor 2007). Spinelli et al used the "Piece-Size Law" to show that productivity increases at a decreasing rate with the increase of the piece size, up to the optimum (Spinelli, Saathof et al. 2009). Yet as the piece size increases beyond the optimum, productivity will fall as the demand on the machine will increase due to the weight of the load. The productivity value therefore exhibits a parabolic behaviour against piece size (m^3).

The measurement of productivity does not often include the cost of achieving that productivity, i.e. fuel consumption. Elton (2010) defined fuel efficiency as a measure of how much fuel a machine uses to complete a certain task, which can be treated as a way to measure task efficiency (Elton, Book 2010). Most hydraulic excavators have a diesel engine that powers the hydraulic system which allows designated duties to be carried out. As shown in Figure 3-2, the engine's fuel consumption is determined mainly by the engine torque and engine speed settings at a given time. A high engine speed setting will results in a greater quantity of fuel being consumed. Furthermore, if the duty demands more power, such as digging through high density material, the hydraulic system will demand more engine torque, forcing the engine to consume more fuel.

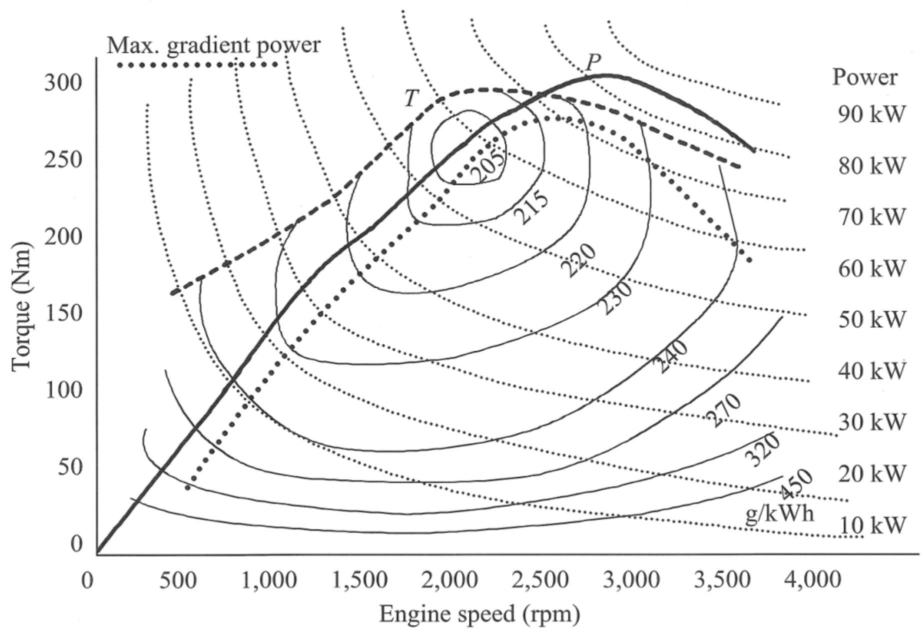

Figure 3-2: Engine Fuel Map

Some industry bodies have attempted to model excavator productivity. For instance, in 1983, the Central Association of the German Building Sector (Zentralverband des Deutschen Baugewerbes) and the German Federation of the Construction Industry (Hauptverband der Deutschen Bauindustrie) published the BML handbook (Handbuch BML: Daten für die Berechnung von Baumaschinen-Leistungen) (Zentralverband des Deutschen Baugewerbes (Central Association of the German Building Sector), Hauptverband der Deutschen Bauindustrie (German Federation of the Construction Industry) 1983), see equation 2. This suggests how to calculate the hourly productivity of a fleet of excavators ($Q^{exc}_{\mathrm{eff,BML}}$), in units of ($m^3$/h).

$$Q^{exc}_{\mathrm{eff,BML}} = 60 \times n_{\mathrm{exc}} \times (V_{\mathrm{cece}} \times f_{\mathrm{fill}})/t^{exc}_{\mathrm{th,BML}} \times f_{\mathrm{swing}} \times f_{\mathrm{depth}} \times f_{\mathrm{E}} \qquad (2)$$

In the 30 years since its publication, most OEMs have derived their own, broadly similar, ways of quantifying excavator productivity.

The key difference between their equations is the additional coefficient known as conversion coefficient (f_{con}), however each OEM defines their factor in a different manner:

- Caterpillar Inc. includes operator skill/efficiency coefficient and machine availability (Caterpillar Inc. 2011);
- Komatsu Ltd. includes a percentage of the actual dig depth against the maximum with the dump conditions (Komatsu Limited 2009); and,
- J C Bamford Ltd. includes a percentage of the actual dig depth against the maximum with the swing angle (J C Bamford Excavators Limited 2007) etc.

There are various factors that can affect the level of achieved productivity and fuel efficiency when operating hydraulic excavators. Factors such as dig depth, swing angle, fuel consumption etc. can be measured by specific instruments installed on the machine, and measurements will be broadcast onto the CAN bus network for the telemetry system to capture and transmit as real time data. With the increase in technological advancement in telemetry systems for the off-highway industry, OEMs should take the opportunity to utilise dynamic data to provide more accurate and real time measurements such as productivity.

3.4 HYDRAULIC OIL CONTAMINATIONS

More than 45% of the world's construction machines are hydraulic excavators (Off-Highway Research 2013), because of their high productivity and ease of operation compared to other construction machines (Edwards, Malekzadeh et al. 2001a). Most excavators are powered by a combustion engine. Unlike a conventional automobile, the generated power of the engine is transmitted to drive the hydraulic pumps which provide the flow within the hydraulic system. These products are often bought in quantity as a fleet and are likely to be in service for 10 to 30 years or more, with multiple exchanges of ownership. Product sales agreements often include a maintenance package and this is perhaps the most common and effective way to ensure that the products maintain a high reliability level (Jardine, Lin et al. 2006). Due to the complexity of off-highway excavators' hydraulic circuits and tough working conditions, the reliability of such systems is always a serious consideration (An, Sepehri 2003). The analysis of hydraulic system operations indicates that the reliability of the system and its components depends on a large number of factors (Jocanović, Šević et al. 2012), such as pressure, flow, temperature, viscosity and particulate contaminants (Jocanović 2010). Douglass, the director of training and education of Muncie Power Products, Muncie Inc. claims 70% - 90% of hydraulic system failures can be attributed to contaminated oil (Douglass 2006). The National Research Council of Canada found on average 82% of wear problems are directly attributable to particle-induced failures such as abrasion, erosion and fatigue (Garvey 2003). The National Fluid Power Centre (NFPC) also argues, in one of their oil contamination management courses, that failure to address and effectively manage contamination will lead to expensive downtime and short component life (NFPC 2014). Caterpillar Inc. maintains that the concentration of wear particles in oil is a key indicator of potential component problems

(Caterpillar Inc. 2007). Hence oil analysis techniques for condition monitoring offer significant potential benefits to operators (Macián, Tormos et al. 2003).

Ingalls and Barnes, president of TBR strategies and vice president of reliability service for Des-Case, defined oil contaminants as dirt, water, air, wear debris, leaked coolant etc. (Ignall, Barnes 2014). Metallic particles, also known as wear debris, are commonly considered to be the most damaging particles for the components within the systems. Wear debris can come in different shapes and sizes, often generated internally from components grinding against metallic built-in contamination or even other generated wear debris. Oil contamination can be measured in accordance to the International Standard Organization (ISO), standard ISO 4406, "Hydraulic fluid power—Fluids—Method for coding the level of contamination by solid particles", introduced a standardised way for determining the amount of particles of sizes, 4µm, 6µm, and 14µm per millilitre of fluid (ISO 1999). Most fluid analysis results are now shown according to ISO 4406. Hydraulic component manufacturers (such as Bosch Rexroth and Parker Hannifin) recommend a range of acceptable contamination levels for various types of systems, based on internal clearance, dirt sensitivity and operating methods of the components (Parker Hannifin Corporation 2011, Bosch 2000). Particle counters can be used to count the number of particles in a fluid system. These counters can be magnetic, optical or pressure difference etc. depending on the application (Mayer 2006).

Hydraulic contamination can never be fully eliminated but can be controlled by taking precautions and installing filters of the correct grade. Although physical oil sampling has been adopted by most OEMs as a routine procedure during service intervals, test results are often used reactively. In addition, the interval periods are often too lengthy to capture the critical moment just before failure (US Air Force 2010). Furthermore, Lunt claims that offline laboratory oil analysis is becoming less acceptable, as maintenance strategies are developing more towards real-time decision making (Lunt 2011). Therefore, although accurate real time hydraulic oil contamination measurement is critical should CBM be pursued, OEMs are reminded that appropriate data mining methods are equally important to operate a successful CBM within PSS.

3.4.1 SUMMARY OF KEY FINDINGS FROM LITERATURE REVIEW

Table 3-1 shows the key findings of each topic within the literature review.

Literature Review	Key Findings
Product Service System	1. The architecture and needs for various types of PSS implementation in industry. 2. The lack of a practical methodological basis for PSS implementation in particular for off-highway industry. 3. The strong correlations with maintenance and real time data in PSS (Use-oriented) implementation and operation.
Maintenance	1. The relationship between the implementation requirement of each PSS types and of maintenance types. 2. Preventative maintenance is the most common form of maintenance, but is prone to uncertainties regarding unrestricted usage behaviours in the off-highway users. 3. Condition based maintenance (CBM) provides the back bone of use-oriented PSS, that is mainly driven by real time data.
Customer Satisfaction	1. A qualitative approach to assess the performance of delivered products or service. 2. Expectation and Perception are key elements in the measurement of satisfaction level 3. Analysis of customer satisfaction data should be only treated as a supplement to real time data in PSS.
Measuring Productivity on Excavators	1. Accuracy in measuring dynamic productivity has always been a challenge for OEMs. 2. There are various formulas adapted by different OEMs. 3. Key dynamic/real data needed to measure productivity can found in the current CAN bus network.
Hydraulic Oil Contaminations	1. 70% - 90% of hydraulic system failures can be attributed to contaminated oil.

	2. There is an international standard practiced within industry to measure oil contamination inline and offline. 3. Metallic particles are the key contributor in the damage of components, thus to PSS's dynamic monitoring requirements.

Table 3-1: Key Findings from Literature Review

4 THE RESEARCH UNDERTAKEN

4.1 INTRODUCTION

This chapter presents the research undertaken in accordance with the aim and objectives described in section 1.4.1, and the research methods stated in section 2.32.4. The chapter is divided into four sub-chapters relating to the four work packages as shown in Figure 1-6. Work packages 1, 2 and 3 are assessment and reviews of PSS key factors, and work package 4 is the proposal put together for the sponsor company to implement. The achievements of each of the work packages' sub-objectives are described and explained with respect to the work involved and the outcomes achieved. Further details, key publications and evidence can be found in the Appendices.

4.2 WORK PACKAGE 1 - THE ASSESSMENT OF CURRENT TELEMATICS ABILITY

4.2.1 SCOPE AND AIM

The purpose of work package 1 is to assess the sponsor company's telematics ability to support PSS. Literature reviews were conducted to assemble all the relevant knowledge and industrial practices that relate to the subject domain, and these were used to identify guidelines for the assessment process. The RE was transferred temporarily to the new JCB Customer Experience Centre (CEC) that aims to operate as a first response centre for global JCB machines, by processing captured telemetry data from JCB products, as well as capturing customer feedback through customer satisfaction surveys. The outcome of work package 1 has largely contributed to the refinement of the EngD project research direction and methodology by identifying the research gaps of both academia and industry. The results of the research within work package 1 are:

1.) Literature review of PSS and customer satisfaction
2.) An assessment of current static data sets for PSS

3.) An assessment of the current telematics capabilities in the sponsoring company

The publication of a conference paper entitled (Appendix V) :

Ng, F., Harding, J. and Rosamond, E., 2012. A Customers' Satisfaction Based Framework for Continuous Development of PSS. *Proceedings of the 4th CIRP International Conference on Industrial Product-Service Systems, Tokyo, Japan, November 8th - 9th, 2012,* pp. 239-244

4.2.2 RESEARCH DETAILS OF WORK PACKAGE 1

The main tasks for work package 1 were conducting a literature review and gaining practical experience by working within the relevant department at the sponsor company hence the work followed an observational descriptive research methodology as mentioned in section 2.4.1. The literature reviews on PSS and customer satisfaction provided critical background knowledge, and understanding which are essential to thoroughly assess the effectiveness of the sponsor's current PSS system. Working within the CEC also provided understanding of the company's business strategy and processing customer satisfaction survey data, which is largely qualitative, gave further knowledge and understanding with the intention of future product improvement. In addition, during work package 1, the RE met with key managers from other functional departments and gained valuable knowledge and understanding on how the utilisation level of telemetry data might be increased to support critical tasks for the improvement of the PSS. Three main static data sets, non-real time data, were identified as already being regularly collected and these are related to product performance, product usage, and feedback from customers as mentioned in section 1.3 in Figure 1-5 as service & warranty data, sales/marketing data and dealers' data.

4.2.2.1 Data sets

The service & warranty data set has the largest amount of data and is the only quantitative data type among the three. Although it is a combination of data from both service and warranty activities, as these both originate in the same department, and have been used in conjunction with each other, they are considered as a single data set in this thesis. Warranty data consists of data such as machine serial numbers, failed part serial numbers, machine failed hours, service codes, cost of claim etc. Service data mainly consists of a verbal description of the machine, issued by the dealer and recommendations from the JCB technical specialist to the dealers on how the issue could be resolved. Both data sets contain a specific code known as Diagnostic Trouble Code (DTC), which is defined by the Society of Automotive Engineers (SAE) standard J2012, and The International Organization for Standardization (ISO) standard BS ISO 15031-2:2010, as codes that are associated with a malfunction reported from the electrical/electronic On-Board Diagnostic (OBD) systems of motor vehicles. With appropriate background knowledge of the structure adopted by the ISO/SAE standard and the OEMs' proprietary DTCs standard, a service technician can decipher any DTCs to assist in the fault finding process. It is apparent that such knowledge is not centralised nor converted for the use of PSS due to the complexity of the sponsoring company's product range. As a result the CEC staff have little training and understanding to enable them to effectively use the telemetry data for PSS purposes. Furthermore, not all real time data generated on the products are being captured from the product's CAN bus and broadcast back to the CEC. The risks involved in using an incomplete set of telemetry data and conducting an unfair assessment of the sponsor's PSS capability are very high and therefore the research strategy was changed and the assessment was conducted directly from a product's CAN bus, see Appendix A & Appendix B for further details.

4.2.2.2 Customer satisfaction surveys

The aim of CEC is to carry out responsive actions based on the data and information captured from the telematics system and surveys, however the lack of standard operation procedures (SOPs) and lack of understanding of the nature of the data, prevents CEC staff from effectively carrying out their daily routine. Therefore, as part of this work package a data processing system was developed for analysing questionnaire results, and this enabled the customer satisfaction centre staff to publish reports with vital feedback for divisions, enriching the sponsor's knowledge repository of the customer needs, product performance etc. The system was developed for the Microsoft Excel environment and is designed to be fully automatic, so that the calculations generated help the company to identify and understand areas of customer's needs. Details can be found in Appendix C and Appendix D. Another part of the project was to investigate and define the meaning of customer satisfaction, and most importantly to understand how to measure it.

4.2.3 KEY FINDINGS / OUTCOMES

There are several key findings and outcomes from work package 1 that contribute to this thesis and determined work package 2's objective and the structure of work package 2. The key findings are as follows:

1.) JCB's telemetry system does not capture all the real time data generated by their products.

2.) CEC staff and service specialists have little understanding of the origin and creation of telemetry data.

3.) There are inefficient associations of DTCs in the current service protocol

4.) There is a lack of telemetric coverage in the products' key systems

5.) There is a lack of real time data for the implementation of an effective PSS strategy.

The findings of work package 1 concluded that the company's telemetry data set is insufficient to match the demand for real time data to support a PSS. It is evident that the sponsor is still within the adoption period, and working to accept and understand the value of having telematics on their products since their introduction in January 2011. The current telemetry data set is a filtered version of all CAN bus data from the products, as a result of cost reduction on data extraction by General Packet Radio Service (GPRS). No records were found regarding the filtering criteria, and a complete list of CAN bus data could not be found in the initial investigation. However it is clear that the CAN bus does not contain data that is generated from the products' hydraulic systems, even though this is one of the key systems of the sponsor's products. Yet hydraulics sensors were found on products' schematics, which suggest that hydraulic related data do exist but are not currently being broadcast by the telemetry system. As a result, it was decided that the infrastructure should be investigated further, particularly regarding the generation of dynamic data within the CAN Bus network on products and the value of the data in the context of PSS should also be assessed in work package 2.

The outcomes from work package 1 are the results of research and investigations into the company's historical data sets, i.e. static data, for PSS. A data analysis procedure was developed to filter out and prioritise the customers that need responding to. The new procedure includes other relevant background information such as service and warranty records, machine models, duty etc. to give a detailed view of the customers and help staff to better understand and deal with the customer feedback. The aim of the new procedure is to clearly present feedback data to various departments, in the context of the customers' expectation and perception. This work was also written up and presented as Conference Paper 1 – A customers' satisfaction based framework for continuous development of PSS, which analyses published academic research work and industry's views, and presents a framework that uses customer satisfaction as a major driver towards the state of "total contentment", to measure performance and develop PSS.

4.2.4 SUMMARY

This work package was conducted primarily as an action research project, following Altichter's cyclical nature of the action research process. Literature on the research subject was reviewed and the company's PSS capability was examined and reflected on. Although, the company's telemetry structure was not strongly focused on PSS implementation, evidence suggested that real time data was being used for fault finding procedures. Telemetric data captured from the machines being used by customers was examined, and it became clear that the level of understanding required for PSS did not exist due to the complexity of the market and machine applications. Table 4-1 summarises the findings in work package 1.

Key Findings	Descriptions
The overall Structural Requirement for PSS	An effective PSS requires OEMs to run a product monitoring program that collect vital real time product data for diagnosis for faults or any undesired condition. A data/information/knowledge system will also be required to store and feed records to support product monitoring and diagnosis.

Table 4-1: Work package 1 Key Findings

4.3 WORK PACKAGE 2 – THE ASSESSMENT OF CURRENT DYNAMIC DATA GENERATION

4.3.1 SCOPE AND AIM

The aim of work package 2 was to investigate the infrastructure for the generation of dynamic data within the CAN bus network on the sponsoring company's machines and to assess the data's suitability to dynamically support PSS. This work package was carried out in two stages consisting initially of exploratory research, understanding all aspects that relate to the CAN bus and then of experimental research, design and hypothesis testing. The availability of CAN bus data was thoroughly investigated on a specific type of a JCB excavator's electronic and mechanical systems, as this generates the largest amount of CAN bus data on a single machine type across JCB's product range. Several preliminary experiments were carried out in order to test and validate the CAN bus data for the purpose of product monitoring in a PSS. It was also crucial to minimise uncertainties regarding the behaviours of the sensor, before any hypothesis was determined and tested. Subsequently nine CAN bus data items were used to measure machine idle times, duty cycles and productivity of excavators, in order to fully explore their potential in commercial contexts. Four tasks were carried out during work package 2;

1.) Investigate the infrastructure of the CAN bus and typical work practices within the industry
2.) Compile a complete dynamic data set for a specific product model
3.) Evaluate the suitability and usability of the current data set for product monitoring
4.) Improve the current product monitoring program and give recommendations for additional dynamic data requirements.

During work package 2, the real time idle time measuring methods were refined for the 20 tonne class excavators, and a method proposed for calculating duty cycle time. A journal paper (appendix W) has also been written which demonstrates how some of the CAN bus data can be used to increase the productivity and fuel efficiency of a hydraulic excavator.

4.3.2 RESEARCH DETAILS OF WORK PACKAGE 2

The adopted research methodology for work package 2 was a combination of exploratory and action research. After discussions with the sponsoring company, a single machine type, hydraulic excavator, was chosen for this part of the research, for several reasons. Among construction machines, excavators are used extensively within the UK construction industry, due to their ease of use, versatility and high productivity, compared to other construction machines (Edwards, Malekzadeh et al. 2001b). Furthermore, each machine type has various electrical and electronic protocols and hydraulic designs, and therefore the research and investigation of each type could be considered as separate projects at this stage.

4.3.2.1 Stage one – The learning curve

The first stage of work package 2 was reviews of industrial standards and practices in the architectural design of electrical and electronic networks for communication and hydraulic systems of typical hydraulic off-highway equipment, through literature review and discussions with experts as mentioned in section 2.4.2. Below are some of the questions that were asked by the RE;

1.) How is each CAN bus signal generated?

2.) What are the criteria and primary functionalities for each of the CAN bus signals?

3.) What is the list of CAN bus signals being extracted and the algorithms to pre-process them and use as telemetry data?

The knowledge gained from these reviews was tested through initial experimentation to identify key factors, which would be important to any experimental work which might be required. Tasks involved in stage one are listed in the Table 4-2 below

No.	Task's descriptions	Outcome
1	Literature review and discussions with experts on industrial standards and general	Understanding of the infrastructure of Controller Area Network (CAN), and the sharing of digital signals in off-highway equipment. i.e. capture and

	practice of CAN bus network adoption within the industry	extractions of dynamic data.
2	Learn the principles and operations of hydraulic systems and identify any dynamic data and its generation algorithm through experimentation	Understanding of the principles of off-highway equipment's hydraulic systems, and identifying the key dynamic data from the chosen machine for the experiment. i.e. key systems for dynamic data generation etc.

Table 4-2: Workpackage 2 Stage 1's tasks

The RE identified several critical areas of understanding which played a vital role when designing stage two of the experiments. There are over 3000 individual signals, seen as dynamic data generated on the machine, of which about 100 signals are from the hydraulic system. Some of these signals are pre-processed by the ECU and then broadcast as messages throughout the CAN bus network. Electronic switches were mainly used as sensing elements rather than sensors as this is a lower cost approach, however, the resolution of signals from these sensing elements is limited. Two preliminary experiments were conducted to test and validate the reliability of these signals for PSS and other critical parameters such as digging patterns and engine speed levels that have direct and indirect effects on productivity as identified from the literature reviews, and interviews with the experienced operators (details can in sections 3.3 and 4.3.3). The experiments were carried out at one of sponsor's test facilities using a 20 tonne class excavator, where the behavioural patterns and performance of each signal and parameter were tested under the simulation / performance of one of the most popular duties for excavators, i.e. trenching and loading, over the duration of 5 – 10 complete duty cycles. CANalyzer, a software tool that specialised in analysis and stimulation of bus communication, was used to record the data traffic and conduct analysis to identify any relationships. Table 4-3 summarizes the two preliminary experiments from this work package.

Preliminary 1	Tasks	Outcome/ Findings
Validate the behavioural patterns of CANbus signals	1. Record real time behaviours of CANbus data while conducting trenching and simulated loading duties. 2. Analyse and filter collected data that are suitable for machine monitoring.	a. Thirteen hydraulic switch signals that sense the pressure of various circuits within the system were deemed to be suitable for product monitoring in PSS. b. They were used to address the inaccuracy of idle time and cycle time measurement.
Assess the effects of five different engine speed ranges and two different digging techniques on fuel efficiency and productivity	1. Record real time CANbus data while conducting trenching and simulated loading duties in seven different engine speed settings (1100, 1200, 1300, 1400, 1700 and 2050) 2. Record real time CANbus data while conducting trenching and simulated loading duties in two different digging techniques with four engine speeds.	a. The most productive and fuel efficient engine speed setting appears to be between 1500 rpm to 1800 rpm. The stage two experiment will focus on these settings. b. A single digging pattern has been chosen to be used for the stage two experiment based on its effects on productivity, fuel efficiency and the normal practice in construction sites. c. Engine torque values, one of the

		most critical factors in fuel efficiency, will be replaced by bucket cut depth (BCD),

Table 4-3: Work Package 2 Key Findings - Preliminary Experiments

At the end of stage one, a complete list of dynamic data was compiled and two improvement proposals for product monitoring were submitted to the sponsor company. A list of validated parameters and the selection of CANbus signals for the experiment in stage two are carried over from the outcomes in stage one. (Screened company's test and development (D&T) reports that record the preliminary work can be found in appendix E). One of the major changes would be the adoption of BCD over engine torque values, due to its erratic and difficult to control behavioural nature. Furthermore, a selection of CAN bus data was selected and validated for further assessment in stage two.

4.3.2.2 Stage two – The Experimental Assessment

While assessing the suitability of the selected CAN bus data, a commercial focus was also included. Despite productivity being a well-researched area within operations research, a review of literature and industry guidance identified a gap in respect of fuel efficiency and productivity for hydraulic excavators. A new variable, bucket cut depth (BCD), has been used in this research as a result of the recommendations from industries and academics. It is the submerging level of the bucket into the material when it is digging. BCD is given as a percentage as shown in Figure 4-1, between 0% when the bucket is skimming on top of the surface (also known as grading) and 100%, when the bucket is fully dug in. A literature review on productivity was conducted to understand the current measurement methods and

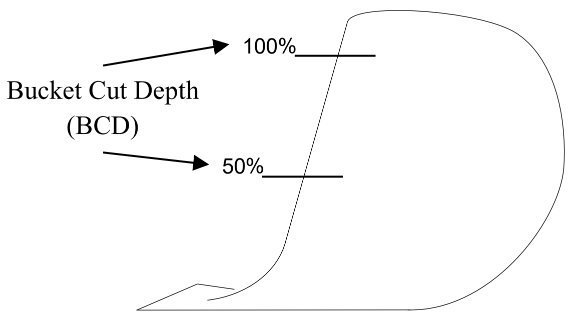

Figure 4-1: Bucket Cut Depth (BCD)

factors that affect both productivity and fuel efficiency. BCD is a new variable outside the CAN bus, that was identified in stage one to have a close relationship with fuel consumption and engine torque values from the CAN bus. In most cases, the engine torque value is a good indicator of the fuel consumption level of the engine and cycle time of the duty being performed. However different engines may have various torque values set up, e.g. 70% engine torque of engine A and B may represent different values in Nm. Furthermore, engine torque is often an engineering language rather than an operation language, and as a result, BCD was deemed to be a more appropriate parameter and terminology to use in operation. Please refer to published paper in appendix W for more details.

The focus in stage two is to explore how to jointly improve both fuel efficiency and productivity in hydraulic excavators. Variables such as engine speed and bucket cut depth, (BCD) are identified to have a direct effect on fuel efficiency and productivity in the preliminary experiments (please see section 4.3.2.1), i.e. a certain amount of fuel consumed and time spent to move an amount of spoil (m^3/hl), of an excavator. Engine speed and fuel consumption were monitored from the CAN bus, as well as being measured by an external mechanical fuel meter to ensure the accuracy of the values.

The experiment was conducted on the 14th and 15th May, 2012 to collect necessary data in order to generate the map. Four engine speeds (1500, 1600, 1700, and 1800) were used with two BCDs, each unique set of experiment was repeated once, in order to obtain the average to increase the accuracy of the results. Therefore, a total of sixteen experiments were conducted, in each experiment the operator was asked to perform standard trenching and loading duty for 10 cycles. The operator was asked to swing the machine 90^0 to have material emptied on a dump truck. The loaded dump truck was then weighed to identify the quantity of the load by weight. The experiment schedule is presented in appendix F. Cycle times were recorded manually by a stop watch, fuel levels were measured by an internal and an external sensors and all the experiments were filmed to validate the results and for the interpretation of the CAN bus data. The plan for the experiment, which can be found in appendix G, includes the preparation and resetting between each experiment and was put together by the RE, for the management of the resources and the progress of the experiment on the day. The sequence covers critical factors such as the consistent ground density and humidity, positioning of dump truck etc. that could affect the accuracy of the results as discovered from stage one. These sequences were planned to reduce the risks of these critical factors occurring.

4.3.3 KEY FINDINGS / OUTCOMES

The tasks conducted in work package 2 shared the same aim of testing the capability of the CAN bus data, but using different approaches for different needs. The outcomes of these tasks proved that the current configuration of the CAN bus will not be able to support the needs and requirements to satisfy the purpose of product monitoring. However, the results provided a much needed validation of the understanding that had previously been gained in work packages 1 and 2 and therefore experienced operators were interviewed to refine the research direction further in accordance with actual operating and working environments, in order to add commercial value to the results captured in the experiment (Figure 4-2). Below are some of questions that were asked to the operators:

Figure 4-2 Interviewing the stakeholder (Operator)

1.) What is the most common trenching (digging) approach used in the field?
2.) What is the most common approach if the operator is asked to save fuel?

3.) What are the typical machines settings that the operator would have to control during a job on his machine?

Furthermore, these results demonstrated the company's potential ability to be able to better understand the working and condition of their products remotely, without the need of expensive installation of devices or programs.

Idle time definition, were focused on the investigation of an excavator's idle time measurement. The level of accuracy of the current idle period definition was questioned by another division within the company. The CAN bus data collected during the machine productivity project, proved the level of inaccuracy given by the current definition, and an alternative approach to measuring idle period of an excavator, was therefore suggested, rather than only measuring the reduction in the CAN % engine torque value.

The cycle time definition, was focused on using the CAN bus data to determine the time each cycle takes during a duty. However, during this research, a new method has been identified to define the cycle time, by using three of the hydraulic signals available in the CAN bus. The aim of work package 2 was to investigate the full capability of the CAN bus to give a clear picture of how the machine has been worked, through additional processing methods with the signals.

The relationship between fuel efficiency (kg/l) and productivity (m^3/h) in excavators was scientifically investigated using two new independent variables, engine speed and bucket cut depth (BCD) within an experimental environment. It has been found that BCD and engine speed settings can affect fuel efficiency and productivity of the operation of a hydraulic excavator. In addition, the results over ruled the existing, common perception that the highest engine speed setting will achieve the highest productivity. The scientific results were further presented in a topographic map format and the ProductivE+ data from this map could ultimately be used to identify the BCD and engine speed required for a given excavator to undertake duties in the most fuel-efficient and productive manner.(Please refer to paper 2 in appendix W)

ProductivE+ can be converted into a database to support innovative technologies or features such as “smart” bucket or auto engine speed, to maximise the potential to serve the development of a novel, intelligent system to automate excavators to improve their fuel efficiency and cleaner productivity resulting in lower GHG emissions.

4.3.4 SUMMARY

The primary objective of work package 2 was achieved and demonstrated by the proposals made to the company on the measurements of idle time, cycle time, productivity and fuel efficiency. The data that are being broadcast through the CAN bus consist of a mixture of individual and pre-processed signals, such as the hydraulic pressure switch status and the engine average fuel economy respectively. A large majority of these signals are considered as low resolution as they are generated by electrical switches rather than sensors, which produce a larger range of measurements. Furthermore, as there are no analytical processes in place for specific signals, these signals cannot offer the level of product insight that is required for PSS. However, as demonstrated by the key findings of the work in work package 2, some of these signals were sufficient if specific analytical processes were applied, e.g. combining engine torque and a few key hydraulic pressure switches, the number of cycles and cycle time can be measured. Based on the outcome, further assessments are required of the values of the dynamic data for PSS on hydraulic excavators by creating additional new hydraulic components condition monitoring data, in order to conduct an empirical investigation of the feasibility and suitability of the recommended dynamic data for product monitoring in PSS. Table 4-4 summarises the findings in work package 2.

Key Findings	Descriptions
Telemetry Architectural Standard	Telemetry serve as a tool that can remotely extract data from the local CAN bus network using GPS or GPRS. Some of these data are a requirement in accordance to SAE standards for communication and diagnostics among vehicle components. The rest are proprietary messages defined by OEMs mostly for diagnostic purposes.
Real time monitoring limitations	There are over 3000 individual CAN bus signals, only 1 out of 30 are hydraulic related signals, which is a limiting factor to a sufficient real time monitoring coverage of a hydraulic system for PSS. Furthermore a substantial, well organised database is required to enrich the data for analysis purpose.

Table 4-4: Work package 2 Key Findings

4.4 WORK PACKAGE 3 – THE ASSESSMENT OF ADDITIONAL DYNAMIC DATA FOR AN HYDRAULIC EXCAVATOR

4.4.1 SCOPE AND AIM

It was concluded from work package 2 that the current availability of electronic signals on the CAN bus is insufficient to achieve the aim of the thesis. It was also identified that the development of hydraulic signals has the highest potential in overcoming the insufficiency. There is currently only limited knowledge and data available to support speculations on the cause of damage and faults on hydraulic components. Therefore, the aim of work package 3 was to conduct a final

Figure 4-3: Typical Hydraulic Valve Block Installation on off-highway machines

assessment on the suitability of dynamic data to support the implementation of PSS. 70% - 90% of hydraulic system failures can be attributed to contaminated oil (Douglass 2006), furthermore an average 82% of wear problems are directly attributable to particle-induced failures such as abrasion, erosion and fatigue (Garvey 2003). Therefore, hydraulic contamination was chosen to be the additional dynamic data. Work package 3 was focused on the design of both the installation of oil cleanliness monitoring tools, and practical experiments that help to validate the claim of the benefits provided by monitoring tools under specific construction machines' operating behaviours and environments. Three tasks were achieved:

1.) Conduct an empirical investigation on hydraulic contamination on a specific model of a hydraulic excavator.
2.) Understand the new technology and techniques required for the generation and capture of the new dynamic data.
3.) Evaluate the suitability of this additional dynamic data for construction OEMs for diagnostic and prognostic purposes in PSS.

4.4.2 RESEARCH DETAILS OF WORK PACKAGE 3

As mentioned in section 2.4.3., a detailed understanding of hydraulic contamination in both stationary and mobile applications was critical to ensure that an appropriate experiment was designed and carried out with the intended focus and results. In order to design the most appropriate experiments to determine opportunities for using hydraulic cleanliness as a machine fault monitoring tool, several preliminary experiments were conducted to ensure the chosen sensors and procedures will not affect the accuracy of the results in the experiment.

4.4.2.1 Preliminary work

Preliminary work was conducted after consulting the four focus groups, comprised of representatives from multiple key hydraulic monitoring suppliers from the market and a hydraulic specialist within the sponsor company. Below are some examples of the questions RE asked in the focus groups.

1.) What is the expected range of fluctuation on pressure flow, pressure and contaminates after the main pump and before the main filter etc.

2.) How frequently should oil samples be taken on an excavator that performs a day and night shifts routine, and how will it be different if compared with the sensors' result?

This preliminary work was done to ensure that all the chosen equipment met the conditions demanded and required within the experiment. e.g. pressure and flow rate fluctuations, data recording and extraction etc. The results assisted the identification of any correlation between hydraulic cleanliness and machine faults, and created a hypothesis that explains the reasons behind the existence of the relationships. As well as helping to identify the typical contamination activities during operational periods and monitoring uncertainties, in order to increase the chance to further understand the behaviours during the core experiment. As a result of the preliminary work, the decision was taken to install two particle counters and special hydraulic oil sampling test points on a brand new machine that was scheduled to run a 1900 hours standard endurance programme run within the sponsor company, under the simulated working conditions of mining & quarry work. The particle counter took a reading every second, and oil samples were taken every 10 hours for detailed elemental content analysis. The data from these readings was analysed and evaluated to assess the need to change the sampling frequency and other parameters to increase data resolution.

Sub tasks were determined for the experiment:

1. Create, capture, and interpret contamination data and information;
2. Link contamination data with occurred events to generate knowledge;
3. Design and evaluate oil contamination measuring methods on mobile applications.

4. Derive a standard procedure for collecting data and determining maintenance intervals.

4.4.2.2 The Experiment

During the experiment, the operators were instructed to follow a straightforward, hourly programme of mining and quarry duties, which included excavating, tracking, lorry loading etc. They were also instructed to record any abnormal events (e.g. having to add new oil into the system or seeing oil leaks) in their end of shift report. All personnel involved in the experiment were briefed and instructed to follow specific SOPs (Appendix H). The machine was subjected to all standard service requirements set out by the OEM of the excavator. The only exception was the installation of particle counters and an oil sampling system, both of which were specifically designed for this research to measure contamination levels within the hydraulic system (see following sections for further details). The particle counters and their installation locations were chosen based on a number of factors including accuracy, flow rate and pressure differential requirements and, size. Due to the dynamic pressure, flow condition and technological limitations, the particle counters could only be installed at the outlet of the pumps. To improve the reliability of the results, two additional sampling points were established at the outlet of the main pump and at the inlet main return filter in the hydraulic tank. The samples, taken from these sample points, as well as the filters were sent to a laboratory for further analysis.

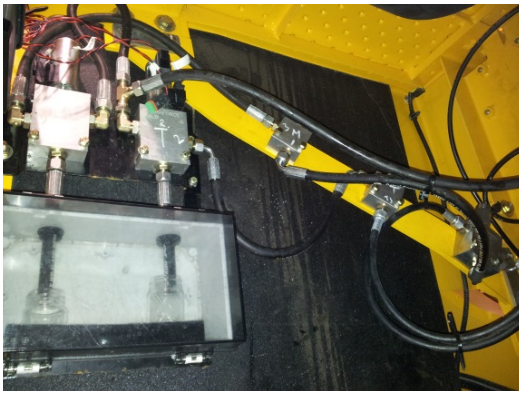

Figure 4-4: Non-remote oil contamination measuring methods

4.4.3 KEY FINDINGS / OUTCOMES

4.4.3.1 Technological limitations

All hydraulic data collected from the experiment illustrate certain hydraulic oil contamination behavioural patterns throughout the 1900hrs endurance program. A number of difficulties were encountered in monitoring the key areas of interest within the hydraulic system, due to the system condition restrictions at those locations. These difficulties demonstrate the lack of suitability of available inline hydraulic sensors on the market for mobile applications, which is the primary environment that is of interest to this thesis. Alternative non-remote measuring methods were derived to overcome these difficulties. The non-remote measuring method, i.e. physical oil sampling, shown in Figure 4-4, provides more accurate and in-depth contamination results with details of 24 individual elements typically found as oil additive, contamination and wear metal, as well as the exact counts of ≤4um, ≤5um, ≤6um, ≤7um, ≤10um, ≤14um, ≤20um and ≤30um particles. In contrast, the particle counters shown in Figure 4-5, function in accordance to ISO4406, which only indicates coarse fluctuations of contamination levels using ISO codes within the hydraulic oil system, however these fluctuations have to be at a certain magnitude to be recognised. With the behavioural patterns exhibited during the excavator's duty recorded and discussed in this work package, data noise levels can potentially mask the true nature of the contamination status. The particle counter used in this research is arguably one of the most advanced sensors of its class on the market, but it is still prone to giving "cleaner" readings than exist in reality, due to aerations within the oil.

Figure 4-5: Oil Contamination Sensors

4.4.3.2 The advantage of understanding contamination and its behaviours

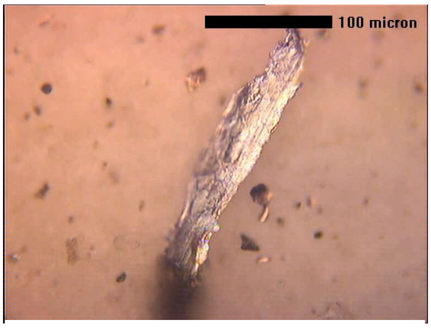

Figure 4-6: 1st filter Microscopic Image

The results achieved during the work package 3 experiments suggest different duties, such as excavation, loading etc., do not have a significant effect on the contamination levels at the same location. Therefore, the same contamination profile can be used on different excavators regardless of the duties they are performing. However, duties that involve a regular breach of the hydraulic system will not be applicable to the profile collected in this thesis. Copper (Cu) is the main contaminant within the system, the consistent increase rate in Cu ppm values between filter change periods suggests the constant wear of bushings in the pumps and other hydraulic components. Despite regular filter changes at every 500 hours and an oil change at every 1000 hours, the ppm count never drops below 9 ppm with the maximum value recorded at the 500th hour. The trapped particles in the filters reveal a large amount of particulates that are over 100 microns and are largely thin straight stripes (Figure 4-6). The shape suggests that these particulates have been generated due to erosion, where material is removed due to particle impacts. Particulates would have been forced through tight clearances, causing high pressure and stress on the contact surfaces and creating severe sliding wear particles. As shown in Figure 4-7, between the period of 1000 hrs and 1900 hrs, an initial significant drop of metallic wear particulates such as Cu and Fe, were observed after the oil and 2nd oil filter were changed at 1000hrs.

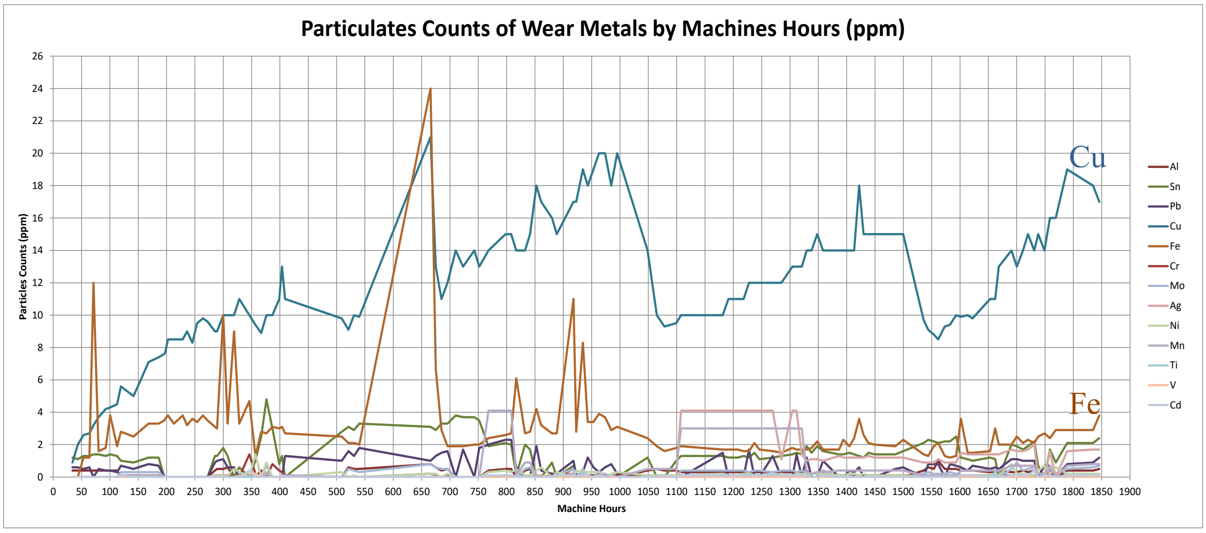

Figure 4-7: Wear Metal Particulates Counts (ppm)

There was evidence to suggest a small water contamination in between 800hrs and 1000hrs, as a similar pattern of fluctuation of both Na and Si was found (as shown in Figure 4-8), which contributed to the increase of wear level within the system. Furthermore the "spike" in Si quantity between 1650hrs and 1700hrs indicates the presence of dirt.

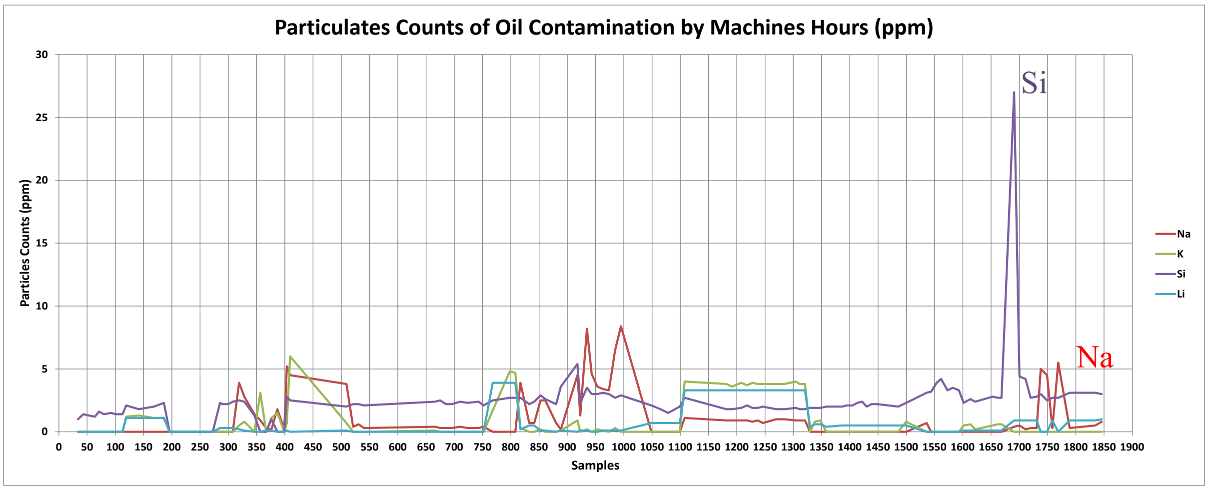

Figure 4-8: Contamination Particulates Counts (ppm)

A sudden surge of 4um and 6 um particles were also detected as shown in Figure 4-9 between the period of 150 and 300 machines hours, at the same time an increase of Cu and Fe particulate counts within the system can also been seen as shown in Figure 4-7. The formation of these particulates is the result of hydraulic components wear by erosion by foreign objects being forced through tight clearances such as in a pump, and this is supported by the particulate's shape and the straight line of scratches on it in Figure 4-6.

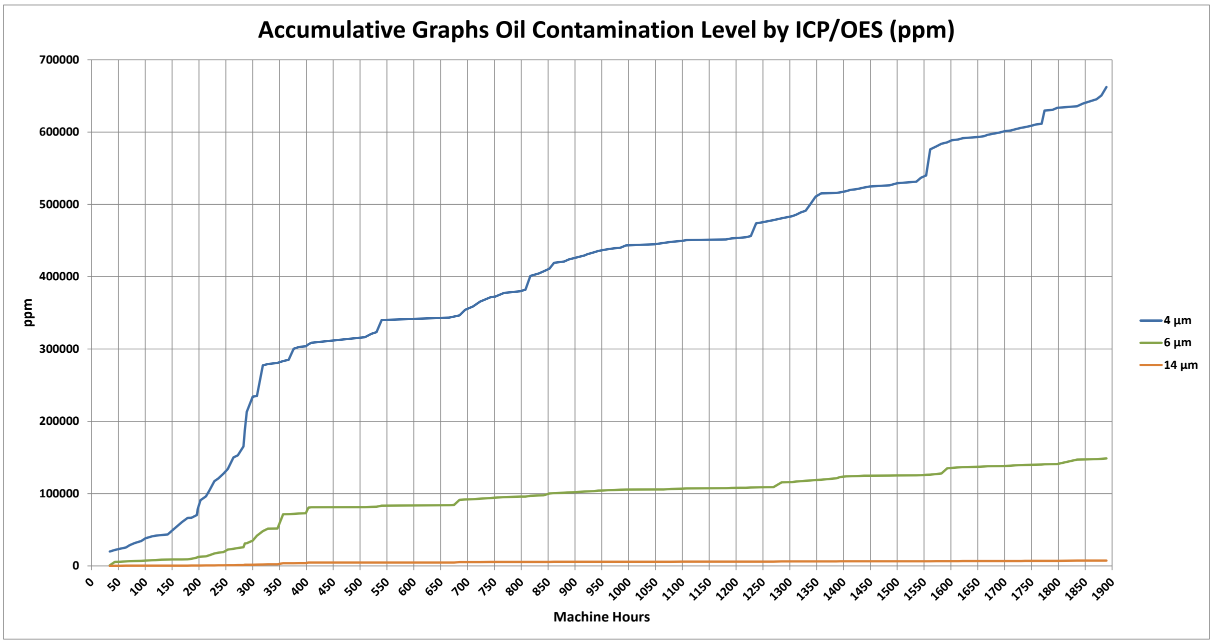

Figure 4-9: Accumulative Oil Contamination by ICP/OES (ppm)

4.4.4 Summary

With the current limited technology for hydraulic contamination monitoring available on the market, off highway equipment OEMs may find implementing real time monitoring in the hydraulic system expensive and unreliable. The results collected within work package 3 allowed an in-depth assessment to be conducted on the value of the additional data sources in product monitoring for PSS. Typical inline hydraulic oil particle counters collect data in accordance with ISO4406, measuring contamination levels less accurately than taking physical oil samples from the machine and processing them in laboratory environments. The findings in this work package conclude that OEMs need a reliable, accurate inline particle sensor that is truly suitable for mobile applications within the construction industry. In addition, the installation of metallic inline detection sensors should be considered that are capable of measuring the size and quantity of specific metallic particulates on a mobile application. Metallic particulates such as Cu and Fe should be the main focus, as they represent the majority of the main materials used in current hydraulic components such as pumps and valve blocks. Table 4-5 summarises the findings in work package 2.

Key Findings	Descriptions
The importance of primary system	The understanding of hydraulic oil contamination allows service technicians to assess the overall system health status and identify damage components.
The interpretation of data	Telemetry data although useful offers little contribution to fault analysis such as Eight principles Problem solving (8Ds) or root cause analysis (RCA), if insufficient historical records or records of sensor data creation are kept.
Responsive protocols/actions	Any data whether it is new or old, needs to be related with a list of relevant responsive protocols, these can be either service actions or further 8Ds analysis requirements in conjunction with other sensors data.

Table 4-5: Work package 3 Key Findings

4.5 CONCLUSION OF RESEARCH UNDERTAKEN IN WORKPACKAGES 1, 2 AND 3

In recent decades, PSS has been increasingly popular due to the demand for increasing aftersales support from customers, PSS also gives OEMs opportunities to gain revenue from the service market. The research conducted for this thesis followed a step by step assessment and review approach to identify and explore the prerequisite needs for off highway OEMs to implement PSS. Each task that was conducted in this research contributes to the identification of appropriate levels of real time product monitoring techniques which are currently lacking in the industry. Work package 1 was summarised by Figure 4-10, which shows the current sources and their inputs that are being used for product monitoring, as well as showing the opportunities to improve the capability within the industry, due to technological advancement and market demands throughout the past decades. (Further details can be found in Appendix A and Appendix B).

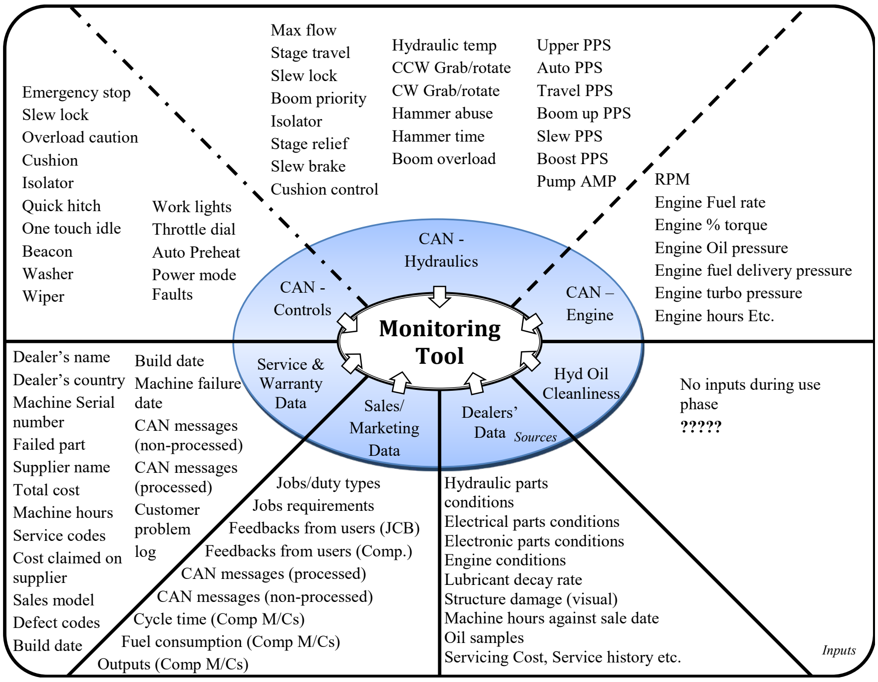

Figure 4-10: Project Map 1

Work package 1 therefore forged a firm foundation for the objectives of this thesis by reassessing the initial aim against reality, exploring the current status of the research and finding the common research gap in both academia and the industry. Work package 2 focused on reviews of industrial standards and practices in the architectural design of electrical and electronic network for communication and hydraulic systems of a piece of typical hydraulic off-highway equipment in an attempt to identify the relevant research gaps.

The research undertook for this thesis has a strong industry focus that reflects the demands of the market, as well as the research gaps in this field identified within the academic community. The research results demonstrate the value of real time data monitoring of products' performance and conditions above the traditional approach of using historical data. Whilst focusing on analysis of CAN bus data and contamination of hydraulic systems, which are two of the key systems for most off-highway equipment in the world, several difficulties were identified, including technological limitations, financial implications, data mining methods etc.

The assessment of the suitability of CAN bus and real time data to meet the requirements of PSS has enabled a roadmap, Figure 4-11, to be constructed for the creation of PSSs, with a strong focus on construction machinery OEMS who wish to implement PSS into their business model. The roadmap clarifies the required prerequisites such as product usage data, real time monitoring strategy, maintenance strategy etc. that OEMs need to determine in order to validate their readiness level towards the adoption of a PSS driven business model. Further explanation and the validation of the roadmap can be found in chapter 4.6.

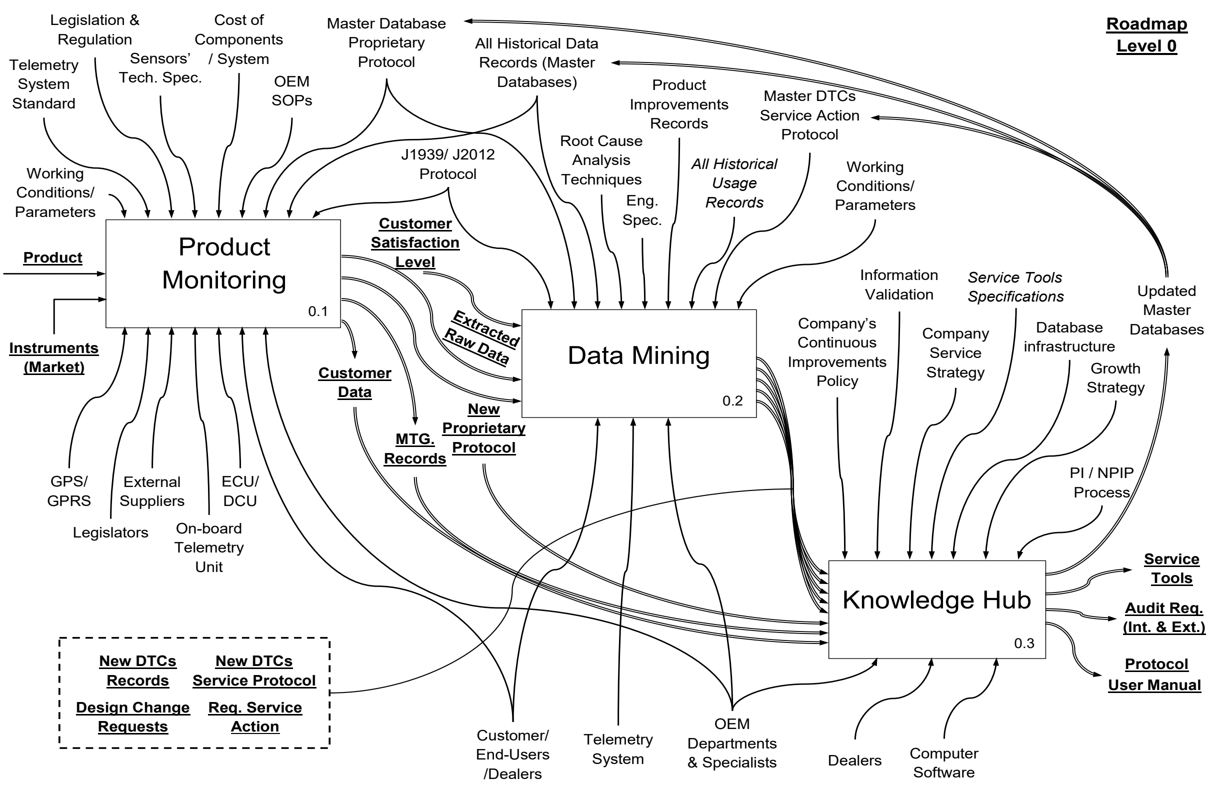

Figure 4-11: The PSS Roadmap

4.6 WORK PACKAGE 4 – CHANNELLING AND MANAGING THE DYNAMIC DATA IN PSS

4.6.1 THE CREATION OF THE PSS ROADMAP

A roadmap was created in work package 4 to fulfil the research aim stated in chapter 1, by utilising and summarizing the key findings from work packages 1, 2 and 3. This work package was summarised in a journal paper that can be found in appendix Y. The roadmap was designed to assist OEMs to clarify the required data and structure prerequisites to determine and validate their readiness level towards the adoption of a PSS driven business model. It also acts as a roadmap template for PSS readiness to enable OEMs to channel and manage their real time, dynamic data collected from the product. Although this roadmap has been developed using a combination of published information and data collected from a particular off-highway equipment company, the approach used in developing the roadmap is intended to be suitable for any OEMs that manufacture medium or high value products, who wish to implement PSS into their business model. The roadmap clarifies the required prerequisites such as product usage data, real time monitoring strategy, maintenance strategy etc., that OEMs need to determine and validate their readiness level towards the adoption of a PSS driven business model. The roadmap also addresses the weaknesses in PSS focus within the research field regarding understanding of data creation in product monitoring and data mining, as although these fundamentals are often assumed to be available to OEMs, this has been found to often not be the case. The roadmap was constructed using IDEF0 (Integrated Computer Aided Manufacturing Definition for Function Modelling), which is a branch of functional modelling (FM) methodology that is based on Structured Analysis and Design Technique (SADT), designed to present complex product development processes, especially those involving interdisciplinary activities in the process (Erden, Komoto et al. 2008). The

IDEF0 approach is therefore generally appropriate for modelling the processes that OEMs require to assess their readiness in adopting a PSS driven model to maximise their chances of successful implementation of PSS.

The roadmap is divided into three clusters; Product Monitoring (PM), Data Mining (DM) and Knowledge Hub (KH). As shown in Figure 4-11, the roadmap contains a mixture of sequential and loop functions between the three clusters, which reflect the nature of analytical root cause analysis such as Fault Tree Analysis (FTA), and continuous improvements of service protocols, SOPs etc. that OEMs implement to achieve service requirements. In this way, a PSS can be treated as a partially "live" system which is comprised of both static and dynamic data as classified by Scheidt (Scheidt, Zong 1994). PM, Figure 4-12, uses the knowledge created and organised in KH to investigate the plausibility and feasibility of applying a real time monitoring strategy on these products or components.

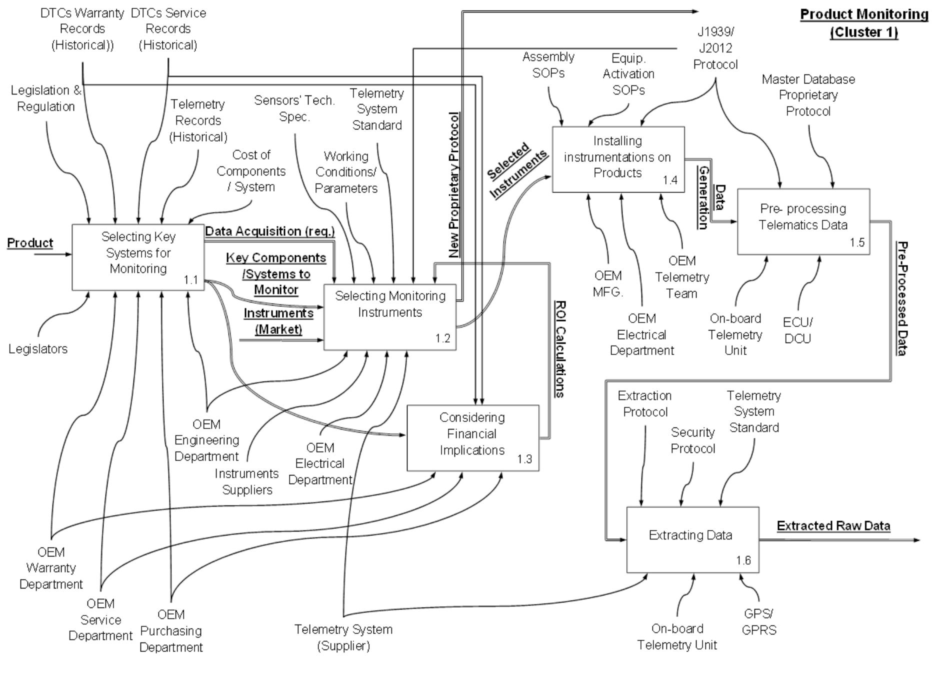

Figure 4-12: Product Monitoring (Cluster 1)

There are six sequential based functions within this cluster, with the first three functions focusing on the selection of sensor and monitoring instruments, and the last three functions focusing on the successful extraction of raw data from the installed instruments in the products in the field.

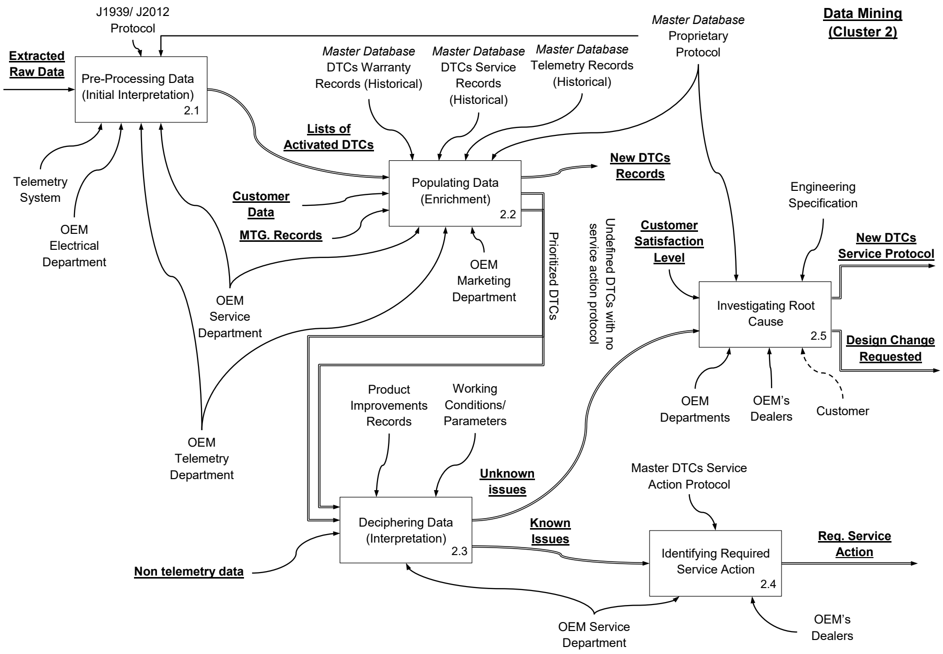

Figure 4-13: Data Mining (Cluster 2)

DM, Figure 4-13, uses the information that the PM has clarified and combines this with the knowledge from the KH to determine the course of service action that the OEM should follow. The extracted raw data can be pre-processed, enriched and interpreted into actionable items for OEMs. Enrichment is the most important function within DM, as it links the pre-processed data with the master database from the KH which provides essential background and historical information and knowledge to each individual activated DTC.

KH, Figure 4-14, manages all the information and knowledge needed to support the functions within PM and DM, as well as setting an internal standard regarding the renewal of the information and auditing of the entire PSS infrastructure. It also analyses the processed historical data from warranty, service and telemetry records, which consist of an appropriate set of information processed by cognitive and analytical methods. This mainly consists of two streams of knowledge that are used in problem solving for current products and innovation for new products as both are essential elements for OEMs to remain competitive in their respective markets.

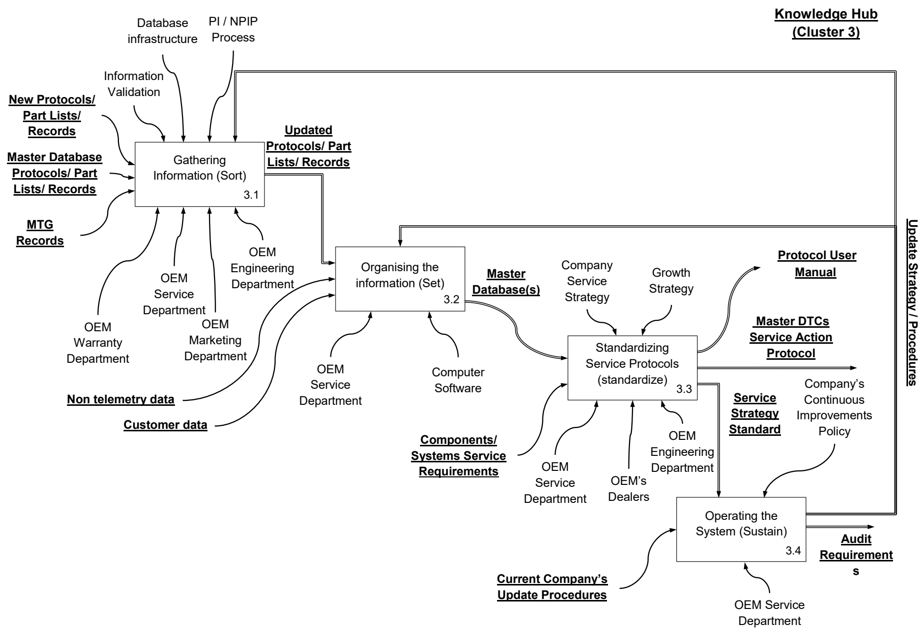

Figure 4-14: Knowledge Hub (Cluster 3)

These clusters are also detailed in Appendix L, Appendix M and Appendix N.

4.6.2 THE VALIDATION OF THE ROADMAP

The concept of the roadmap was field tested and developed between November 2014 and May 2015, its impact and contribution during and after the period are explained in detail in chapter six. Through this field testing, care was taken to ensure that the content of the roadmap was at a high technology readiness level (TRLs) so that it could be easily adopted by industry.

4.6.2.1 Background

A fleet of twenty-nine off-highway machines that complied with the Tier 4 Final (T4F) of European Emission Standards and with Tier 4 of United States Environmental Protection

Agency (EPA), were sent across the globe to test and evaluate their performance and actual operational behaviours in working conditions defined by the customers. Several documents were created in the form of a database, standard daily reports and interpretation mechanisms to achieve the functionalities addressed within each cluster of the roadmap. The majority of these documents were created using Microsoft Excel, to manage knowledge databases and perform data mining functions. Microsoft Excel was deemed to be an appropriate platform to monitor such a small fleet of machines, although Matlab was also used several times in order to process larger quantities of data and perform more complex calculations such as calculating a 6 months roll on average for each month from values filtered out by multiple criteria.

The main tasks undertaken during this evaluation period are listed below:

a.) To evaluate the machines' performance by analysing all the DTCs captured by the telemetry system.

b.) Provide data driven analysis (telemetry) to initiate, support and facilitate the root cause investigations of identified faults.

c.) Create and develop service protocols to support each DTC.

d.) Provide daily and weekly executive and operational reports to drive continuous improvements of the fleet.

e.) Undertake regular updates of database and records of telemetry, non-telemetry and customer data.

4.6.2.2 Applying the roadmap

The RE was initially asked to take responsibility in the analysis of telemetry data generated from the twenty-nine off-highway customers' machines, (T4F fleet) from November 2014 onwards. However a few weeks into the project, the RE's responsibility was escalated and became one of the key stakeholders as a data analysis specialist advising engineering, service and marketing managers to support the T4F fleet from a PSS point of view. The RE's basic routine was as follows:

4.6.2.2.1 Create and distribute machine performance (telemetry) reports

The reports contain all telemetry data (DTCs) from the previous 24 hours of the entire T4F fleet. The reports were created and distributed to all related engineering, service and marketing managers and directors at 0800hrs daily. Each division receives a report that contains their own fleet, and which also contains data from not just customers' machines, but also endurance machines and training machines. The report also contains vital information for engineering and service to react and act upon the presented information accordingly, such as the duration of the activated DTCs, the descriptions of the DTCs and its individual help file. The Help file is a document that contains service protocols for service technicians to follow in order to rectify any issues addressed by any DTCs.

The RE created a spreadsheet which pre-processes and enriches the raw telemetry data to help the engineering and service departments to act. A centralised master database that contains all the essential information of each known DTC such as SPN, FMI, parameters that trigger, consequent machine reaction, help file description etc. was created by the RE to make pre-processing and enriching of the raw telemetry data possible. This structure can be found in function 2.2 of cluster 2 data mining within the roadmap. A screen shot of the report can be found in appendix R. In late May 2015, in order to validate the readiness of the fleet for signing off as reliable, sale ready machines, a report was created to measure and visually display the fault rate of the fleet. A target fault rate had been set, based on required performance set by warranty and service department, as the maximum acceptable fault rate for the T4F fleet to be signed off.

4.6.2.2.2 Daily review telephone conferences

The RE chaired six daily review telephone conferences with all relevant T4F divisions that are based in UK and US, to review the daily machine performance reports and plan the subsequent responsive actions accordingly, with consideration from engineering, service, marketing and telemetry. The RE also provided information such as individual work hours and historical records to ensure any current issues were being dealt with as agreed previously. All discussions from the conferences were recorded, reviewed by the RE and presented as a report to the company's executives daily at 0800hrs (Appendix S). The daily executive report only contains an overview of the running of the T4F fleet which includes daily hours, total hours and issues without the engineering and service details presented in the daily machine performance report described in section 4.6.2.2.1. Any unknown DTCs or issues will trigger routine investigations to identify the root cause(s), as described in function 2.5 of cluster 2 data mining within the roadmap. If any new information has been identified, it will be added into the master database as described in cluster 3 knowledge hub within the roadmap. Below are examples of tasks that the RE conducted as a result:

a.) Check whether master database telemetry records are up-to-date, if so, update and interpret the data again.

b.) Decipher the SPN, FMI and SA combinations based on J1939 standard to work out the system this unknown is representing, and its potential fault mode.

c.) Follow up with the dealer and approach the customer if any feedback could be captured that may be related to the unknown DTCs. Arrange visit to the machine and download data logger if necessary. etc.

4.6.2.2.3 Create and distribute weekly T4F performance executive analysis

The executive analysis combines all the information and knowledge and transformed into graphical format allowing the T4F performance status to be visually presented in the executive reviews. The graphs are split into two level, the top level graphs contain information such as date of faults, faults types and quantity, daily machine work hours etc. Each graph only represents a group of specific type of T4F machines originated from the same division. e.g. backhoe loaders, telescopic handlers, excavators etc. The second level graphs (in-depth) provides supplement information on specific faults, investigation progress and historical behavioural pattern which often used to identify critical paths within T4F project for reaching specific deadlines. These analyses are also provide the needed data driven support to the decisions made by engineering and service. Appendix T gives an example of the graphs RE put together for the executive reviews.

4.6.2.2.4 Supporting the Roadmap – spreadsheets

Table 4-6 below is a summary of all the spreadsheets created and used by RE to support the functionality described within the roadmap and used for the T4F project.

Spreadsheets/Reports	Functionality
machine performance (telemetry) reports	To pre- process, enrich and interpret raw telemetry data into information such as DTC-FTB, Descriptions, Help files etc.
Daily Executive Report	To collate relevant T4F daily performance data / information by machine types into a daily executive report, and store as historical records and information for help files.
Weekly Executive Report	Analysis information and knowledge and present the performance status of the fleet, supported by technical information of the investigating faults in root cause analysis and other service / engineering decisions.

Table 4-6: Supporting the Roadmap - Spreadsheets

4.6.2.3 The Validation

The roadmap was used to underpin the real-time product monitoring strategy of a high profile project within one of the leading OEMs from the off-highway industry. Excel spreadsheets were created to allow the analysis of data and provide support for decision-making within the project. Upon project completion, six individual interviews were conducted with key personnel including: project general manager, project engineering manager, quality engineer, component OEM manager, marketing engineer and service manager.

Interviewees were asked to review the roadmap based on their own experience within the industry, and offer comments on its structure, and usability (i.e. suitability and relevance to the industry). Interviewees were also asked to provide detailed feedback on the roadmap, including any positive or negative impacts on the project. Their feedback confirmed that the roadmap allowed the OEM to realise the value of using telemetry data, allowing project completion to be achieved sooner and more economically. Issues were detected, investigated and responded to at a much swifter rate compared to previous projects. However, a number of refinements were also suggested to further improve the roadmap's suitability for the industry, in particular:

1.) Early participation from end-users and customers in functions 1.1, 2.2, 2.3 and 2.5.
2.) New output, "No Change", for function 2.5 to include acceptable faults that do not have significant effect to performance of the product.
3.) New mechanism, "OEM Sales Department", for function 3.1 include end-users' and customers' feedbacks.

Hence, the final version of the Roadmap, which reflect the above requirements, is presented in appendix O, P and Q.

Table 4-7 summarises the findings in work package 4.

Key Findings	Descriptions
Unexpected data and system noise	Unrecognised SPN, FMI and SA can affect the integrity of the data and its analysis. Such noise has to be identified and eliminated before any analysis can be conducted.
The dynamicity of service protocols	Each DTC-FTB needs to be linked to a service protocol for OEMs/service providers to follow. Further to trigger a service protocol, information such as duration of the activation period, the activation condition etc. needs to be validated, to ensure the protocol is up-to-date and adequate to rectify the fault.
Data driven PSS	PSS demands an intense real data driven strategy in order to extract the adequate service protocol for OEMs and Service providers to react instantly to the given fault condition. Furthermore, OEMs need to be prepared to invest in data storage to facilitate the up-keep of telemetry data records as well as information and knowledge generated from day to day analysis.

Table 4-7: Work Package 4 Key Finding

5 FINDINGS

This chapter presents the main findings of this EngD research project. A bespoke PSS roadmap for off-highway equipment OEMs has been designed based on the knowledge and understanding created from the work described in chapter 4. The roadmap was one of the outputs from work package four and combines all the main findings of the research project and achieves the overarching aim described in chapter 2. The roadmap was developed and validated over a six month period which was spent monitoring a fleet of twenty-nine new machines across the world, proactively responding to faults flagged on machines using the daily analysed telemetry data.

5.1 THE KEY FINDINGS OF THE RESEARCH

All the key findings from work packages 1 to 3 can be seen as milestones which contribute towards the final roadmap constructed in work package 4 to fulfil the aims of this research project. The key findings for each work package are summarised in Table 4-1, Table 4-4 and Table 4-5. Each key finding contributes to a significant focus within the roadmap and also reflects some of the critical elements of PSS.

5.1.1 OBJECTIVE 1 – THE METHODS TO UNDERSTAND THE LIFE OF A PRODUCT

The research gaps of PSS within both academia and industry projects were identified through literature reviews of both academic and industrial materials. Although a variety of tools and methodologies have been put together for OEMs to consider when designing a suitable PSS, there is lack of research focus on PSS implementation guidance, and in particular a lack of guidance that has been tested in an actual industrial or business environment. As a consequence, some essential understanding is lacking regarding the problems which need to be addressed when implementing a PSS, such as how to deal with the complexity of networks that exist between OEMs, dealers and customers and the critical effects that these may have on the fundamentals of PSS such as product condition and performance. Traditionally, feedback gathered by OEMs on factors such as product condition, performance issues etc. is considered as historical records which consist of both quantitative and qualitative data. These records could provide very useful knowledge to quantify typical product usage and components failure rates in the field and hence could naturally play a key role in the design and development of new and current products as well as providing valuable input to service schedules for preventative maintenance programs. However, although these records can give OEMs an overview of how products are being used in reality, they are insufficient to allow OEMs to implement PSS beyond the product-oriented type as all the data they provide is historical in nature, and this restricts the exploitation of PSS in any predictive way, such as the implementation of advanced PSS in ways proposed by the academic research community.

A number of OEMs in the off-highway industry have introduced telemetry as part of their product support structure to their customers. This is as a result of decreases in the cost of telemetry systems over recent decades, as well as the demand for greater remote transparency of the operation of the machines from the market. The use of telemetry is no longer restricted to high value product OEMs such as Rolls Royce and due to falling costs, some off-highway equipment and automotive OEMs may also take advantage of real time data and attempt to achieve benefits using the design and methodologies of PSS proposed by academia. Appendix I and Appendix J provide benchmark tables of telemetric features of the key players in the off-highway equipment industry, based on reviews conducted in 2010 and 2015. Both tables clearly show the new sets of information which may be gathered by using telemetry systems to support the service elements of PSS, as well as the new comers and development of telemetry systems in the off-highway equipment industry in just five years. The capabilities of telemetry systems, and the information that they can provide are not necessarily considered during PSS design, and this makes PSS vulnerable during its operational phase. For example, the measurement of a duty cycle, is likely to be an element of product data that a PSS designer would have taken for granted as being available, however, in reality, as the RE experienced in work package 2, measuring a duty cycle is it not an easy or straight forward task.

5.1.1.1 Key Findings of Work Package 1

There are gaps in academic research related to PSS due to lack of understanding of the product data and information that industry collects and possesses. Product data and information are often considered as critical fundamental elements of advanced PSS, which can provide significant commercial and social benefits to both OEMs and society. However, it is only in recent years, that off-highway equipment OEMs have gained access to many pieces of real time data, through the implementation of telemetry systems and industry is still assessing their value for the design and development of new and current products as well as for the planning of service schedules. In truth, OEMs have been offering customers various preventative maintenance programs as part of the PSS, simply based on the support of customer feedback and historical data. The historical, non-real time nature of the data has been a restraining factor on the development of PSS programs in industry and their uptake and progress has therefore not been as quick as research within academia. Furthermore, PSS development work from academia often fails as it assumes that key information such as lifecycle data, duty cycles, monitoring abilities in key system (hydraulics) etc. are available and well understood by OEMs.

5.1.2 Objective 2 – The truth behind Telemetry Data

The collection of telemetry data creates significant opportunities for OEMs to gather more information and insight into their product's condition during its use phase from the real time data collected. Telemetry is a system used by several industries, in particular within the aerospace industry, to monitor the condition of products remotely. The primary function of the system is to extract raw or pre-processed data and transmit the data by means of wireless communication devices remotely to a dedicated radio receiver for real time monitoring, data analysis etc. Telemetry systems do not create any data, but may pre-process raw data in order to lower the transmission cost by reducing the amount of data before transmitting. Data are typically signals created by electronic devices, installed at the key areas or components that require close monitoring within the product, and the data are broadcast as messages onto a CAN bus, being a specialised internal communication network that connects components inside various types of equipment ranging from agriculture and construction to on and off-highway vehicles.

The CAN bus is the standard which allows electronic devices to communicate to each other, without the requirement of a host computer. J1939 and J2012 are vehicle standards that dictate the communication and diagnostics between vehicle components and electronic devices. All messages are communicated as groups of binary codes categorized by a parameter group number (PGN), each PGN generally consists of 8 bytes of data. Some PGNs are already pre-allocated in J1939 to contain specific messages such as engine temperature. However OEMs are allowed to create other own PGNs as proprietary CAN bus messages to be broadcasted globally within the CAN bus. Table 5-1 is an example of a PGN and the information it contains;

Name	Engine temperature 1 - ET1
Transmission rate:	1s
Data Length:	8 bytes
Extended Data Page:	0
Data Page:	0
PDU format:	254
PDU specific:	238
Default priority:	6
PG Number:	65,262 ($00FEEE_{16}$)

Description of data:		
Byte:	1	Engine Coolant Temperature
	2	Engine Fuel Temperature 1
	3, 4	Engine Oil Temperature 1
	5, 6	Engine Turbocharger Oil Temperature
	7	Engine Intercooler Temperature
	8	Engine Intercooler Thermostat Opening

Table 5-1: Example of a PGN definition

In this particular example, there are 6 messages embedded in the PGN. Due to the size of the message, two of them require 2 bytes to store the data. This is because engine temperature has to be measured at an increment of 0.03125 ºC/bit between a data range of -273 ºC to 1734.96875 ºC, in take into considerations extreme conditions and required resolution. 1 byte can only achieve a much lower resolution increment value of 7.84362793 ºC/bit for the same data range, therefore 2 bytes were used instead (SAE International 2015).

A Suspect Parameter Number (SPN) is assigned to each message in the PGN. SPN is a 19 bit number, ranging between 0 – 524287 for redefined messages and 520198 – 524287 for proprietary messages. Each SPN contains information about how the data can be interpreted in the units of the particular SPN. Table 5-2 is an example for such definitions and as the resolution is 0.4% per bit, any data captured from this SPN will need to be multiplied by 0.4 to obtain the true value before any analysis can be done.

SPN 38 – Fuel Level		
Ratio of volume of fuel to the total volume of fuel in the second or right-side storage container.		
Data Length:	1 bytes	
Resolution:	0.4% bit, 0 offset	
Data Range:	0 to 100%	Operational Range: Same as data range
Type:	Measured	
Supporting Information:		
PGN reference:	65276	

Table 5-2: SPN Definition

On some equipment, the Electronic Control Unit (ECU) may support the diagnostic functions and be able to broadcast Diagnostic Messages on to the CAN bus, that contains a Diagnostic Trouble Code (DTC) to address suspected trouble or problem areas, and an indicator is used to dictate the appropriate service procedure. Each DTC is a combination dictated by SPN, FMI and the source address in accordance with ISO 15031-6:2010. A 3-byte DTC is the common structure adopted by OEMs, allowing them to create their own DTCs but also constraining them to use DTC that are controlled by ISO/SAE standards. As a result, an accurate record of all the OEMs' proprietary DTCs definitions is essential to enrich the data for interpretation so that an appropriate service procedure can be selected.

However, as for any complicated electrical systems that consist of multiple functions, OEMs also need to be conscious of the data reliability. The proprietary list may be poorly maintained and became inadequate if it fails to capture any obsoleted or newly introduced DTCs. Furthermore, faulty sensors from the suppliers or "bugs" in the diagnostic programs may remain undiscovered until a challenge is raised. Therefore, historical records such as warranty and service records were used to clarify hypotheses during this research project.

5.1.2.1 Key Findings of Work Package 2

A major finding from work package 2 is the significant effect of BCD on the productivity and fuel efficiency of a hydraulic excavator.. While productivity is a well-researched area within operations research, a review of literature and industry guidance identified a gap in respect of fuel efficiency and productivity for hydraulic excavators. It has been found that BCD and engine speed settings can affect fuel efficiency and productivity of the operation of a hydraulic excavator. In addition, the results over ruled the existing, common perception that the highest speed setting will achieve highest productivity. Conversely, low engine speed settings do not necessarily consume the least fuel to complete the same task. The results also scientifically prove that a half-filled bucket (50% BCD) can have a maximum effect of 30%

improvement on productivity (m^3/h), 24% saving on fuel efficiency (l/kg) and an overall amount of 62% more spoil moved per hour and litre of fuel consumed. The relevant published paper can be found in appendix W. It is also important to understand that telemetry is not the source of real time product data but is merely a tool to remotely extract data from the local CAN bus network on the machine. The extracted data are signals generated by various electronic devices installed on the machines to monitor the behaviour of specific areas of interest. These signals are constantly being broadcast as simple messages such as fuel level or diagnostic messages in the form of DTCs. These messages are either controlled by ISO/SAE or are reserved as proprietary messages for particular OEMs, but all messages require the understanding of specific rules in order to decipher them into meaningful information. Applying an appropriate analytical process to the current hydraulic CAN bus messages on a JCB twenty-two tonne class hydraulic excavator, enables these messages to be understood sufficiently to provide a certain level of product insight as required by PSS.

5.1.3 OBJECTIVE 3 – THE MONITORING VALUE WITHIN HYDRAULICS

Hydraulic oil contamination is a well-known issue among industries that use any form of hydraulic systems in their products, yet its significance has not been of similar interest within the academic research community. About 70% - 90% of hydraulic system failures can be attributed to contaminated oil, failed to address or ineffectively managed contamination will lead to expensive downtime and short component life (Douglass 2006). Contaminations that are caused by particulates contribute on average 82% of wear problems such as abrasion, erosion and fatigue (Garvey 2003). As a result, vast amounts of technology such as filtration, monitoring, and analysis methods etc. have been developed in the industry to address the demands and requirements of contamination issues. At the same time international standardization organisations such as ISO and SAE continue to publish standards to facilitate international trade ensuring the quality, safety and efficiency of the products in the market.

For example, ISO published standard ISO 4406, "Hydraulic fluid power – Fluids - Method for coding the level of contamination by solid particles", which introduces a standardised way for determining the amount of particles of sizes, 4μm, 6μm, and 14μm per millilitre of fluid as a measure of contamination present in the oil. A scale of ISO code numbers is used for each particular size to represent the quantities of a specific range of particulates, e.g. ISO 20 represents any counts from more than 5000 to 10000 particles per millilitre. ISO 21 represents any counts from more than 10000 to 20000 particles per millilitre etc. A step ratio of two is generally used through the scale.

Using ISO 4406 as a guideline, hydraulic component manufacturers (such as Bosch Rexroth and Parker Hannifin) recommend a range of acceptable contamination levels for various types of systems, based on internal clearance, dirt sensitivity and operating methods of the components. To ensure products remain at their peak performance, some OEMs offer oil analysis as part of a preventative maintenance package to their customers, and provide services based on the level of contamination identified by the analysis. Any oil samples that are taken physically from the hydraulic system are likely to be analysed under laboratory conditions by Inductively-coupled plasma/Optical Emission Spectrometry (ICP/OES). ICP/OES is regarded as one of the most powerful and popular element analytical tools that measures 21 different elements, and gives the result in particles per millilitre (ppm) values for wear metals, contaminants and oil additives.

Although inline particle counters provide a much needed real time insight into the contamination levels in the hydraulic system, they are not able to detect metallic particulates and coarse ISO 4406 code report structure, and therefore there is an imbalance in the return on investment (ROI) in generating the data. Furthermore, despite being marketed as a mobile application, results shows they are unreliable in terms of performance and accuracy, due to the working conditions and system behaviour of typical off-highway equipment, recommendations were therefore made to the supplier used in this research, that more robust particle counters need to be developed for this industry.

5.1.3.1 Key Findings of Work Package 3

The condition of oil provides vital information that can help service technicians to follow and conduct suitable service procedures to prolong product's service life and prevent downtime. The majority of oil analysis facilities and contamination monitoring equipment available on the market measure and represent the contamination level in accordance with ISO standards such as ISO4406. Although, such standardization eases the difficulties for industries to address oil cleanliness targets for various components, it does not provide sufficient resolution for accurate measurements which can take into account the contamination level fluctuations and origin of particulates within the system. More advanced oil analysis methods such as ICP/OES are available and do provide the data that inline particle counters fail to provide. These methods are capable of measuring the size and quantity of specific metallic particulates. Metallic particulates such as Cu and Fe should be the main focus, as they are considered as wear metal and represent the majority of the main materials used in current hydraulic components such as pumps and valve blocks.

Although Inline particle counters do offer a real time capability in monitoring the hydraulic system for OEMs, the compromises that they make in contamination measurement and their inability to measure metallic particulates, make the tangible implementation costs higher than the intangible gains. OEMs need a reliable, accurate oil contamination sensor that monitors wear (metallic) particulates. It is therefore also strongly recommended that the research community work with industry to design inline particle sensors that are truly suitable for mobile applications within the construction industry. The relevant published paper can be found in appendix X.

5.1.4 KEY FINDINGS OF WORK PACKAGE 4

As mentioned earlier the telemetry data are captured from the CAN bus and transmitted out of the machines. This data then requires accurate interpretation into information to decide the appropriate service protocol to follow. Occasionally, unrecognised combinations of SPN, FMI and SA from the master database proprietary protocol were collected from the machines, and these could not be pre-processed or enriched in the data mining stage, and therefore they were classified as unknown. It was later discovered that some of these combinations are known and do represent a number of critical DTCs but they were not included in the master database proprietary protocol due to human error and out of date hardware. As a result, a process was developed to investigate these unknown combinations, and this involved working with identified key champions, telemetry or electrical and electronic managers from each division, to ensure that the master database proprietary protocol was constantly checked and updated.

It is also important to gather and process all feedback on service protocols, no matter how simple the activity is, as this will contribute and ensure that an effective up-to-date service procedure is being followed. DTCs are activated due to certain pre-set thresholds having been reached, however there could be more than one cause which triggers the activation of a particular DTC. Therefore, most service procedures often include additional checks for the service technicians to validate whether the speculated root cause is likely and justifiable. This can be done by deliberately repeating the fault, to check if it can be the actual cause of the triggered DTCs. This extra validation at service time ensures that all services conducted are actually needed and allows OEMs to have a complete failure mode for the faults represented by the DTCs.

By adopting the telemetry data driven servicing strategy, a proactive and responsive manner of service support outcomes can be achieved. However, OEMs should expect a significant investment to be required, and this is not necessarily solely due to the need for an organizational structure change, nor the additional cost of sensors required to generate the telemetry data, but is also in part due to the costs of resources that operate the knowledge management and data mining aspects of PSS. If the roadmap is to be implemented on a global fleet, over half a million off-highway machines will be included. In order to manage and analyse such vast amounts of data, bespoke data analysis management software will be required. The deciphered data has to be understood by most parties such as engineers, service technicians, dealers etc. The data analysts will need to be trained to understand the engineering and servicing aspects within PSS, in order to present the information at the right time for the right audience. The findings from work package 4 demonstrate the benefits and difficulties of real time data being used to support PSS by following the structure stated in the roadmap in a typical off-highway equipment industry. This is supported by the feedback from key personnel from the T4F project stating that the roadmap allowed the sponsor to realise the value of using telemetry data, allowing project completion to be achieved sooner and more economically. Issues were detected, investigated and responded to at a much swifter rate than in previous projects. The relevant published paper can be found in appendix Y, and recommendations for the industry will be discussed in chapter 6.

5.2 CONCLUSIONS FROM KEY FINDINGS

This chapter has covered all the key findings in the thesis and shown how they achieve the overall aim of the thesis. The combined findings from work packages 1, 2 and 3 demonstrate the possibilities of using the dynamic real time data for a more proactive maintenance approach in PSS, through several assessments to measure the ability of the sponsor's product to provide appropriate remote monitoring. These dynamic data were assessed within the fields of excavators' productivity and fuel efficiency, as well as hydraulic oil contamination. These findings were summarised in publications that can be found in appendix V,W and X. Work package 4 saw the creation and validation of a PSS roadmap that aims to assist OEMs during PSS employment; it is divided into three clusters Product Monitoring (PM), Data Mining (DM) and Knowledge Hub (KH). Each cluster provides unique functions which are carried out with the support of specific documentation and by particular departments within the OEM. The clusters will require a mixture of sequential and iterative steps, which reflect the nature of analytical root cause analysis such as Fault Tree Analysis (FTA), and continuous improvements of service protocols, SOPs etc., which OEMs need to implement to determine the service requirements. Hence PSS needs to be treated as a partially "live" system which works with a combination of static and dynamic data. As in other work packages, key findings of work package 4 were summarised and published as a journal paper (appendix Y).

6 IMPLICATIONS & CONCLUSION

This chapter draws conclusions from the findings presented in the previous chapter of this thesis. The findings from work packages 1, 2 and 3 provided the essential building blocks for the PSS implementation and validation roadmap which was constructed and field tested in work package 4. Subsequent to the completion of work package 4 (and to the completion of the research elements of this EngD project), effort has been put into exploiting the understanding gained through this research by driving a new machine monitoring approach within the company and in parallel designing a new department to continue this work. Whilst the major research contributions of this project are the understanding gained to support PSS implementations and the validation of the Roadmap described in section 4.6.2.3, the major contribution for industry will be the impact provided through more effective machine monitoring approaches which will enable the sponsoring company and the off-highway equipment industry generally to provide better, more predictive service offerings within their PSSs. Details of this impact are explained in this chapter.

6.1 IMPLICATIONS/IMPACT

It is the nature of an EngD thesis to be very industrially focused and to exhibit a high level of industrial relevance and integration into the commercial world. Technology Readiness Levels (TRLs) as used by the Ministry of Defence (MoD) provide metrics for systematic measurements to assess the maturity of particular technologies. At the end of work package 4, a model was set up using a Microsoft Excel platform to process all of the DTCs transmitting from a fleet of 29 machines that are used by some of JCB’s customers under known operating conditions. Two more models were also created to support the further analysis and presentation of fleet performance in executive reviews etc. Based on the achievements of these Microsoft Excel models, and using the TRL definitions provided in Table 6-1, the results of this research can be classified as TRL 6.

TRL 1	Basic principles observed and reported.
TRL 2	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.
TRL 4	Technology basic validation in a laboratory environment.
TRL 5	Technology basic validation in a relevant environment.
TRL 6	Technology model or prototype demonstration in a relevant environment.
TRL 7	Technology prototype demonstration in an operational environment.
TRL 8	Actual Technology completed and qualified through test and demonstration.
TRL 9	Actual Technology qualified through successful mission operations.

Table 6-1: Technology Readliness Level used by MOD

6.1.1 CONTRIBUTION AND IMPACT ON THE SPONSOR

The thesis provides fundamental knowledge and guidelines, as discussed in the key findings and the creation of the roadmap in sections 5.1.1.1, 5.1.2.1, 5.1.3.1 and 5.1.4 as well as Appendix O, Appendix P and Appendix Q for the sponsor to further develop bespoke mechanisms that will allow effective analysis of all necessary data for a proactive real time service strategy. The contribution of these mechanisms to the successful operation of a proactive real time service strategy is reflected in the significant drop of, faults per machine rating by 150 % after 3 months and stabilization at that level (Appendix U). The bespoke mechanisms were built on Microsoft Excel platform and have become an essential part of the daily fleet performance analysis for the sponsor. It provides a common language between the engineering and service departments to tackle the DTCs, and supporting information such as descriptions and service protocols are included in the basic level of the report, as this promotes communication between departments. The mechanism also accommodates any unrecognizable DTCs or faults captured by the telemetry system.

To maximise the impact gained from this EngD research, the sponsoring company are currently forming a specific team to identify and subsequently resolve unknown issues which are identified. This could result in product improvement requests being raised for engineering or in new service protocols being implemented to address the identified root causes. The excel model based mechanism is a physical representation of the benefits that the roadmap possesses and the mechanism has provided immediate benefits and impact to the sponsor, raising awareness among employees as well as demonstrating the intangible value that dynamic data have when utilised at the operational level. In summary, this EngD research has made three key contributions to the sponsor:

1.) The assessments and knowledge gained in work package 1, 2 and 3, as detailed in chapter 5.1, exposure of the fundamental requirements for PSS and knowledge of how to support and satisfy the PSS requirements.
2.) A PSS roadmap mentioned in work package 4, as detailed in chapter 4.6, an infrastructure has been built and tested within the sponsor's environment, enabling them to convert their service strategy from a passive focus to a proactive focus (use-oriented PSS), through a telemetry data driven analysis approach. This roadmap also draws out another critical PSS characteristic, to ensure any service protocols, databases, components information etc. are up-to-date, as discussed in section 5.1.4.
3.) The mechanisms built in accordance with the roadmap created in Microsoft Excel environment as discussed in chapter 6.1, have helped to restructure the existing documents that define telemetry data and thereby simplify and improve the interpretation of information that is needed in PSS.

The research has also produced three key contributions to the academia:

1.) The roadmap created in this research connects and enables commercialisation of critical PSS developments addressed by academia into OEMs' industrial environments, hence providing the missing link between theoretical PSS and the application of PSS.

2.) The roadmap addresses the academic assumption that most OEMs would have an extensive understanding of the product usage by their customers or remote monitoring analysis systems, which are essential to the application of PSS.

3.) There has only been a limited amount of focus from academia into the development of service applications within PSS. OEMs would need an infrastructure to ensure that the links between service protocols and product feedback can be exploited to deliver the right service at the right time, as flexibly as possible, especially when an unknown issue is identified.

6.1.1.1 Impact

The major physical impact for the sponsor is the creation of a new department that is dedicated to customer support that is driven by the analysis of telemetry data. The sponsor has recognised the benefits of using the analysed telemetry data, as the main source of information to estimate the actual service or repair requirements requested by the machine without the need to contact the dealers. The analysis and reporting methods determined in work package 4 have helped the sponsor to shorten their response times dramatically and enable the company to investigate issues before they escalate to a critical level. The new department will monitor customers' machines at a global scale, and raise instructions for any required service based on the information gained from the analysed data. All the data analysis will be conducted by in-house analytical software powered by the central computer, using the approach specified and demonstrated in the roadmap and work package 4. Another major impact for the sponsor is the integration of telemetry data analytical procedures into their current data analytical system. In order to support the new department at a global scale, the prototype analytical infrastructure designed by the RE will be migrated into a larger-scale, highly analytical environment.

As a consequence of the above changes for telemetry driven service provision, there are various other changes and impacts in different departments within the sponsor, including the new product introduction and internal standard departments. A new procedure will be included in the sponsor's new product introduction process, to ensure that all documents as shown in the KH are validated to protect the integrity of the outputs in PM and DM as shown in the roadmap. This is necessary to fulfil one of the usages of the roadmap, i.e. to act as a prerequisite check list for OEMs to assess their PSS readiness at the machine level. The new procedure will focus on the verification of DTC information available for triggering the service protocol, should the DTC be flagged during usage.

6.1.2 CONTRIBUTION AND IMPACT ON THE WIDER INDUSTRY

The three journal papers in appendices W, X and Y, each have a major contribution to the wider industry. Firstly, the quantification of BCD's benefits to two of the key subject areas, productivity and fuel efficiency, responds to the need for the industries to move towards cleaner productivity, by identifying an appropriate means to achieve better productivity and fuel efficiency at the same time. Secondly, the assessment of current methods in measuring hydraulic oil contamination expose both technological methods, and at the same time raises questions about the benefits of current maintenance routines, e.g. the effectiveness of oil change in removing contamination from the system. Thirdly, the literature review in chapter 2 highlighted that despite of the vast amount of interest shown in the development of PSS infrastructures proposed by academia in recent decades, there is little practical guidance available to enable industry to take advantage of the benefits offered by PSS development.

There has also been much less academic interest shown in the fundamentals of PSS such as product data collection and product usage understanding, especially regarding aspects of data creation in PM and DM, as these fundamentals are often assumed to already be available to OEMs within the industry. Furthermore, products that are capable of performing more than two types of duties, such as the majority of off-highway equipment will have complex data that requires up-to-date background information to allow OEMs to take appropriate actions.

This thesis contributes to addressing the practical needs of industry should they wish to adopt PSS as their business model, while addressing the research gaps stated in this thesis by providing guidelines that are suitable for OEMs to understand and adapt at both strategic and operations levels. It is anticipated that other OEMs within the industry will experience similar challenges to the sponsoring company and in consequence demands will increase for more sophisticated but cost effective remote monitoring sensors from suppliers, which could promote innovation within the remote monitoring (telemetry) market. Following work package 3, several meetings were held with a hydraulic remote monitoring supplier to seek new directions for the next generations of sensors.

6.1.2.1 For the Industry

The demand for real time monitoring has increased dramatically in recent years. Telemetry technologies are no longer only the province of high value products such as aero-engines and trains, but are now accessible for medium value products such as off highway equipment, due to the reduction of their implementation cost. It is therefore recommended that industry should evaluate their understanding of their product usage behaviours by organising all their relevant information and knowledge as described in the KH section of the roadmap. OEMs are encouraged to use the roadmap to identify their missing product data or behaviour information, and explore the telemetry market for adequate sensors that can provide the necessary information as well as being reliable under the expected working environment. However, any additional sensors should be considered as an investment to protect and support products, rather than used as a marketing tool. OEMs need to transform the roadmap into their own language and adapt it into their infrastructure between the elements of product and service. It is possible that OEMs may come to realise that it is not only the dynamic database that they are missing, but also a certain level of involvement from key departments or even complete records of key service protocols. Finally, the industry should increase their participation and partnership with PSS research communities in the development of practical PSS implementation procedures, increasing the awareness of fundamental PSS prerequisites. The research community should also shift their focus more towards the implementation aspects of PSS in various industries depending on product types and usage profiles.

6.1.2.2 For the Academic Research

The thesis has also identified several further research focuses for industry and the research community. The roadmap could be developed as software to enable OEMs to assess and develop their PSS ability. The roadmap can be developed in the form of business management software such as Enterprise Resource Planning (ERP), as this approach could ease the complications of its integration into the current OEM's infrastructure. The new variable, BCD, was found to have significant effect on productivity and fuel efficiency, and further work is needed from the research community to derive a method to allow industry to harvest its benefits into their products. As identified in work package 3, it is strongly recommended that the research community should work with the off-highway equipment industry to design inline particle sensors that are truly suitable for mobile applications within the construction industry, as well as capable of measuring the size and quantity of specific metallic particulates.

6.2 LIMITATION OF THE RESEARCH

The aim of the thesis is to develop a PSS implementation roadmap for off highway equipment OEMs. It has a strong focus on the off-highway equipment industry due to the business nature of the sponsor, as well as the change in business strategy within the company in recent years. All equipment used in this research were production specific machines provided by the sponsor, and experiments were designed to conduct several tests in parallel with the work described in the thesis. The machines accumulated a certain amount of down time as a result of unexpected failure, or were recalled to fulfil other critical business demands. These downtimes could be considered as a factor that affects the accuracy of the research results. However, these unexpected disturbances to the experiment were taken into account in the calculations in the planning of work packages, and procedures were put into place to minimise the effect of the disturbances to the data integrity of the experiment. Furthermore, these unexpected downtime periods are deemed to be an acceptable representation of actual field working conditions by the industry. Therefore the results are appropriate and sufficiently accurate to achieve the aim of the thesis.

A specific class of hydraulic excavator was used in the assessment of CAN bus data in work package 2, which subsequently led to the assessment of hydraulic contamination data for PSS in work package 3. The results arguably are specific to hydraulic excavators which dictate the types of system behaviours, due to different types of duties they are capable of performing. However, most off-highway equipment is powered and controlled by an engine and hydraulics, and the fundamental configuration is mostly identical to other types of off-highway equipment. There might be differences in channelling hydraulic flow to axillary circles, which may affect the level of exposure of contamination in that particular part of the circle, yet the primary systems such as hydraulic pumps, solenoid valves, hydraulic cylinders etc. will, in the main, be the same. Therefore, the results will still be applicable to most off-highway equipment within the industry.

Although the roadmap was created to be as generic as possible in order to be applicable to most OEMs within the industry, elements such as the mechanism and controls in the roadmap have still been heavily influenced by the sponsor, an off highway equipment OEM. Therefore should the roadmap be used outside the off-highway industry, some functions of elements may need to be modified, omitted or added to increase its suitability to the specific industry.

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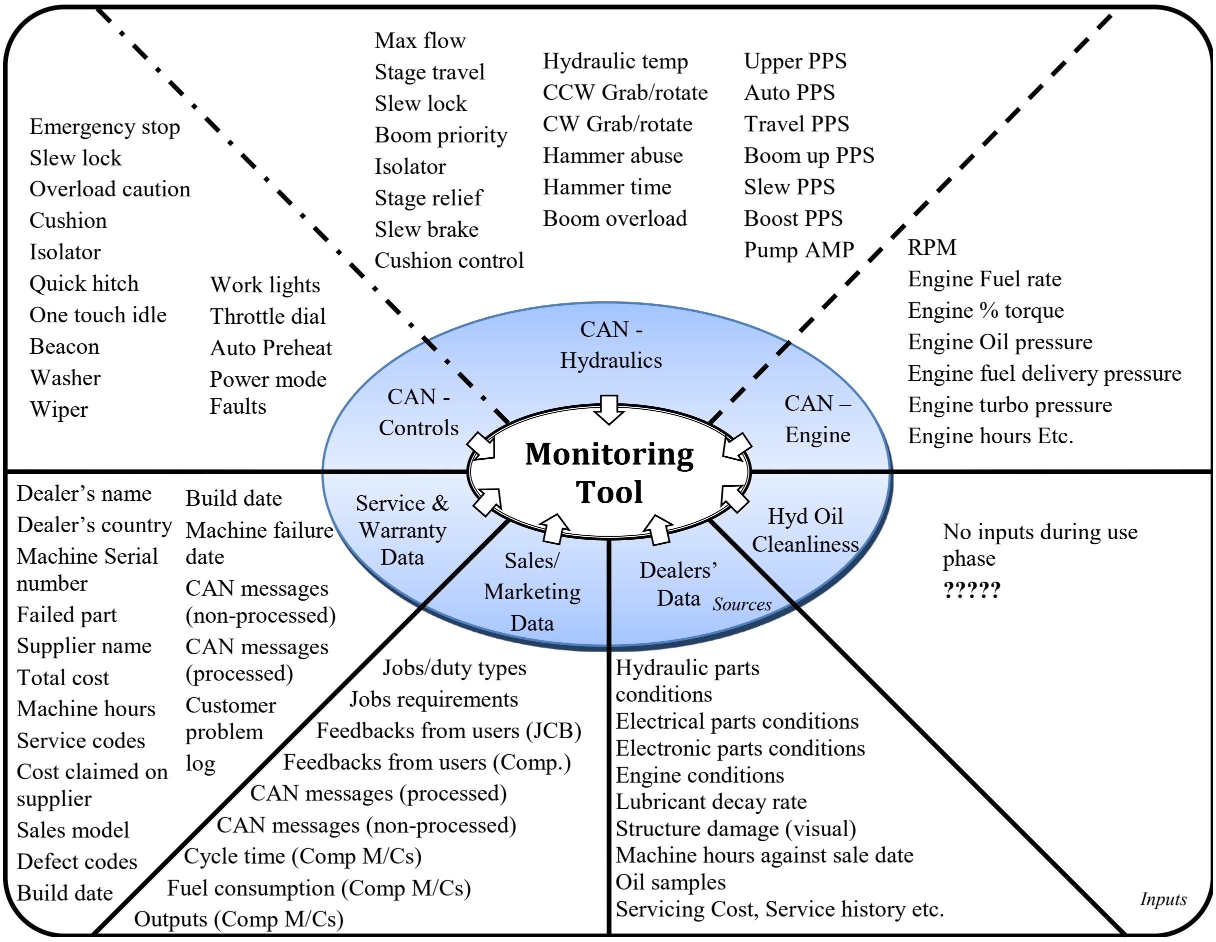
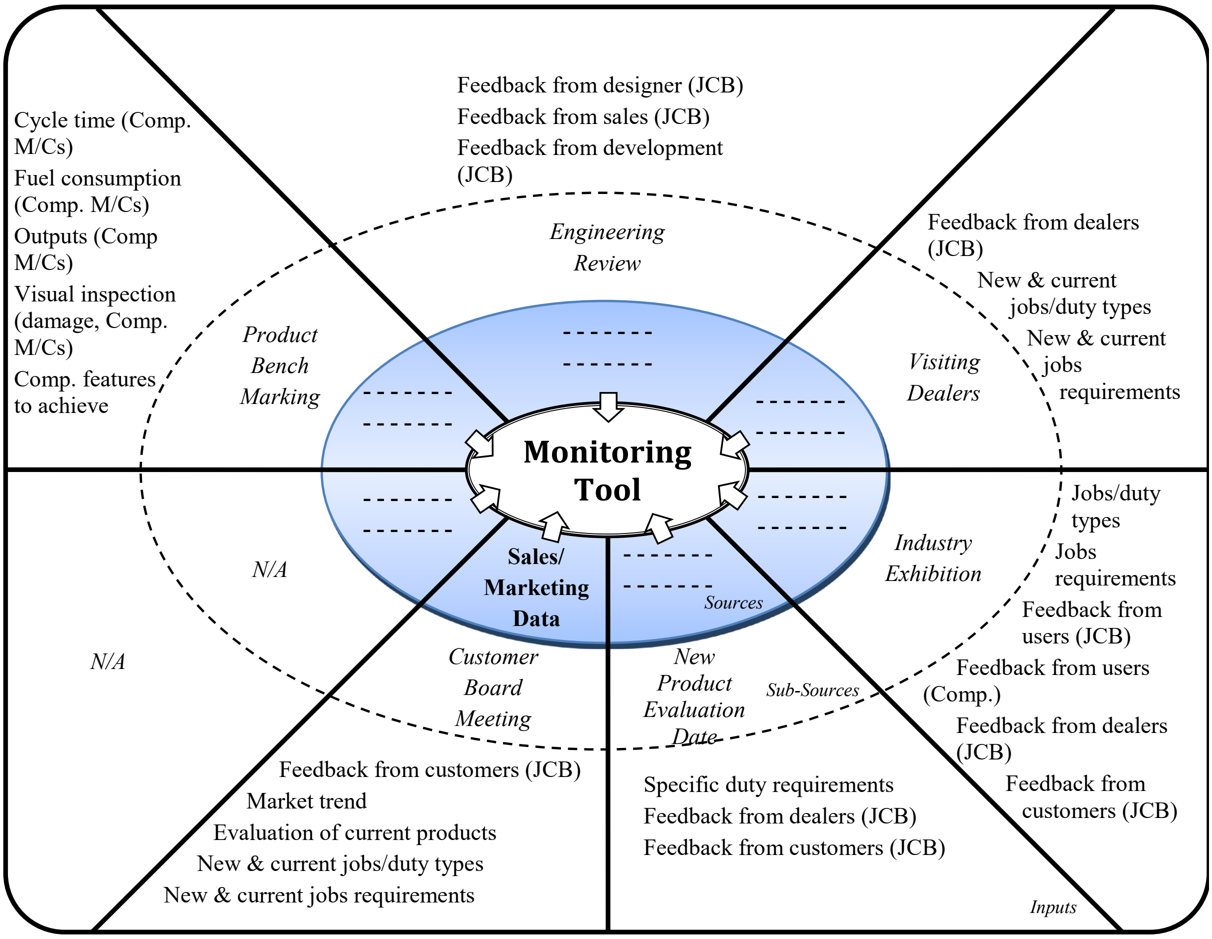
APPENDIX A PROJECT MAP 1



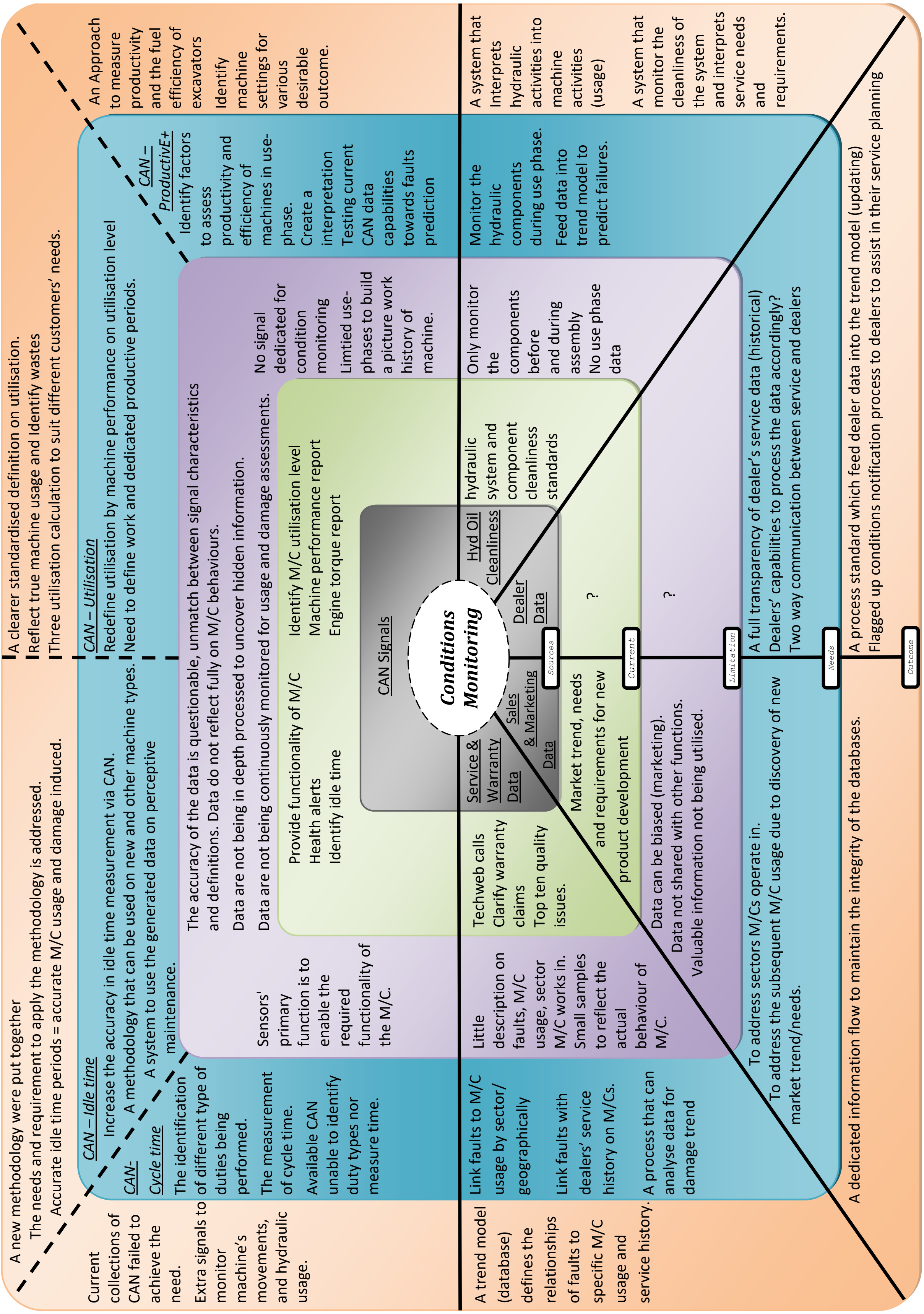
Abbreviations:

CAN	Controller Area Network
PPS	Pilot Pressure Switch (On/Off only)
RPM	Revolution Per Minute
(C)CW	(Counter) Clockwise
AMP	Ampere (Electrical current unit)
Sources:	
CAN – Hydraulic	All hydraulic sensors signals visible on CAN
CAN – Engine	All Engine sensors signals visible on CAN
CAN – Controls	All driver control and switches signals in the Cab visible on CAN
Warranty Data	Information regarding to any claims on warranty due to machine faults
Service Data	Information regarding to the machines' maintenance record
Sales/Marketing Data	Information on customers' feedbacks and machines' usage
Inputs:	
CAN data	Can be found in CANbus, a structure within CAN for devices to communicate to each other
Slew , Travel and boom up PPS	On when slewing, and off when station
Travel PPS	On when tracking, and off when station
Boom up PPS	On when boom is raising
Auto PPS	On when dipper arms and bucket are being operated
Upper PPS	On when any services are being operated. (Ex. Tracking)
Feedbacks from users(***)	Comments from the people who used the machine (JCB users /competitors' users)
Outputs	The amount of material moved during an operation

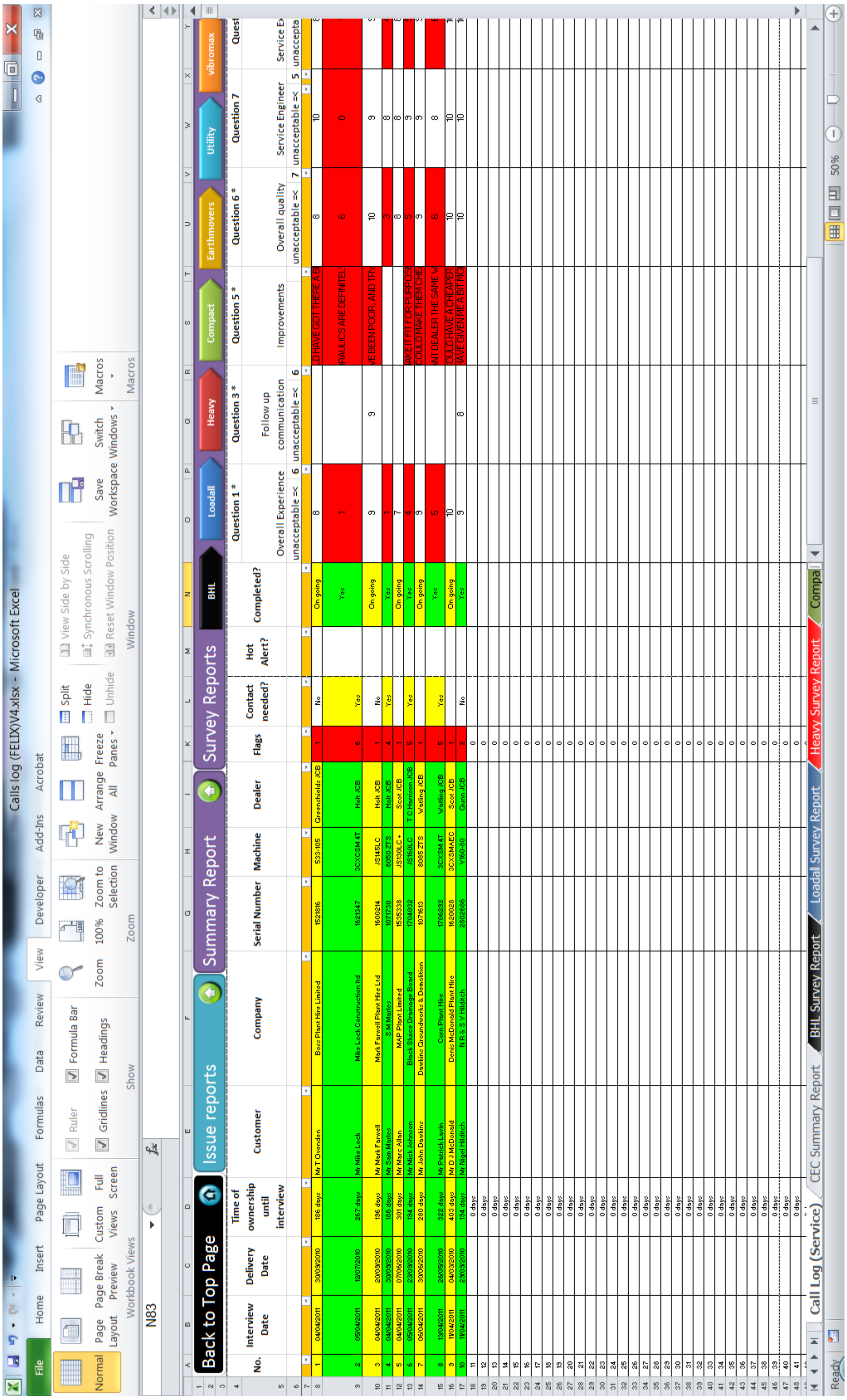


Abbreviations:	
CP.	Competitors
M/C	Machine
Sources:	
Engineering Review	Weekly meeting of engineering managers from all divisions
Visiting Dealers	JCB dealers visits to particular divisions to discuss products
Industry Exhibition	OEMs exhibit their latest machineries to the market
New Products Evaluation	Specific JCB dealers and customers are invited to evaluate new prototypes/ideas
Customer Board Meeting	A committee form by JCB , customers and dealers to share experiences and information
Product Bench Marking	Hired in CP. M/Cs to conduct testing and bench mark JCB's.
Inputs:	
Feedback from designer	Comments on the products from a designer's point of view. e.g. the parameters of the components are designed to perform at.
Feedback from dev.	The area of the machine that has been focused to improve on. That will required monitoring
Feedback from sales	The pro and cons of the machine in use phase
Feedback from dealers	Pro and cons of M/C, an assessment of M/C fitting to the market needs from a dealers perspective.
Feedback from customers	Pro and cons of M/C, an assessment of M/C fitting to the specific sectors' needs from a customers' perspective.
Feedback from users	Pro and cons of M/Cs, e.g. M/C's ability to specific job/duty's needs from a users' perspective.
Jobs/duties types	The types of work/approach conducted in various sectors
Specific duty requirement	The particular operations' requirement within the sector to carry out the operation.
Jobs/duties requirements	The features/attachment required for the M/C to carry out the operations
Output	The amount of material moved during an operation
Cycle time	The time to take to perform a single duty within a operation, e.g. to conduct one pass in trenching

APPENDIX B PROJECT MAP 2



APPENDIX C CUSTOMER FEEDBACKS INFORMATION MANAGEMENT TOOL



APPENDIX D INSTRUCTION MANUAL "CUSTOMER FEEDBACKS WITH DIVISIONAL BUSINESS REPORTS" AND "ISSUE REPORTS

Instruction manual for excel workbook "Customer feedbacks with divisional business reports" and "Issue reports)

Last Edited by Felix Ng, (20/6/11) – JCB Research

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If you have any comments or enquiries on the manual please contact me.

Table of Contents

Introduction

This document contains instructions to show how the workbook, "Customer feedbacks with divisional business reports", can be used to clearly present feedback data capture by Aura via questionnaires.

The first spreadsheet of the workbook contains portals which link to all spreadsheets within the workbook.

The second and third spreadsheets are the call logs for both sales and services type of feedback.

The fourth spreadsheet consists of two summary reports for both calls types.

Fifth to thirteenth spreadsheets are divisional business reports

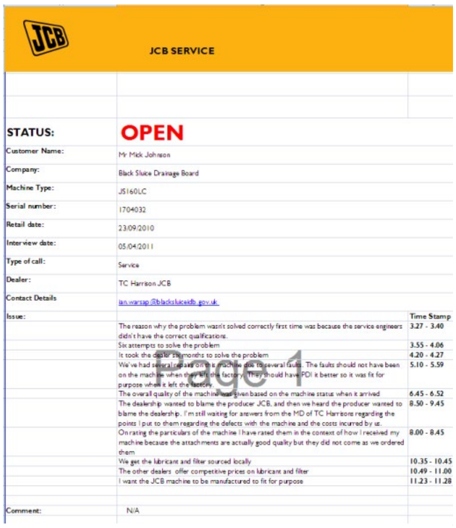
The last spreadsheet is the database of the entire workbook, hence should not be altered unless critical update is required.

This document also consist of procedures how information should be captured and represented in issue reports.

2. General Instruction/procedures

Calls should be logged into the call logs at once when they are uploaded by Aura to www.jcbcustomerexperience.com . These calls should then be prioritised to listen according to the number of flagged items shown in column J for each call. Instructions for how the logs are to be filled in properly can be found by clicking this link or alternatively, go to page 3. Calls that are prioritised should have their status changed to "ongoing" in column M, and "Yes" upon completion.

An issue report is record of customers' reason of dissatisfaction and suggestions towards JCB products based on their experiences with our products. Issue reports for each month will be loaded when the issue report button on the top left corner of the call logs spreadsheet is pressed. Issue report is required to be produced when users felt the customer have raised very negative feedback towards their experience with JCB. Click on this Link to move to the guide in filling the issue report or alternatively, go the page 7.



JCB SERVICE

STATUS:	OPEN	
Customer Name:	Mr Mick Johnson	
Company:	Black Sluice Drainage Board	
Machine Type:	JS160LC	
Serial number:	1704032	
Retail date:	23/09/2010	
Interview date:	05/04/2011	
Type of call:	Service	
Dealer:	TC Harrison JCB	
Contact Details	ian.warsap@blacksluiceidb.gov.uk	
Issue:		Time Stamp
	The reason why the problem wasn't solved correctly first time was because the service engineers didn't have the correct qualifications.	3.27 - 3.40
	Six attempts to solve the problem	3.55 - 4.06
	It took the dealer six months to solve the problem	4.20 - 4.27
	We've had several repairs on this machine due to several faults. The faults should not have been on the machine when they left the factory. They should have PDI it better so it was fit for purpose when it left the factory.	5.10 - 5.59
	The overall quality of the machine was given based on the machine status when it arrived	6.45 - 6.52
	The dealership wanted to blame the producer JCB, and then we heard the producer wanted to blame the dealership. I'm still waiting for answers from the MD of TC Harrisons regarding the points I put to them regarding the defects with the machine and the costs incurred by us.	8.50 - 9.45
	On rating the particulars of the machine I have rated them in the context of how I received my machine because the attachments are actually good quality but they did not come as we ordered them	8.00 - 8.45
	We get the lubricant and filter sourced locally	10.35 - 10.45
	The other dealers offer competitive prices on lubricant and filter	10.49 - 11.00
	I want the JCB machine to be manufactured to fit for purpose	11.23 - 11.28
Comment:	N/A	

Figure 1 - issue report

Survey Report is a report to be produced for each business unit for each month. Click on this Link to move to the guide in filling the issue report or alternatively, go the page 9.

3. Top page

Figure 2 - smart chart graphic

The first page when user open the excel file "customer feedbacks log with divisional business reports" should be the top page. It is all pages would be locked, but it still allows user to input information. It is critical for user to enable macro every time when the page is opened. This can be done by responding the security warning shown between the tool bars and the excel sheet. (Security Warning Macros have been disabled [Options...]). Click on options and check the "Enable this content" box, and click OK to finish. The top page contains a smart chart graphic (Figure 2), which contains of all the spreadsheet within the workbook (excluding the top-page, datasheet). Each circle are hyperlinked to the respective spreadsheet, you can simply click once on the reports you desire, it will take you to the report or log you want to work on. The circle in the centre named "issue reports" is linked to the templates for issue reports.

4. Call log (Sales + Service)

The table in both call log spreadsheets display information in a table format to show the satisfaction level of the customers. All these information can be manually feed through the JCB portal (www.jcbcustomerexperience.com). Figure 3 is an example of the feedback we received from XXXXX weekly. The tables below show what information to feed in to the spreadsheet from the table.

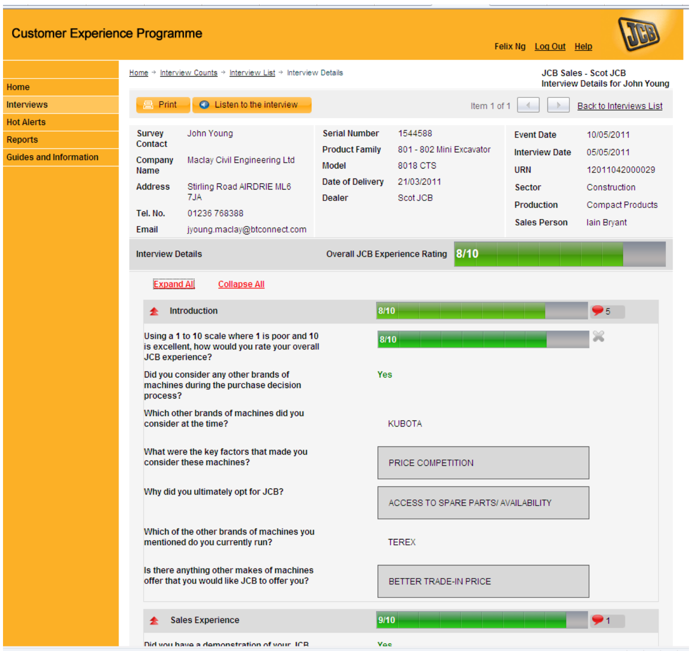


Figure 1 - Customers' feedback questionnaire

Call log (Sales)	JCB portal	Description
Column A	N/A	Show the number of entered items
Column B	Interview Date	Date of interview
Column C	Date of Delivery	Date of machine/service delivered
Column D	N/A	Automatic calculation of the number of days between interview date and delivery date (ideally= 6months)
Column E	Survey Contact	Customer’s name (the row will be highlighted in pale red to indicate a fresh entry, until a new status has been identify from column M, it will remain highlighted.
Column F	Company Name	Company name
Column G	Serial Number	Serial number of the machine
Column H	Model	Machine model code (Drop down menu for selection)
Column I	Dealer	JCB sold the machine to the customer (Drop down menu for selection)
Column J	N/A	Automatically filled in via entry from column N to column AC (counting the number of unacceptable scores)
Column K	(recorded clip)	Listen to the recorded clip and trace for any call back requirement address by the customers. (Drop down menu for selection)
Column L	Exclamation mark	Select from the drop down menu; Yes or No
Column M	N/A	Select from the drop down menu; Yes (Green), complete call. Ongoing (Yellow), unfinished by started.
Column N-O	Overall JCB experience	Select from the drop down menu; 1 -10 (acceptable

Column P-Q	Would you recommend the Sales Person you spoke to?	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell Q6, cell will be highlighted in red if an unacceptable score is entered.
Column R-S	How would you rate the follow up communication	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell S6, cell will be highlighted in red if an unacceptable score is entered. If no follow up communication were performed, leave blank
Column T-U	(recorded clip)	Pick up any resolution offer by the dealer (cell will be highlighted in red, when entry is made)
Column V-W	(recorded clip)	Pick up any improvement suggests by the customers (cell will be highlighted in red, when entry is made)
Column X-Y	Please rate the overall quality of your machine	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell Y6, cell will be highlighted in red if an unacceptable score is entered.
Column Z-AA	Has your JCB Machine lived up to your expectations?	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell AA6, cell will be highlighted in red if an unacceptable score is entered.
Column AB-AC	How likely are you to repurchase from JCB based on your recent sales experience?	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell AC6, cell will be highlighted in red if an unacceptable score is entered.
Column AD	(recorded clip)	Any commend picked up from the clip that has business values.

Table 1 - Call log (Sales)

Call log (Service)	**JCB portal**	**Description**
Column A	N/A	Show the number of entered items
Column B	Interview Date	Date of interview
Column C	Date of Delivery	Date of machine/service delivered
Column D	N/A	Automatic calculation of the number of days between interview date and delivery date (ideally= 6months)
Column E	Survey Contact	Customer’s name (the row will be highlighted in pale red to indicate a fresh entry, until a new status has been identify from column M, it will remain highlighted.
Column F	Company Name	Company name
Column G	Serial Number	Serial number of the machine
Column H	Model	Machine model code (Drop down menu for selection)
Column I	Dealer	JCB sold the machine to the customer (Drop down menu for selection)
Column J	N/A	Automatically filled in via entry from column N to column AC (counting the number of unacceptable scores)
Column K	(recorded clip)	Listen to the recorded clip and trace for any call back requirement address by the customers. (Drop down menu for selection)
Column L	Exclamation mark	Select from the drop down menu; Yes or No

Column M	N/A	Select from the drop down menu; Yes (Green), complete call. Ongoing (Yellow), unfinished by started.
Column N-O	Overall JCB experience rating	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell O6, cell will be heighted in red if an unacceptable score is entered.
Column P-Q	How would you rate the follow up communication	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell Q6, cell will be highlighted in red if an unacceptable score is entered. If no follow up communication were performed, leave blank
Column R-S	(recorded clip)	Pick up any improvement suggests by the customers (cell will be highlighted in red, when entry is made)
Column T-U	Please rate the overall quality of your machine	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell U6, cell will be highlighted in red if an unacceptable score is entered.
Column V-W	Would you recommend the engineer who serviced your machine?	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell W6, cell will be highlighted in red if an unacceptable score is entered.
Column X-Y	How would you rate your overall service experience?	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell Y6, cell will be highlighted in red if an unacceptable score is entered.
Column Z-AA	How likely are you to repurchase from JCB based on your recent sales experience?	Select from the drop down menu; 1 -10 (acceptable level is changeable in cell AA6, cell will be highlighted in red if an unacceptable score is entered.
Column AB	(recorded clip)	Any commend picked up from the clip that has business values.

Table 1- Call Log (Service)

Items to beware of:

There are also a number of hyperlinks on top of the pages to enable user to navigate through business reports and issue reports inside and outside the workbook.

There are data between BB8 to BI1007, They are not to be deleted at any circumstances.

Acceptable level can be changed according to the circumstance; once the acceptable level has been altered, all other features within the workbook that link to the acceptable level would be changed accordingly automatically.

In some scenario due to some condition has not been met during the interview in the questionnaire, some questions may not turned up as a result. If this is the case, leave the cell blank. (Don’t not enter zero into the cell)

5. CEC Summary Report

All the information from this report is directly feed through both call logs (Figure 4)

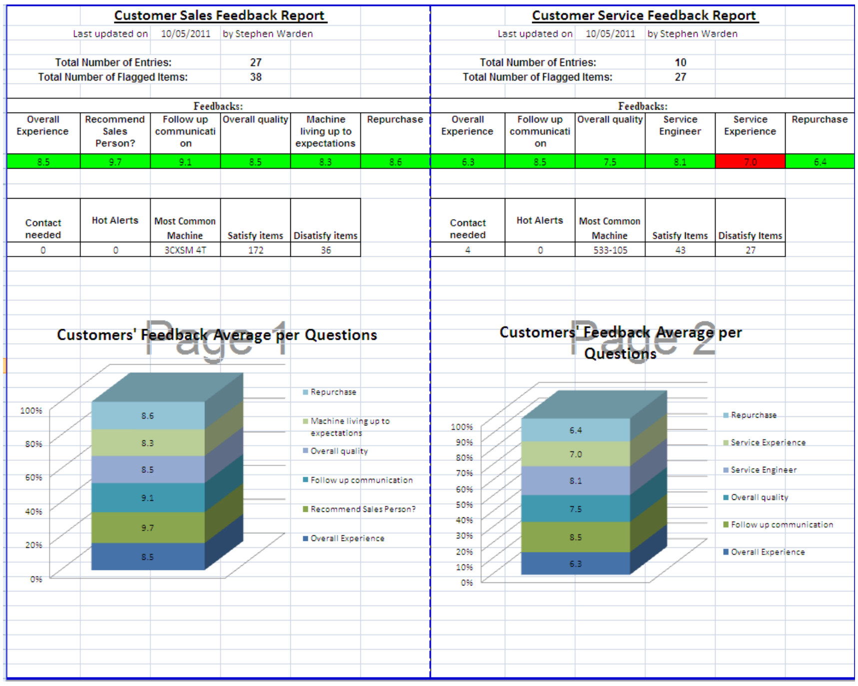


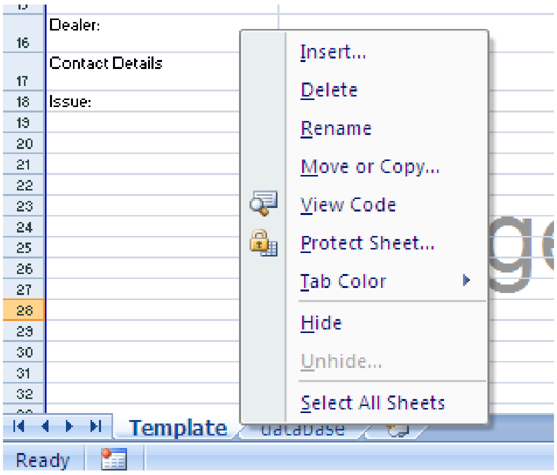
Figure 1 - Summary Report

The summary report present data that is entered into the both call logs, sales and service. The spreadsheet consists of both reports for sales and services. These reports have already split into two pages, hence two separate reports will be printed out automatically during print. The line below the report tile shows, the date the report was printed and the person who printed it. The date change automatically daily, but the name has to be altered manually.

The report shows several information captures from the calls:

no	Items	Description
1	Total Number of Entries	The total number of entries of the particular call type
2	Total Number of Flagged Items	The total number of flagged items of the particular call type
3	Overall Experience	The average score of over experience
4	Recommend Sale Person	The average score of recommend sale person
5	Follow up communication	The average score of follow up communication
6	Overall Quality	The average score of overall quality
7	Machine living up to expectations	The average score of machine living up to expectations
8	Repurchase	The average score of repurchase
9	Contact needed	The total number of customers requested to be contacted
10	Hot Alerts	The total number of customers raise hot alerts
11	Most Common Machine	The Most common machine on the list
12	Satisfy items	The number of feedbacks that are satisfied by customers
13	Dissatisfy items	The number of feedbacks that are dissatisfied by customers
14	Graph (3D-stacked column)	A graphical representation of customers feedbacks

6. Issue reports



Issue report file for the month can be opened by clicking the issue reports button on top of the page within the workbook. Issue report only needed whenever a customer has produced any unsatisfied comment and require to be followed up.

Once the issue report file is opened, right click the tab named “Template” and select “Move or Copy”. A window will pop up, click to box “Create a copy” and click “ok”. Rename the newly created workbook to the customer’s company name. All data from the fields “Customer Name” to “Contact Details” should have already been captured from listening to the recorded interview previously and is available in both call logs.

The data for fields: issue, comments can be captured from the recorded interview, please remember to put the time stamp of the comments for each entry.

The status field should be changed according to the condition of the call, there is a drop down menu at cell B8, which user can select (**OPEN**), (**CLOSED**), (**NONE**), they should be selected if:

Status	Description
OPEN	Call is open for action
CLOSED	Call was opened and appropriate action has been applied.
NONE	Call does not require any attention

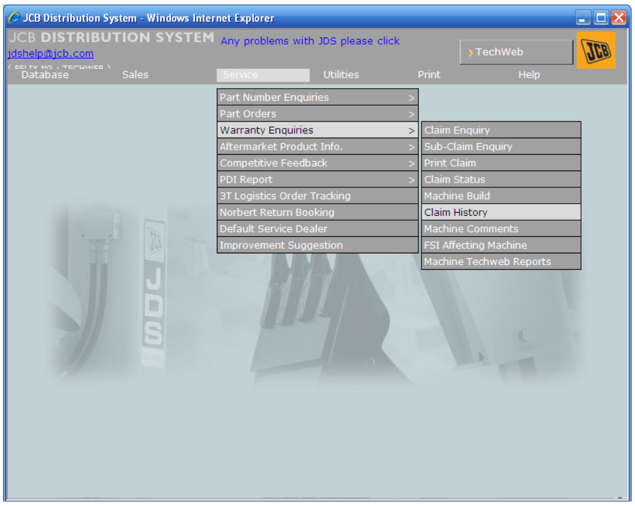
Once all the fields have been filled in, the worksheet should be printed off for further action or archive. Once it is saved, the sheet should be save as PDF, and save into the issue report (PDF) folder of the current month. Please save the PDF into the correct sales or service folders. There are three folders called (Awaiting for action), (Open), (Closed) and (None), PDF should be saved into these folders according to the status of the report:

Status	Description
Awaiting for action	Any calls that required to be clarified by Amy or Stephen
OPENED	Any Open calls
CLOSED	Any Closed calls
NONE	Any Calls do not require any attention

8. Techweb calls

Techweb calls for that particular customer can be found at JDs website (https://business.jcb.com). Once logged on, click on JDS on the left. When the window appears, click: Tech web -> Bulletin Board -> Search. Enter the serial number of the machine and click search, copy down any history that the database may contain. Drop down the techweb call no and its description.

7. Warranty Claims



Warranty Claims can be found in JDS website (https://business.jcb.com). Once logged on, click on JDS on the left. When the window appears, click: Business system, and move the cruiser without clicking to: service -> Warranty enquiry -> Claim history, Click on "Claim History" to select. Enter the machine serial to search for its claim history. Copy the claim no. and description if any.

7.1. Field Service Visit Reports

This field requires user to locate any field service visit report on the particular machine serial number. Field service visit reports can be found in: U:/shared on 'wlpfp02' -> WLP-WP -> Service -> Customer Experience Centre -> Customer Experience Survey -> Field Service Friday Reports -> Friday reports 2011 -> Friday Report 2011.xls, Search for any visit report with serial no and customer's name.

7.2. Action taken

Any action taken for the particular issue report should be recorded here.

9. Survey Reports

There are eight different survey reports within the workbook. Each survey report presents information for specific division. Users can click on the buttons on the top right for the required report. The table below explain the short forms for each division.

Short form	Description
BHL	Backhoe Loader Division
Loadall	Loadall Division
Heavy	Heavy Products Division
Compact	Compact Product Division
Earthmovers	Earthmovers Division
Utility	Cecilly Mills Division
Vibromax	Vibromax Division (Germany)
Landpower	Landpower Division

There are three fields that required users to manually input information in a survey report. They are other brands considered, positive feedback and specific customer issues. The data for these fields should have already been captured from listening to the recorded interview and is available in both call logs and issue report. Hence filling these fields in is only simple copy and paste operation. (NOT LISTEN TO THE CALL AGAIN!)

Other fields such as calls, models, dissatisfactory and dealers are automatically filled in when users populate the call log pages. It should not be altered at any circumstances.

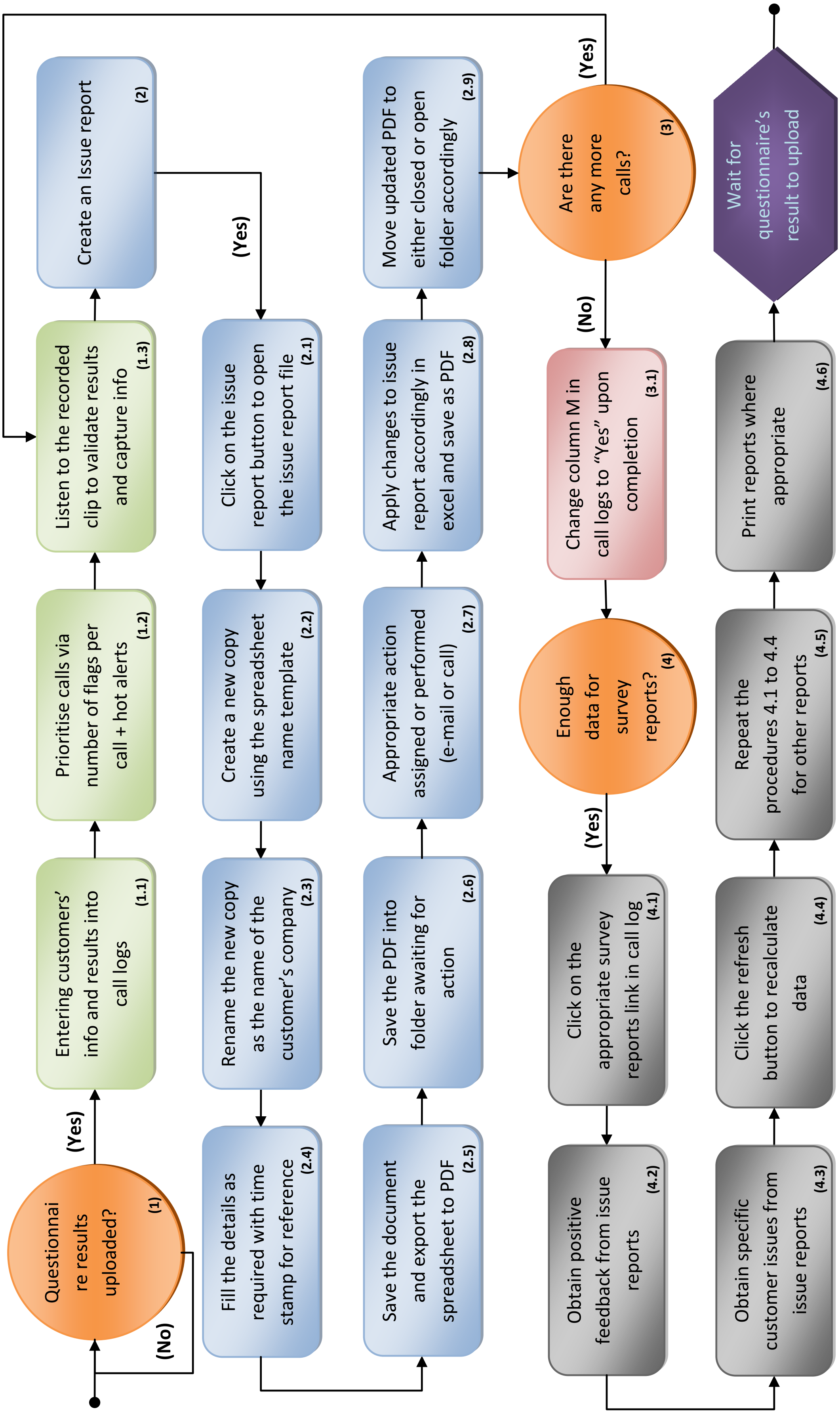
New rows can be added into positive feedback and specific customer issue, if the existing space is not enough

At the end of each month, when a report is required to produce for each division, please right click the worksheet tab at the bottom and click on “unprotect sheet”. This will allow you to refresh the pivot table and generate all necessary data.

To finish the report for printing, click the refresh button in the red Refresh box just outside the print area of the top right hand corner to regenerate the data within the auto fill fields.

The report has already been set to print 2 pages report when press print. However, do use preview to check whether the report is presentable before consider printing.

10. Flow chart for capturing customers’ feedback



11. Folder management for (Monthly issue Log)

All the folders can be found at U:\WLP-WP\Service\Customer Experience Centre\Customer Experience Survey\Monthly issue log

At the beginning of each month the folder named “Template” within the folder should be duplicated and rename according to the month the folder is created. e.g. “201104”. Meaning April 2011, the reason for this formatting is to allow window to automatically arrange them into ascending order. By January 2012, the folder should look something like in Figure 5. The template folder contain two separate folders, “Call Logs + reports (Template)” and “Issue report (PDF)”. At no circumstance these folders should not be moved or renamed as it will destroy the hyperlink within the workbook. Instruction manual can also be found.

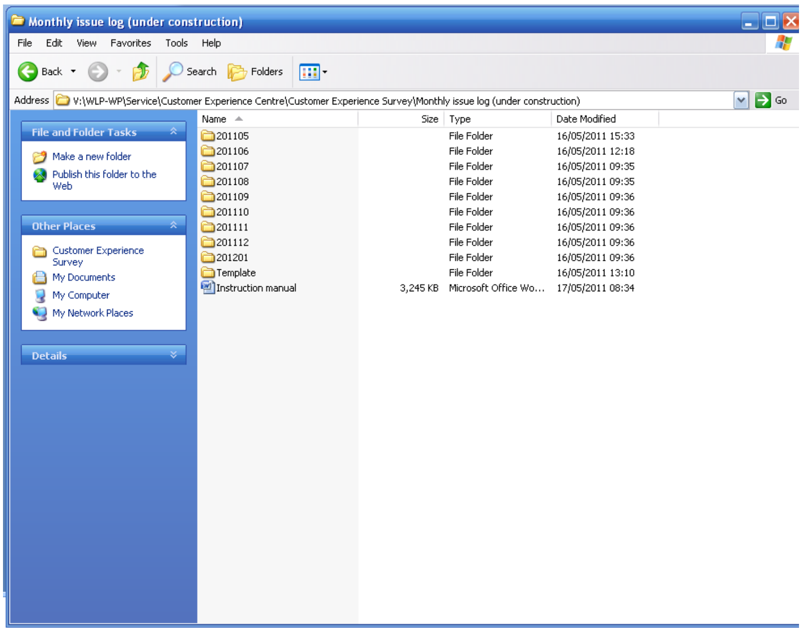


Figure 1 - Folder management

12. Updating database

It is almost certain that to close to the near further, the list of machine's models will need to be updated as new products are introduced into the market or livelink is covering a larger range of machines e.g. 4DX in India. The following instructions are for updating different aspects within the document.

12.1. Machine list (database)

A complete list of all JCB machines model numbers and the division where it belongs to can be found in columns G2 to H in the database spreadsheet. The list is arranged in ascending order according to the name of the divisions. The order appearing in the spreadsheet will be exactly the same as in the drop down menu in column H of both call logs.

The procedures to add new machine model number:

1.) Unprotect the sheet by right click the "database" spreadsheet tab on the bottom.
2.) Highlight cells G4 to H4.
3.) Right click -> insert ->shift cells down->OK.
4.) Enter the new machine model number and its division.
5.) Click the filter button in cell H1 with the name "division".
6.) Click Sort A to Z.
7.) Protect the sheet with password
8.) Save the document

At this stage you should have successfully added the new model number. The next step is to make sure the survey business reports will incorporate the newly added machine model.

1.) Got to the relevant business report of which the new added machine model belongs to.
2.) Go to the table between column AB and AE.
3.) Unprotect the sheet
4.) Extend the table to include all machine model of the particular division. e.g.
    - Compact products has machine numbers from G41 – G86
    - Go to table between column AB and AE in Compact Survey Report.
    - Ensure the first two bordered cell of the machine column (AB8) have the formulas "=Database!$G41" and "=Database!$G42" respectively . (Please be aware that is only an example, the exact number may vary in the actual document).
    - Highlight the first two cells and move your mouse to the bottom right of the second cell, hold until a black cross appears.
    - Hold and drag until the last cell of the column contains the formula "=Database!$G86"
5.) Highlight the first two cells of column AC, AD and AE.
6.) Use the same method in (4), extend these columns to the end of the table. (Use the machine column (AB) as an indicator, where the end of the table should be.)
7.) Show the sum of all Sales and Service at the end of the table of each column by entering the following formulas:
    - Sales -> "=SUM(AC8:AC53)"
    - Service -> "=SUM(AD8:AD53)"
8.) Click anywhere on the pivot table on the right.

Select the options in the Microsoft excel under pivot table option. (Different version of Microsoft excel may be different)

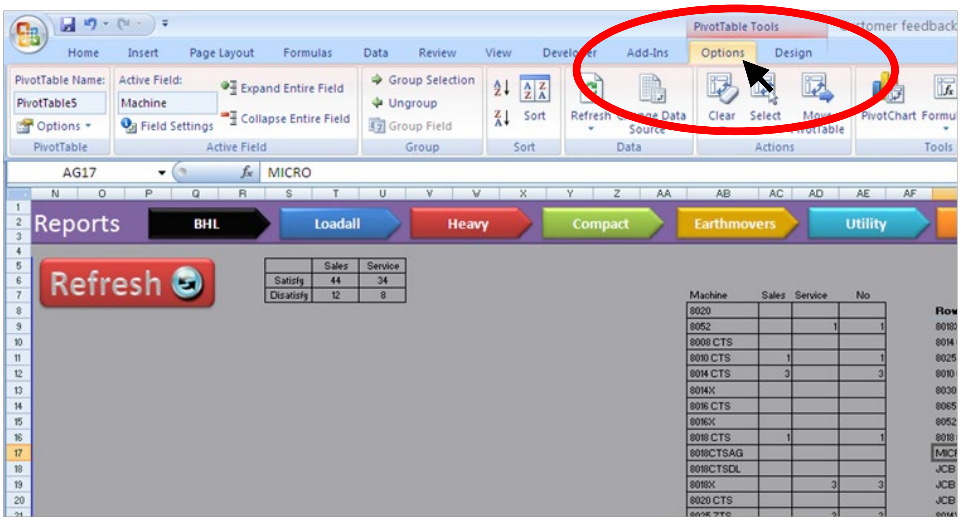


Figure 1 - Microsoft Excel 2007

1.) Click on “Change Data Source”.
2.) The “Change PivotTable Data Source” window should pops up. And bordering the current selected data source for the pivot table.
3.) Reselect the table to ensure new rows of the table are selected. (Make sure the row that contains Machines, Sales, Service, No is selected also).
4.) Click ok to finish.

At this stage the survey report is fully award of the newly added machine number, the next step is to have the report include of the change.

1.) Cell C12 and D 12 should be the cells showing the number of machines mentioned in Sales and Service respectively. Hence contain the formulas:
    - Sales -> “=AC54” -> formulas should link directly to the sum of sales from the bottom of the table.
    - Service -> “=AD54” -> formulas should link directly to the sum of service from the bottom of the table.

The fourth table of the survey report, which shows the machine models and the number of times they were mentioned in the calls. Extend the table to include the new model numbers

1.) Highlight the last cell which contains “-” and the empty cell on its right. The cells should contain something like: (The numbers are very likely to be different)
    - The cell that contains -> “-” -> “=IF($J33=0,"-",$AG54)”
    - The cell that is empty -> “ =GETPIVOTDATA("No",AG8,"Machine",$AG54)”
2.) Move the mouse to the bottom right of the highlighted cells until your mouse change to a black cross.
3.) Hold and drag the cells for a few cells down, stop when the cells begin to fill with “#REF!”
4.) Delete all the cells with “#REF!” in them.
5.) System updated. Protect the sheet again.

13. Changing appearances of the reports

It is highly not recommended to change the appearance of the report, the action may potentially alter the relationships of formulas and damage the functions of the entire system.

However, here are the few rules when altering the reports:

	Action	DO	DO NOT
1	Adding new row	Highlight cells that is equivalent to the width of the entire printout area, just above where the new row should be, right click and select insert. Select "shift cell down" and click ok. (you might need to unmerge some cells before adding new row)	Select the entire of the sheet and insert a new row, as this might break the links of formulas on the far right hand side of the spreadsheet
2	Adding new column	Highlight the equivalent column in size to the right of where you want the new column to be. Move your mouse the edge of the highlighted cells until a small back cross with arrows at the end appears at the tip of your mouse. Move the highlighted column away, put borders in to make a new bordered column, finally move the column back to the right of the newly bordered column.	Select the entire of the sheet and insert a new column, as this might break the links of formulas on the far right hand side of the spreadsheet. Highlight an equivalent column in size to the right, right click -> insert-> shift cells to the right. This may affect the formulas on the far right hand side of the spreadsheet.
3	Copy and paste cells	Only copy the content within the cell, and paste the content after selecting into cell.	Copy cells and paste to another cells directly
4	Deleting rows	Only if you wish to delete the entire row of the printout. Highlight the row you want to delete, right click -> delete -> shift cells up	Select the entire of the sheet and delete the entire row, as this might break the links of formulas on the far right hand side of the spreadsheet
5	Deleting columns	Delete the content of the column and move (if there is any) the column on its right hand side to fill the space. (DONOT COPY &PASTE)	Select the entire of the sheet and delete the entire column, as this might break the links of formulas on the far right hand side of the spreadsheet. Highlight an equivalent column in size to the right, right click -> delete-> shift cells to the left. This may affect the formulas on the far right hand side of the spreadsheet.

APPENDIX E COMPANY'S TEST & DEVELOPMENT REPORT (SCREENED)

RESEARCH **TEST & DEVELOPMENT REPORT**

JCB Research Ltd. Lakeside Works, Rocester, Staffs ST14 5JP, Great Britain Tel: +44 1889 590312 Fax: +44 1889 591289	Report No: Date of Completion: dd/mm/20XX
Machine Type: Hydraulic Excavators 22 tonnes	Date of Report: dd/mm/200X
Model: JS220LC	Page: 1 of X
Serial No: JCBJS22DH01460746	Engineering Instruction:
Engine Type: ISUZU Engine 4HK 128.4KW Drive/Steer Arrangement: XWD/XWS	AP1355
Transmission Type: Project Reference: Data Acquisition	Test/Development Procedure No:
DVPSOR No:	

Component: JS220LC – 15000 mm Bucket 1.18 CuM, DLA, CANSniff, CANoe

Object: To discover and interpret the hidden message in CANbus to describe machine movements. To identify the full capabilities of CANbus towards machine condition monitoring.

Conclusion:

All the signals being broadcasted on CANbus only give a very limited picture on the behaviours of the machines, although a clearer picture, such as movement of the machine, can be generated through additional processing procedures on existed CANbus messages, yet the information is still not substantial enough for the purpose of condition monitoring.

However, extra information such as number of cycles, swing angle during a duty can be estimated to give a value on the machines' duty level throughout its life.

Recommendations:

There is a capability for CANbus messages to be analysed, to assess the conditions of the machine. However, additional signal will be required to be broadcasted, hydraulic based signals are recommended to first consider.

Keywords:

Responsible Manager: Jon Lyle	Circulation: Dev Mgrs			
Prepared by: Felix Ng				
Authorised by: Jon Lyle				

RESEARCH TEST & DEVELOPMENT REPORT

Test Report Continuation Sheet

Introduction

This exercise is conducted to explore the opportunity in only using CANbus messages to gain the understanding and interrupt machine movements. A major data collection on CANbus messages was conducted within other experiments. These experiments were conducted to determine the relationship of fuel consumption, cycle time, RPM (report no: XXX), (report no: XXX). This exercise is part of the data acquisition project on product feedback data processing and management system.

Parts Involved

GP bucket 1500mm, 1.18cm^3 (981/00431)
DLA
CANSNIFF
CANoe

Test Procedures

A JCB diagnostic link adaptor was used to connect the laptop to the CANBUS network of the machine. In-house software was used to capture all CANBUS messages during the experiment. Data such as cycle time, fuel consumption that are collected during the experiment, would also be used in helping to interrupt the capture data. CANoe will be used for interrupt and process the collected CANBUS messages. CANoe is a program written by vector, a company who provides tools, software components and engineering services for the networking of electronic

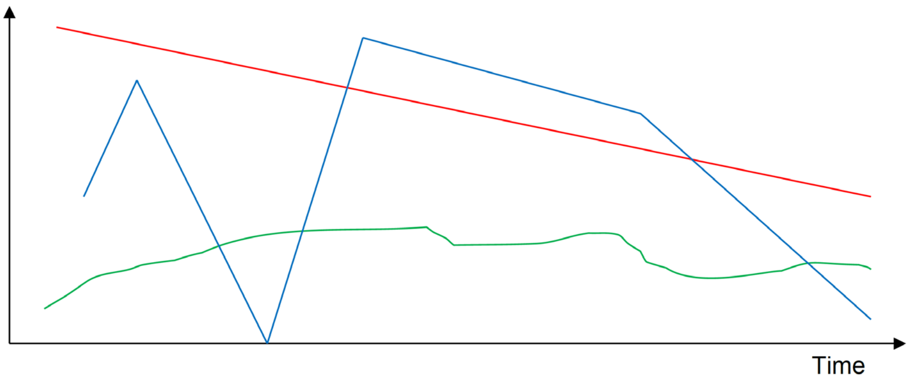


Figure 1 - Example

systems in the automobile and related industries.

RESEARCH TEST & DEVELOPMENT REPORT

Test Report Continuation Sheet

CANbus messages are categorised in different Parameter Group Number (PGNs), each PGN may contain a number of messages depends on the size of them. In order to achieve the goal, these messages are displayed on the same graph with the same x-axis as the time scale. Due to the nature of the messages, the y-axis may consist of various units depending on the selection of the messages.

After studying the hydraulic schematics, few messages are decided to be used for processing data, the table below shows the messages and description used.

CAN Signals	PGNs	Description
Engine Speed	0xF004	The speed of the engine in the unit of RPM. (Resolution: 100ms)
Actual Engine – Percent Torque	0xF004	The torque of the engine experiencing in %. The percentage is calculated by Isuzu, and the equation is unknown. (Resolution: 100ms)
Engine Fuel Rate	0xFEF2	The fuel use rate at the particular point. The equation use to calculate the rate is unknown, and had proven to be incorrect.
Upper Pilot Pressure Switch	0xFF02	Switch only turns on when any services, dipper, boom rams, slew motor and any options, are being activated. Excluding tracking.
Auto Pilot Pressure Switch	0xFF02	Switch only turns on when it is arm ram is in used, (requires validating)
Travel Pilot Pressure Switch	0xFF02	Switch only turns on when the machine is tracking.
Boom Up Pilot Pressure Switch	0xFF02	Switch only turns on when the boom ram is pushing the boom up.
Slew Pilot Pressure Switch	0xFF02	Switch only turns on whenever the machine is slewing in any directions.
Boost Pilot Pressure Switch	0xFF02	Switch only turns on when the pressure from services reaches certain pressure.
Boom Priority	0xFFB1	Solenoid at 8 valve station, activate to offer more flow to boom
Slew Brake	0xFFB1	Solenoid at 8 valve station, activate to offer apply slew brake
Slew Lock	0xFFB1	Solenoid at 8 valve station, activate to lock slew
Max Flow	0xFFB2	Solenoid at 8 valve station, restrict pump flow in different modes
Servo Isolator	0xFFB2	Solenoid at 8 valve station, lever lock to restrict machine operations
2 Stage Relief	0xFFB2	Solenoid at 8 valve station, Power boost to divert flow

Table 1 - CAN Signals

RESEARCH **TEST & DEVELOPMENT REPORT**

Test Report Continuation Sheet

Discussion

Three signals were used in the first attempt to understand machine movements, they are slew pilot pressure switch (green lines), boom up pilot switch (red lines) and CAN % engine torque (orange lines). Both slew and boom up pilot pressure switches can only be in two statuses, on / off. When the slew switch is shown to be at on status, it is interrupted as the machine is performing a slewing motion, regardless the slewing speed, rotation direction and the angle. When the slew switch is off, it can only be interrupted as the machine is not performing any slewing motion at all. When the boom up pilot switch is on, both boom rams will be extending out pushing the boom structure out. When the boom switch is off, the rams will either no moving at all or going down. The CAN % engine torque is defined by ISUZU, who is the OEM of the engine. As mentioned in Table 1, it is unknown that the actual torque of the engine is experiencing. Therefore the percentage value can only be treated as a scale of increase, with no quantification on the actual torque. However, its behavioural pattern can still be useful in understanding the movements of the machine at any given time.

Before this report continues, a few definitions should be defined to allow logics to be created in a more straight forward manner.
Let slew pilot switch as "Slew", and its status 0 to be off, i.e. not slewing, and I to be on, i.e. it is slewing. Let boom up pilot pressure switch as "Boom_up", and its status 0 to be off, i.e. whenever the boom is not going up, but station or going down, and I to be on, i.e. the boom is raising up.

Condition a)
If Slew= 0 & Boom_up =0;
It can be interrupted as digging or station or loading dump truck
Condition b)
If Slew=0 & Boom_up =1;
It can be interrupted as digging or loading dump truck

Condition c)
If Slew= 1 & Boom_up=0;
It can be interrupted as slewing back to the dig area or loading dump truck

Condition d)
If Slew =1 & Boom_up=1
It can be interrupted as slewing to dump area/truck, loading dump truck

	Boom_up = 0	Boom_up = I
Slew = 0	Digging/ loading	Digging/Loading
Slew = I	Slew(bck)/Loading	Slew(to)/Loading

RESEARCH TEST & DEVELOPMENT REPORT

Test Report Continuation Sheet

Table 2 – Logic conditions by slew and boom up

Loading is current defined by Heavy Products as "Loading a dump truck, crusher, hopper etc - Within 360˚ rotation, up to full working height / reach. Any load within capacity". It is possible to monitor the slew time to predict basic information such as whether the machine has been slewing in 45°, 90°or 180° intervals. This shall be discussed later in the report. In this scenario the operation Loading is defined as the operation that transport the material in a prefilled bucket, slew to the dumping area/truck, dump and return with an empty bucket before the material is refilled into the bucket. If so, Loading can be potentially split into at least four stages.

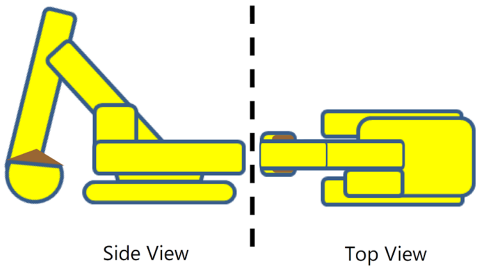


Figure 2 - Stage 1 (Loading)

The first stages would be a fully loaded bucket, ready to be slew to the dumping area/truck, if trenching was the mean of filling the bucket, the starting point of the first stage will the moment when the bucket tear out and detached completely from the tempered ground. (Figure 2)
The second stage is the transition period of a fully fill bucket moved to the point, where the operator decided the start dumping the load. It is often, especially for experience operator, that

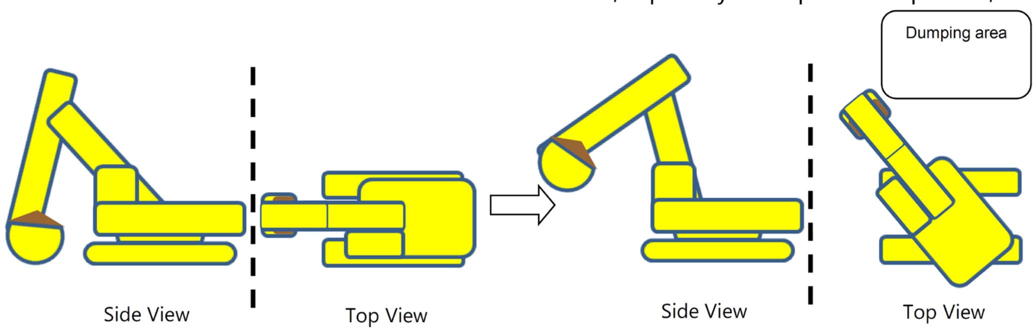


Figure 3 - Stage 2 (Loading)

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Test Report Continuation Sheet

the slewing and dumping operation can often to be continuous, which means it is not necessarily to see a significant change of slew switch status. (Figure 3)
The third stage is the bucket is unloading the material off the bucket by using mainly

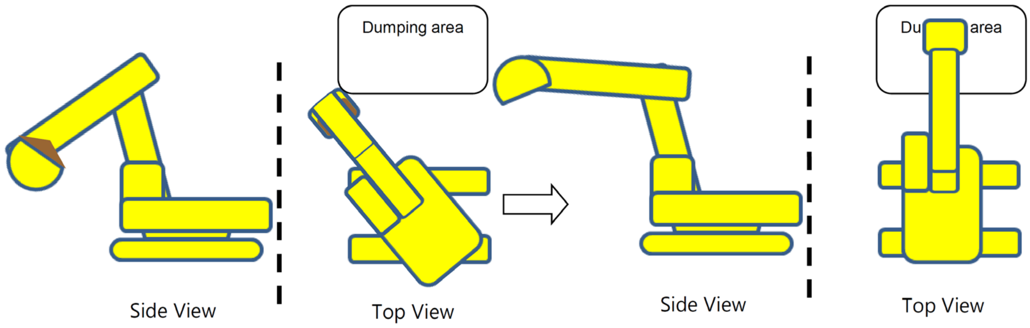

Figure 4 - Stage 3 (Loading)

gravitational pull, sometime operator may also shake the boom or the dipper to set free material track within the bucket, this stage ends when the bucket is fully unloaded. (Figure 4)
The final stage is the transition period for empty bucket to move back to the ground and collect material, this stage will terminate just before the bucket come in contact with the ground or has gone below the ground level. (Figure 5)

RESEARCH TEST & DEVELOPMENT REPORT

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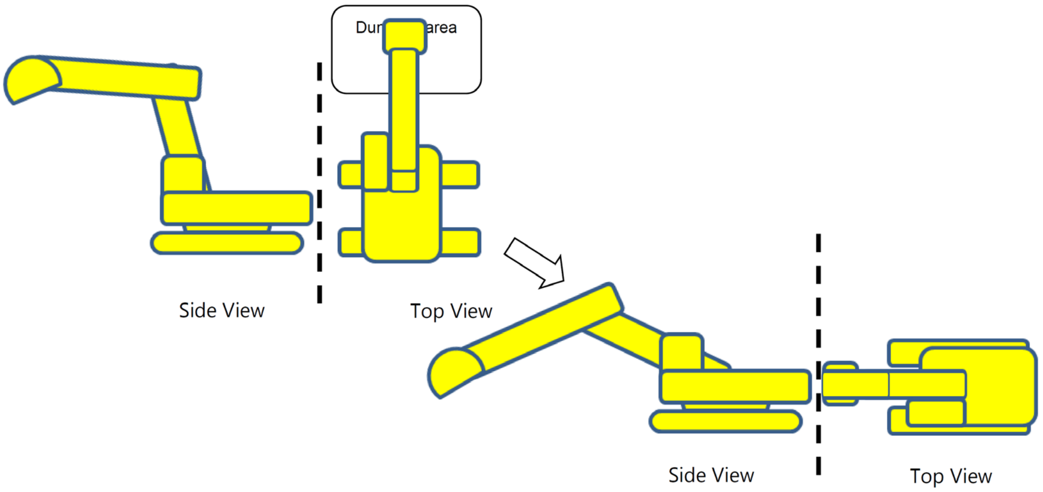

Figure 5 - Stage 4 (Loading)

The reason for such redefinition on loading is to allow the characteristics of the switches to be able easily recognised and interrupted. As a result, the 4 logic sates shown in Table 2 can be redefined further. The loading operation defined at Slew=0 & Boom_up=0 can be considered as stage3. At Slew=0 & Boom_up=1 can be considered as stage 1. At Slew=1 & Boom_up=0 can be considered as stage 4. And finally Slew=1 & Boom_up=1 can be considered as stages 2. Hence table 2 should be written as:

	Boom_up = 0	Boom_up = I
Slew = 0	Digging/ Stage 3 loading	Digging/ Stage 1 Loading
Slew = I	Slew/ Stage 4 Loading	Slew(to)/ Stage 2 Loading

Table 3 - Logic conditions by slew and boom up (refined)

There are number of situations when the boom is going up; a.) The boom lift off from the ground, and to clear any obstacles by swinging freely in order to dump to load. b.) The boom ram was used to increase the available forces required to tear in and out of the material. To distinguish these two scenarios, CAN engine % torque and slew switch status need to be available during the processing stage, to give the minimum picture. In the next section, the methodology in interrupting the signals into information on machines' movement shall be explained in detailed.

RESEARCH **TEST & DEVELOPMENT REPORT**

Test Report Continuation Sheet

Interpretation

Figure 17 represents a 10 cycles trenching operation set at 2050 RPM in A-mode in the appendix. The number of cycles can be counted as shown in Figure 6 below: The cycles defined below are

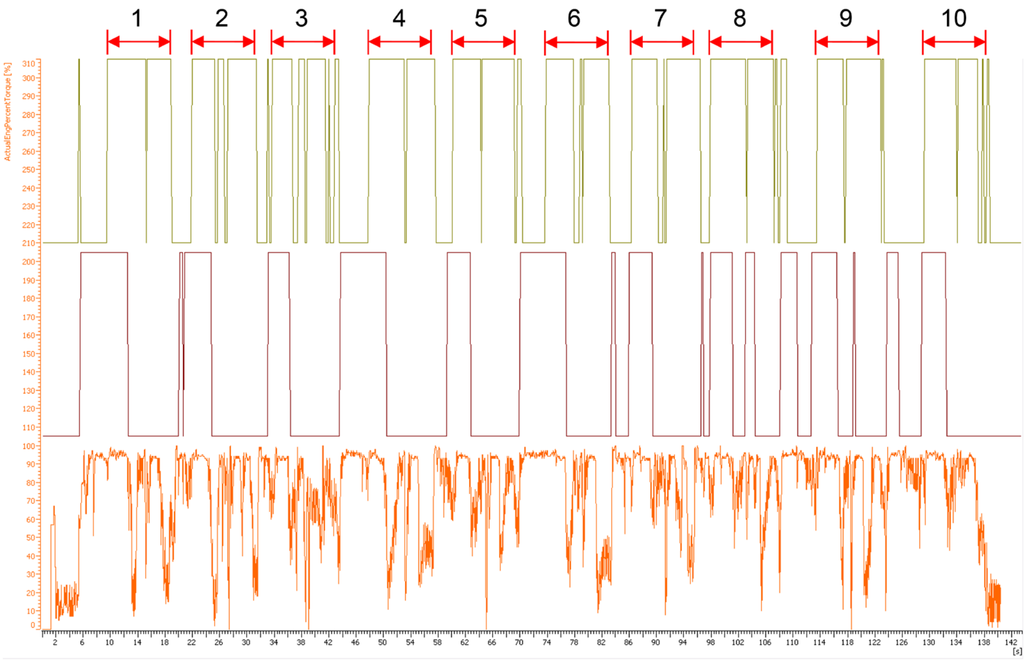

Figure 6 - 2050rpm (counting cycle no.)

Another redefinition of cycle time is required in order to be able to interpret the signal. Please note that the new interpretation is only for the purpose in processing CAN signals and shall not be adapted by divisions over the traditional way in defining the cycle time.

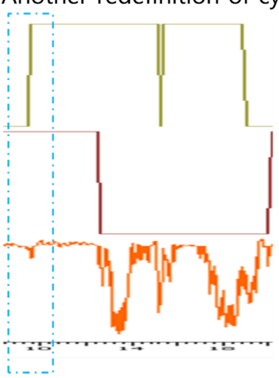

Figure 7 - Cycle 1a

Cycle 1 shall be used as an example how the signal shall be translated.

Digging can also be redefined into two meaning; a.)When boom_up = 0 and slew = 0, if CAN% torque is at its peak, this can interpreted as digging using either digger or bucket, and both at the same time. When boom_up = 1 and slew =0, this can be interpreted as boom is being used to pull the bucket, and very likely that the bucket would have started its crowd cycle. Dipper and bucket are likely to be

RESEARCH TEST & DEVELOPMENT REPORT

Test Report Continuation Sheet

involved in the early stage, but once the bucket has left the ground, which should be noticeable in the CAN % torque, the boom rams will be the only components to use to lift the structure up. The dipper would only be used when the boom is approaching the dumping area.

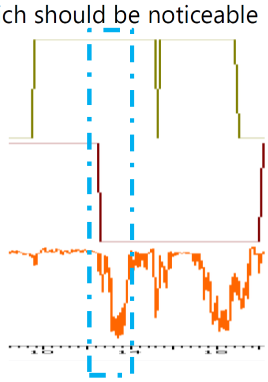

Figure 8 - Cycle 1b

Cycle 1 is split into 4 sessions and is each marked by the blue dotted box shown in Figure 7 - Figure 10. The first session which shown in Figure 7, based on the status of the switches, it is can be considered as digging using the boom and possibility along with the dipper and bucket. When the slew is on, it is in stage 2 loading, which meant the bucket just left contact with the ground. The small "dip" shown in the CAN% torque at the time when the slew switch turns on indicates the bucket just "torn" through the ground.

Cycle 1b is the next session with any significant changes of pattern in the signals. At the stage, the machine is still slewing and the boom has just stopped going up. It is worth noting that the CAN % torque has dropped dramatically and seems to indicate there is a drop of pressure and demand. However this is only true in an engine's point of view. The engine no longer required to produce the power to the hydraulic pump to generate the pressure to overcome the weight of the structure, i.e. Boom, dipper arm, bucket + load. The pressure within the system is retained by the holding valve being closed.

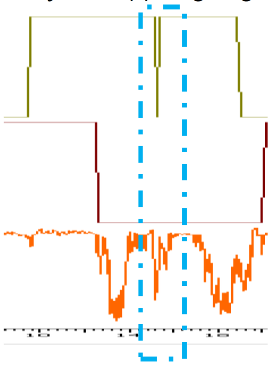

Figure 9 - Cycle 1c

Cycle 1c is the next significant event in cycle 1. At this stage, the machine finished emptying its bucket and is slewing back to the trenching after reaching the 90° mark, which is suggested by the quick "dip" of the slew signal. A small decline of engine % can also be observed at this stage. This suggests the dipper arm and the bucket has reached its desirable manoeuvres and was stationed for that split second, approximately just under one second. As explained earlier, this is only a point of view from the engine, in truth the pressure is still there by only retained within the hydraulic system by holding valves.

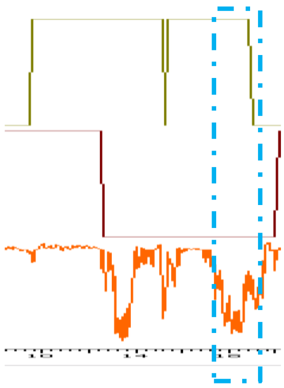

Figure 10 - Cycle 1d

Cycle 1d is the last part of the cycle, hence the last significant event that can be identified within a cycle. The dramatic drop of the engine % torque suggests the entire structure, boom, dipper arm and bucket, was manoeuvred back down the trench, while the machine slewed 90°. Due the nature of gravity pull, the engine and the hydraulic system do not required to do much work to drop the structure, hence the explanation

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RESEARCH **TEST & DEVELOPMENT REPORT**

Test Report Continuation Sheet

of the dip. The small peak of engine % torque before reaching the maximum torque suggests the manoeuvre of dipper arm and bucket. This is common as the operator wants to realign the edge of the trench before beginning the next cycle. At the point slew pilot pressure switch is off, suggests the operator has started the next cycle. All these interpretation were conducted with a synchronised video, filmed of the entire operation, with the data being recorded. They are synchronised by event of engine crank on CANBUS and the light on the cab.

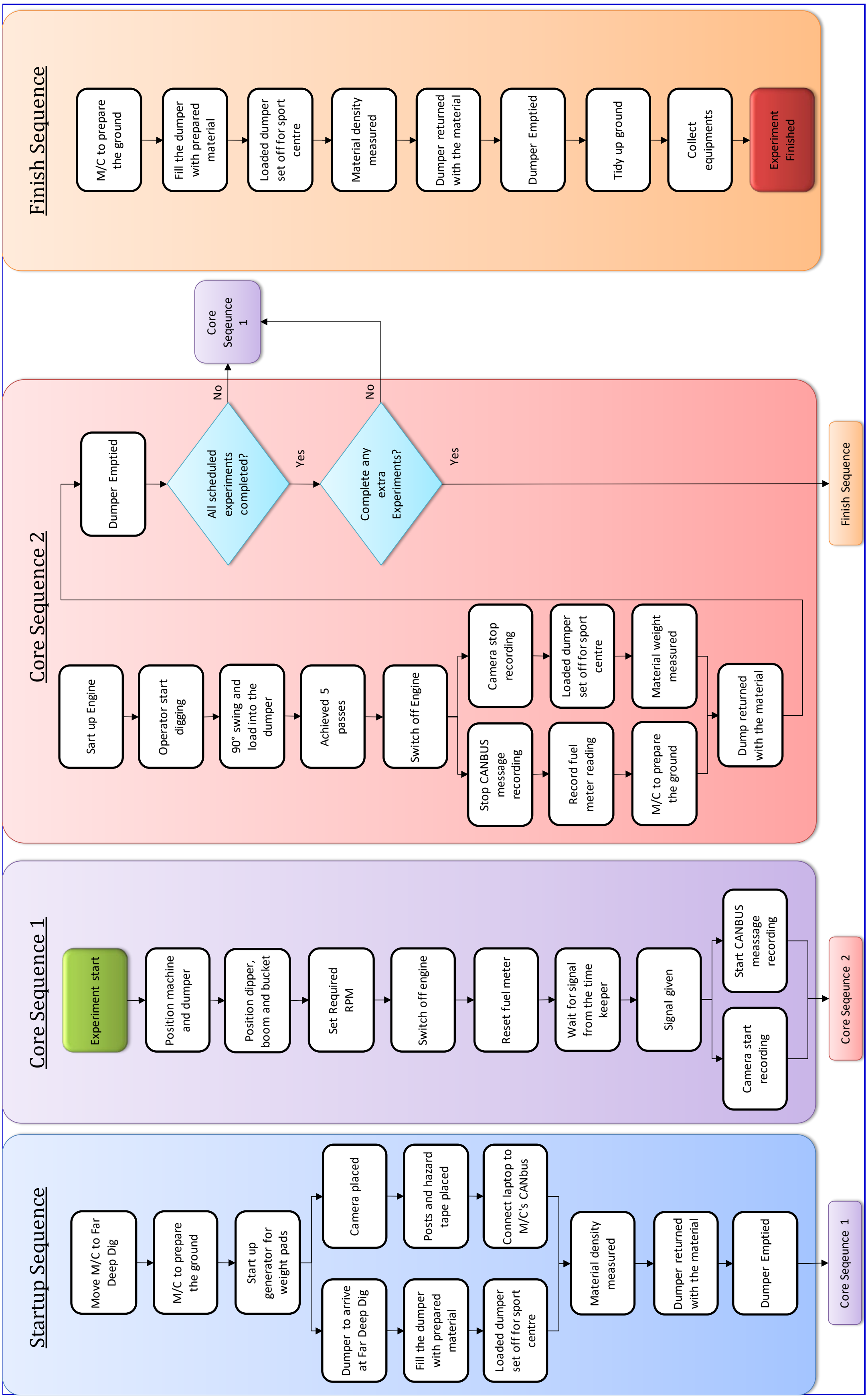
Conclusion

This was an exercises conducted to test the feasibility of CANbus messages to remotely interpret the behaviours of the machine. It has proven a certain level of ability in the attempt to create an understanding as discussed earlier in the report. CAN% engine torque was used as a primary source to drive the understanding. However, there are still a large number of unknown events which there is no knowledge of, moreover the behaviours of CAN% engine torque is not 100% understood at this stage. The data used to generate the knowledge was only based on one type of application of JS220. It is strongly advices that each division should start to create an understanding of how CANbus messages behave, when different duties are being performed by the machine, to fully explode the potential of the existed CANbus messages for monitoring purpose in different divisions.

APPENDIX F PRODUCTIVITY EXPERIMENT TIMETABLE

	Tuesday	Wednesday	Thursday
08:00:00	Measuring mass of the material	Measuring mass of the material	
08:30:00	Measuring mass of the material	Measuring mass of the material	
09:00:00	Setting up the experiment	Setting up the experiment	Cushioning period / Extra Experiment
09:30:00	Setting up the experiment	Setting up the experiment	
10:00:00	900-25% x2	1500-25% x2	
10:30:00	900-50% x2	1500-50% x2	
11:00:00	900-75% x2	1500-75% x2	
11:30:00	900-100% x2	1500-100% x2	
12:00:00			
12:30:00	Lunch		
13:00:00	1100-25% x2	1700-25% x2	
13:30:00	1100-50% x2	1700-50% x2	
14:00:00	1100-75% x2	1700-75% x2	
14:30:00	1100-100% x2	1700-100% x2	
15:00:00	1300-25% x2	2050-25% x2	
15:30:00	1300-50% x2	2050-50% x2	
16:00:00	1300-75% x2	2050-75% x2	
16:30:00	1300-100% x2	2050-100% x2	
17:00:00			
17:30:00	End of Day		

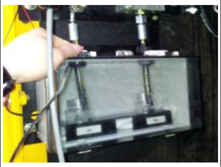
APPENDIX G EXPERIMENT RESET SEQUENCE



APPENDIX H SOPS FOR HYDRAULIC OIL SAMPLING

SOPs for Hydraulic Oil Sampling

Pre-Sampling Requirements
a.) Ran 30 minutes include all services(NOT IDLING) B.) PPE must be worn. (Nitrile gloves) C.) Sample only with bottles supplied.

Seq.	Description	Images	Seq.	Description	Images
1	KEEP the engine ON. Open the BATTERY BAY door.		8	PRESS and HOLD [Sample] UNTIL the bottle is filled to SHOULDER HEIGHT. Then RELEASE [Sample],	
2	TURN the handles ANTI-CLOCKWISE to OPEN the valve.		9	Switch OFF the circuit. (LED will go out)	
3	Switch ON the circuit. (LED will light)		10	TURN the handles CLOCKWISE to CLOSE the valve.	
	PRESS and HOLD [Flush] for no less than 30 SECONDS. Then RELEASE [Flush],			UNCLIP and OPEN the box, REMOVE bottles and TIGHTEN their caps back on. (Avoid sampled oil from touching anything)	
	UNCLIP and OPEN the box (You may need to remove bottles, that are already there)			CLOSE and CLIP the box (If bottles were present before sampling, please put them back)	
4	Take the SAMPLE BOTTLES (A+B) out of its postal container. *(Do not throw the containers away!!!)*		11	Fill the FORM. 1. Job no. 2. Your name 3. Date 4. Location	
5	REMOVE the sample BOTTLE CAPS and place into the CORRECT SLOTS according to the letters.		12	REPLACE EVERYTHING back into the container. Take ALL the FILLED sample bottles back to the OFFICE at the end of your shift.	
6	CLOSE and CLIP the box			**Remarks:** If in doubt, STOP and ASK. Contact **Felix at JCB Research - (ext.3793)** You may need to remove bottles that hold the leakage from the valve. Please put them back into the slots when you finished taking the samples. Empty the bottles whenever possible at the oil bin.	

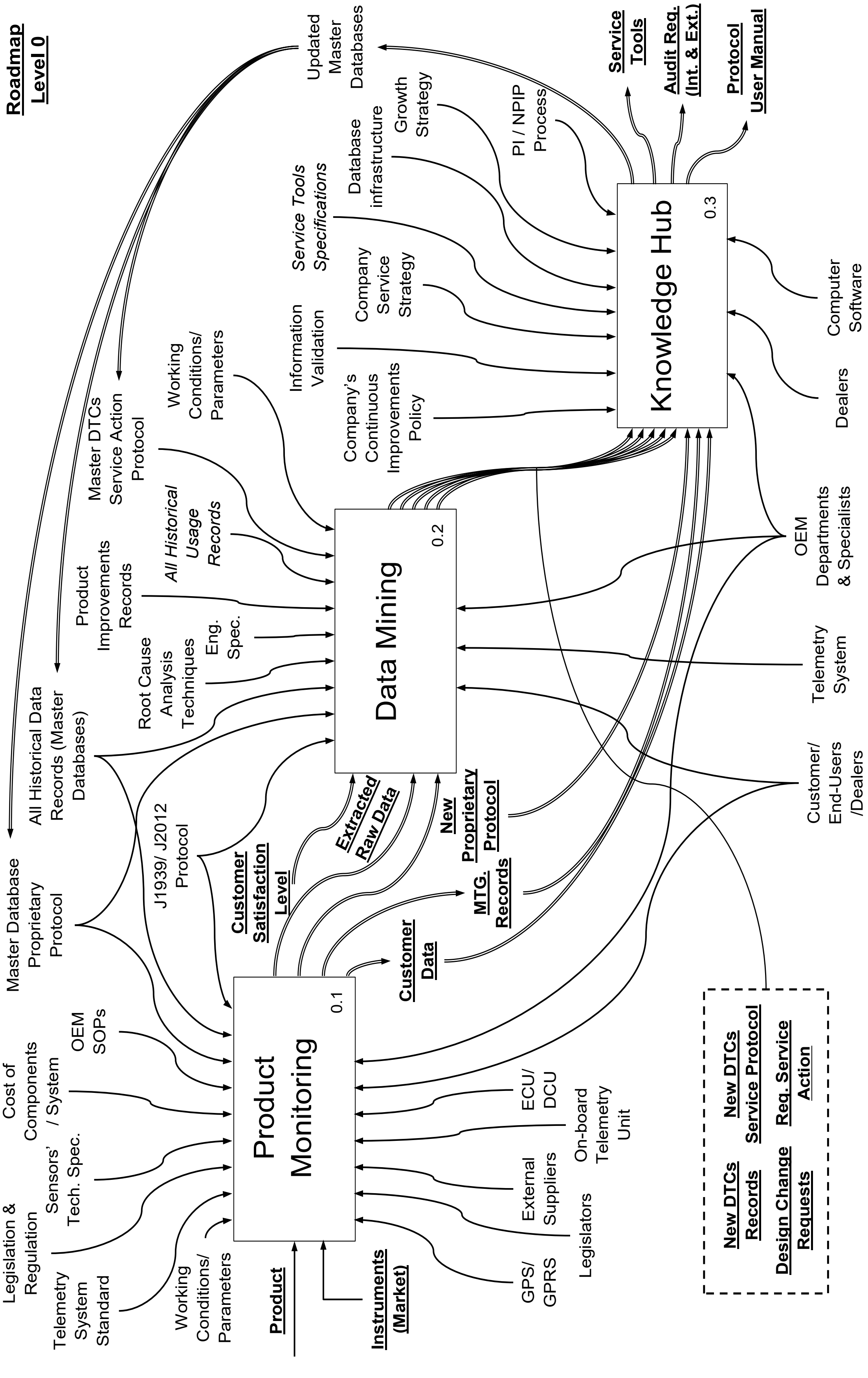
APPENDIX I TELEMETRY BENCHMARKING 2010

	Feature Set	LIVELINK			Cat Product Link	KOMTRAX	CARETRACK	GPS based systems	GSM Based Systems
		LiveLink Lite	Mid Range	Heavy Line	Health Watch	PC130 upwards	Advanced		
General & Security	Location & Mapping	✓	✓	✓	✓	✓	✓	✓	
	Geofence & Time Curfew	✓	✓	✓	✓	✓	✓	✓	
	Backup Battery	✓	✓	✓				✓	
	Tow-away Alert	✓	✓	✓					
	Theft Recovery								✓
	Real Time Security Alerts	✓	✓	✓			✓	✓	
	Machine Disable					✓		✓	
	Subscribed Reports Capability	✓	✓	✓					
Health & Maintenance	Machine Hours	✓	✓	✓	✓	✓	✓	✓	
	Service Alert & Notification	✓	✓	✓	✓	✓	✓	✓	
	Service History Record	✓	✓	✓	✓	✓	?	?	
	Monitor of Fluid Temps.		✓	✓	✓	✓	✓		
	Real Time Problem Alert		✓	✓			✓		
	Problem / Event History		✓	✓	✓	✓	✓		
	Fleet Health Summary	✓	✓	✓					
Performance & Efficiency	Machine Hours	✓	✓	✓	✓	✓	✓		
	Idle Time monitoring			✓	✓	✓	✓		
	Type of Work			✓	✓	✓	✓		
	Fuel Consumption		1/2	✓	✓	✓	✓		
	Fuel Level			✓	✓	✓	✓		
	Re-fuelling History			✓	✓	✓	✓		
	Fleet Performance Summary			✓					

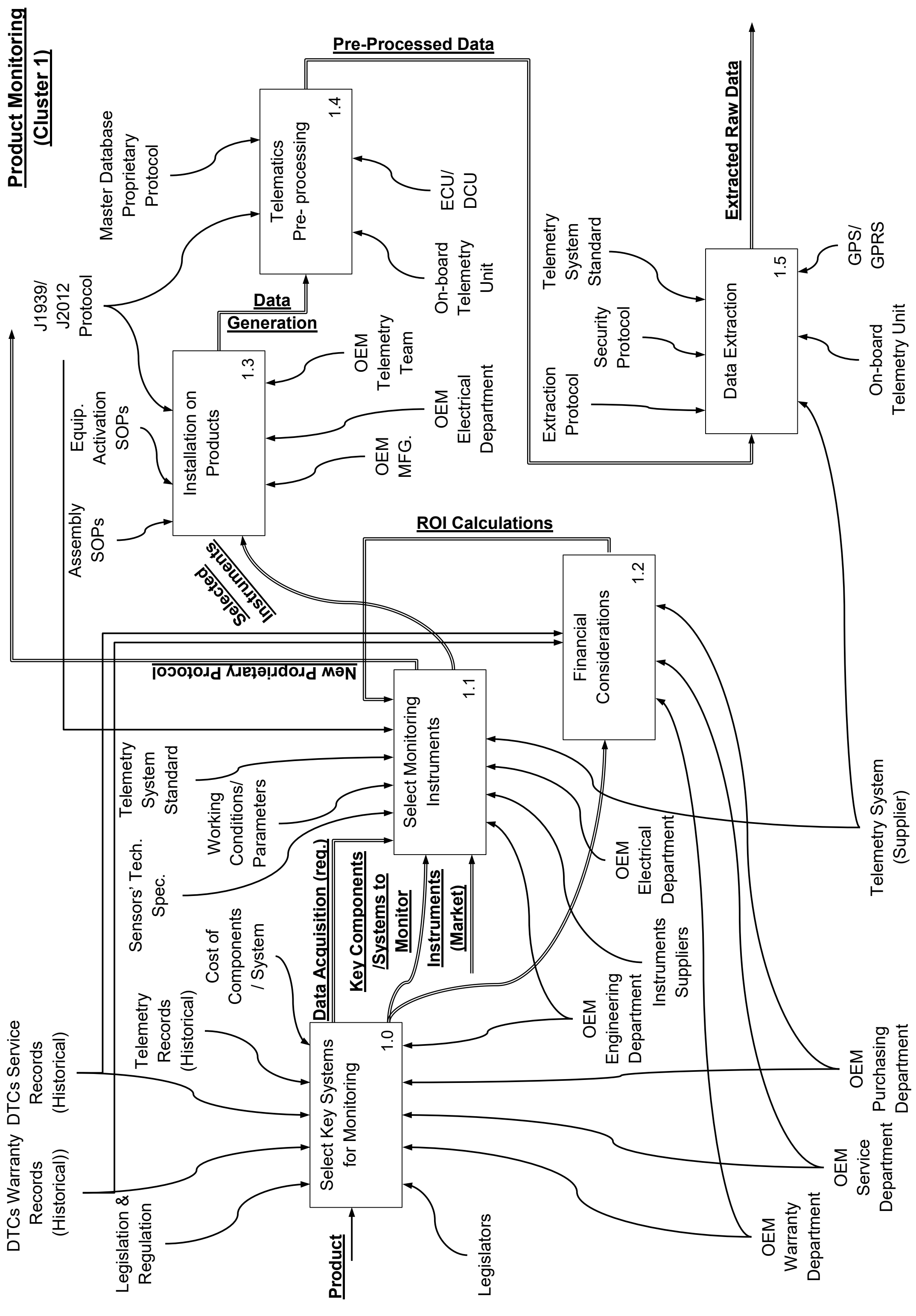
APPENDIX J TELEMETRY BENCHMARKING 2015

Telematics Comparison (Jan 2015)										
Manufacturer	**JCB**	**Manitou**	**CAT**	**John Deere**	**Komatsu**	**Volvo**	**Hitachi**	**New Holland**	**Case**	**Hyundai**
Product Features	LIVELINK	Easy Manager	Product Link™	JDLink™	KOMTRAX	CareTrack®	ZXLink™	FLEETFORCE	SiteWatch	Hi-mate
Machine Location	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Geofencing and out of hours alerting	✓	✓	✓	✓	✓	✓		✓	✓	✓
Back-up battery	✓	✓				✓				
Internal Antenna	✓	✓				✓				
ECU Pairing	✓								✓	
Duty Cycle reporting	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fuel economy & Engine load	✓		✓	✓	✓	✓	✓	✓	✓	
Flexible report generator	✓	✓	✓	✓	✓					
Remote configuration of ECU software	✓			✓						
Remote Control of Immobiliser	✓				✓	✓	✓			
GPRS Option	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Standard Subscription on Heavyline machines	3 years on Heavy equipment	no	3 years on heavy equipment	Varies by region	5 years on all equipment	3 years on Heavy Equipment	3 years on heavy equipment	3 years on heavy equipment	3 years on heavy equipment	
Standard Subscription on mid range machines	2 years on mid range	no	Opion?	no	no	no	no	no	no	
Platform										
Driver Advice reporting					✓					
Weigh load reporting			✓	✓	✓	✓				
Driver Performance Reporting						✓				
Connected worksite Management			✓	✓						
Links to Parts systems			✓							
Satellite Option			✓	✓	✓	✓	✓			✓
Customer Support Centre									✓	
Remote Service Master Connection				✓						

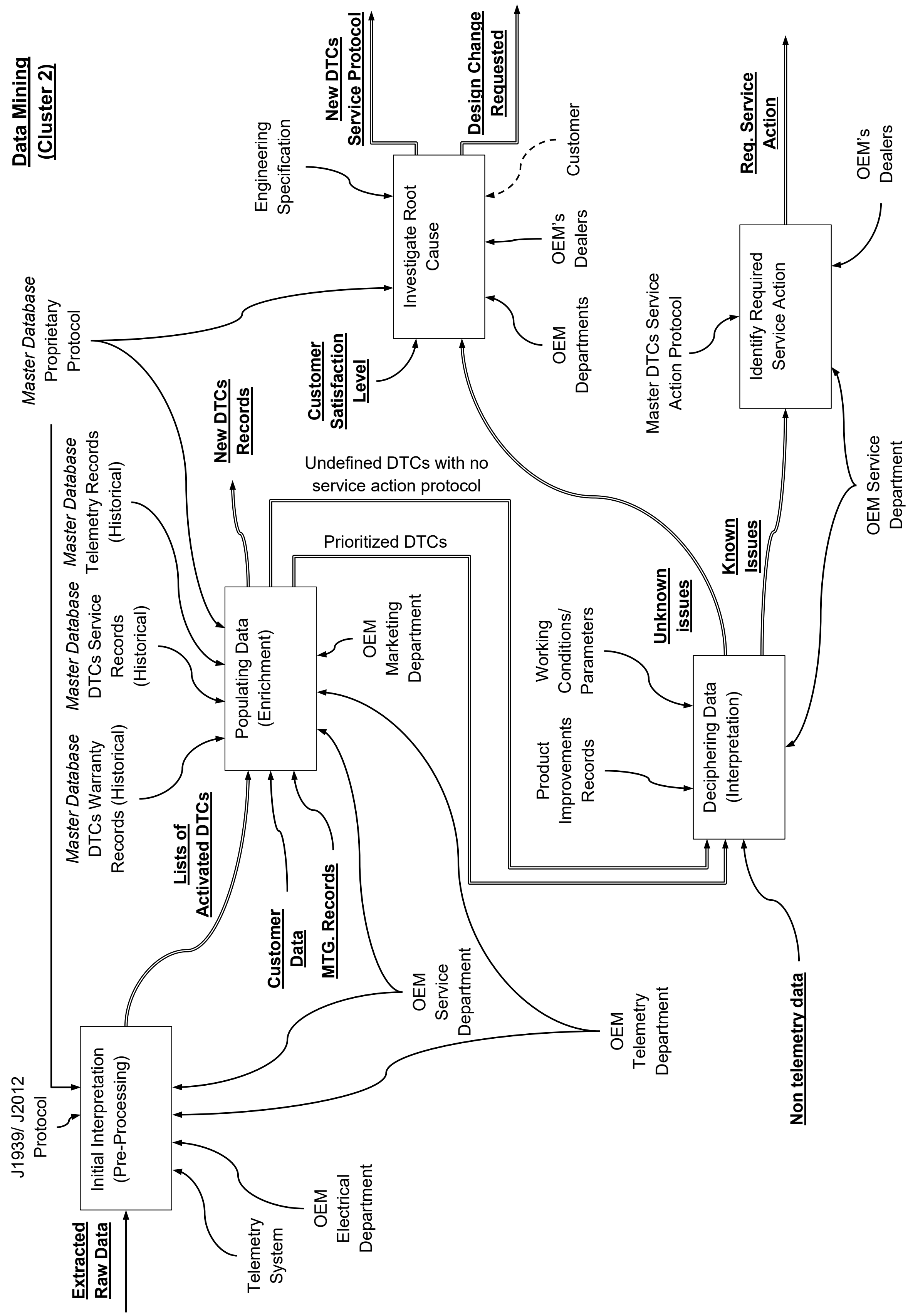
APPENDIX K ROAD MAP LEVEL 0



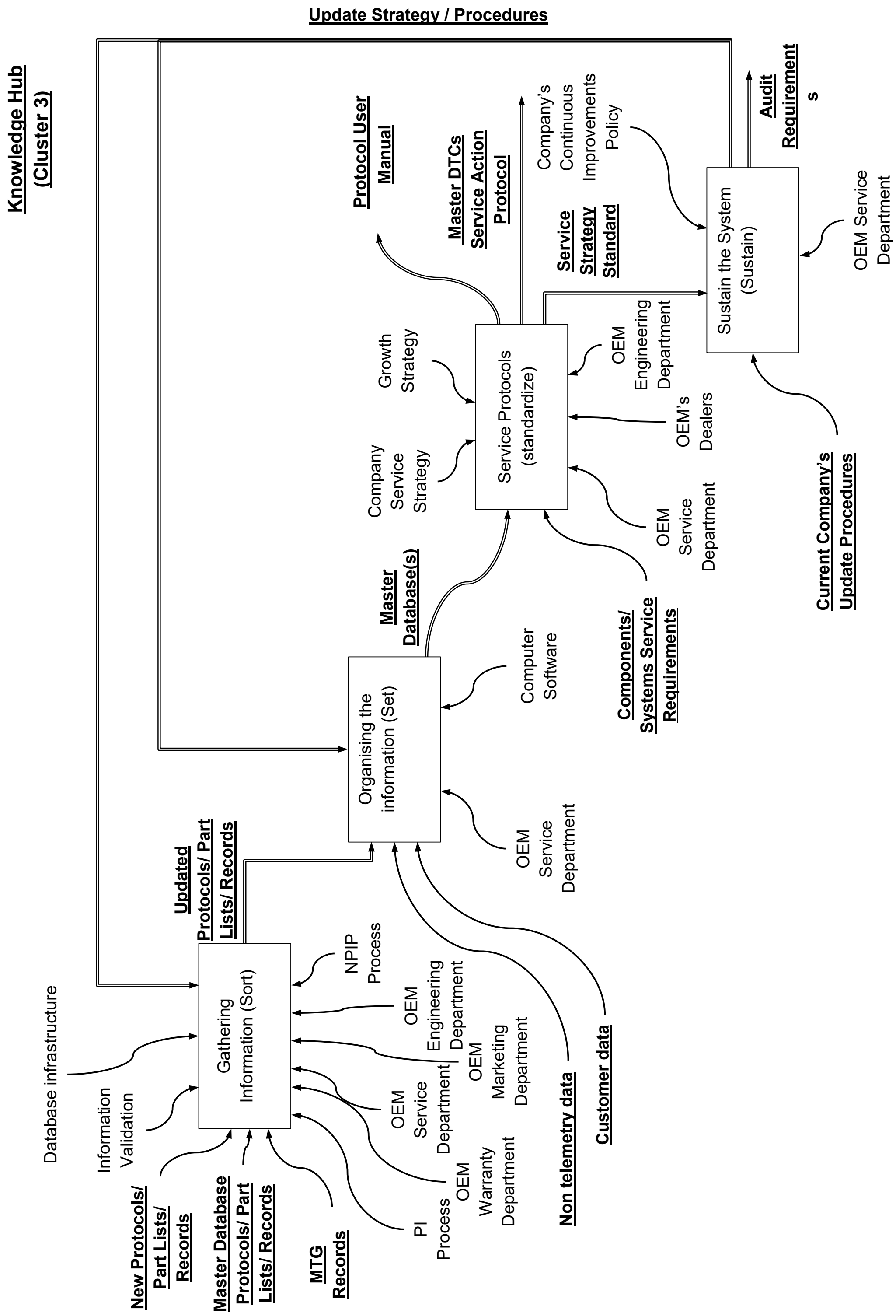
APPENDIX L ROAD MAP CLUSTER 1 – PRODUCT MONITORING



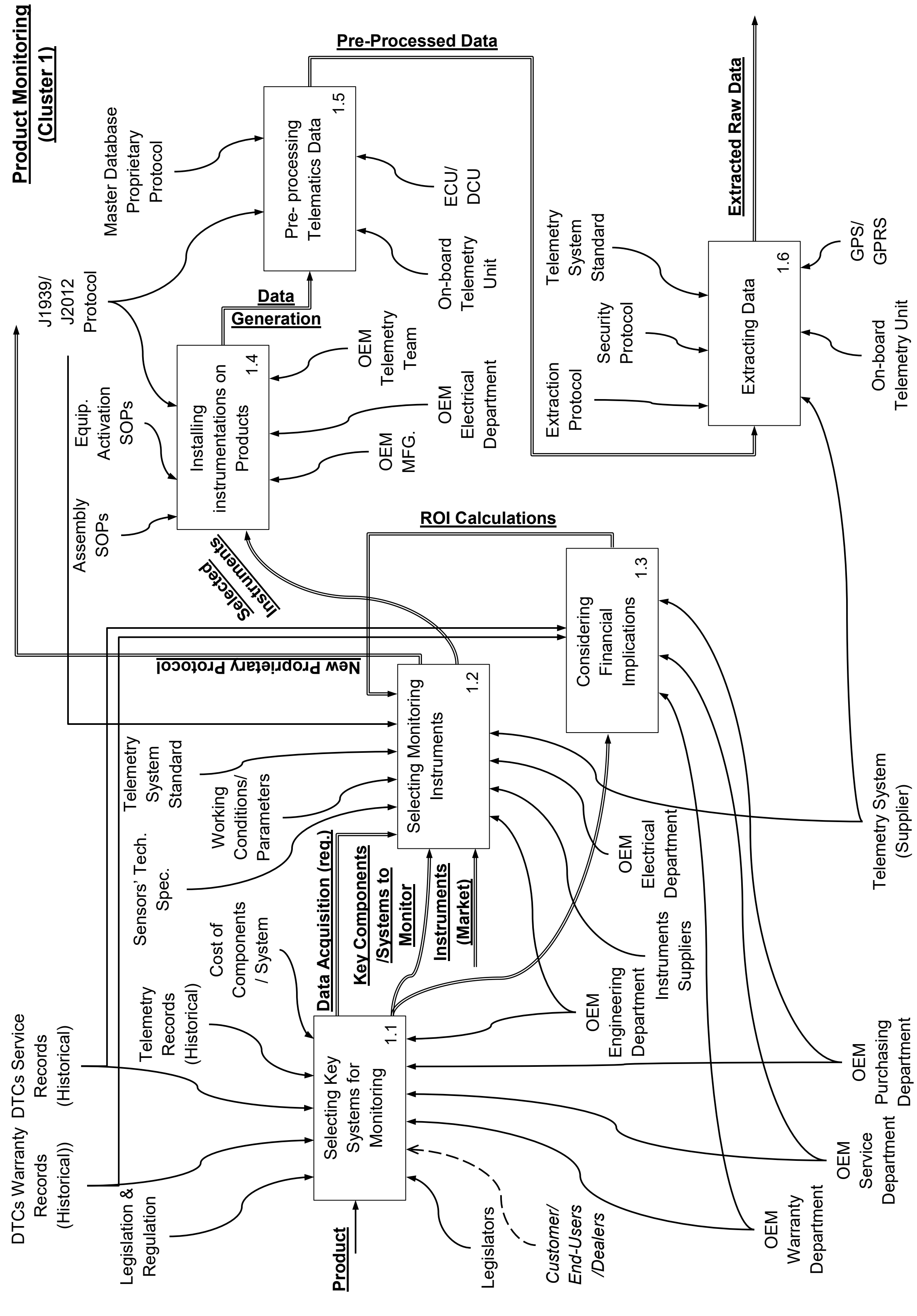
APPENDIX M ROAD MAP CLUSTER 2 – DATA MINING



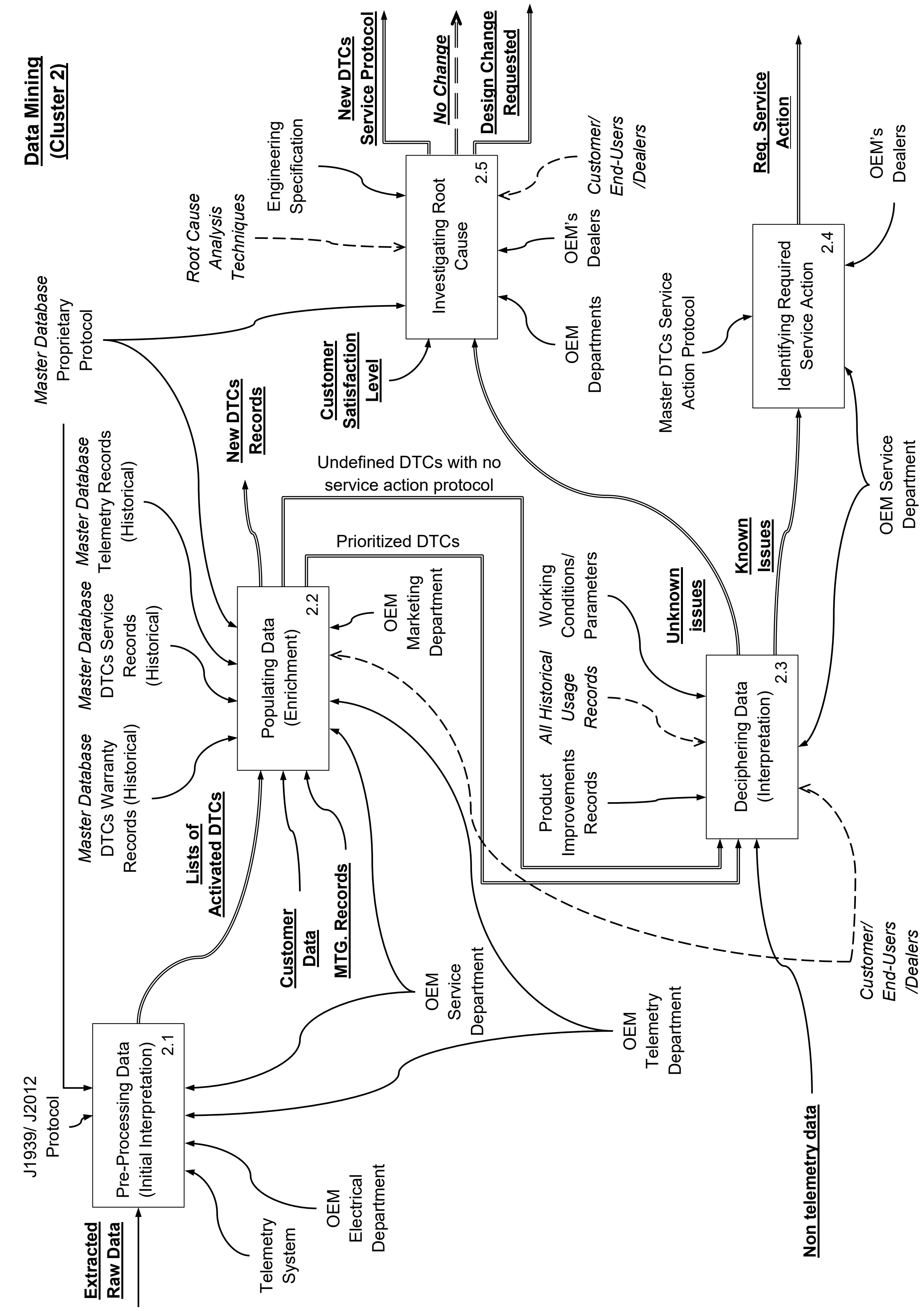
APPENDIX N ROAD MAP CLUSTER 3 – KNOWLEDGE HUB



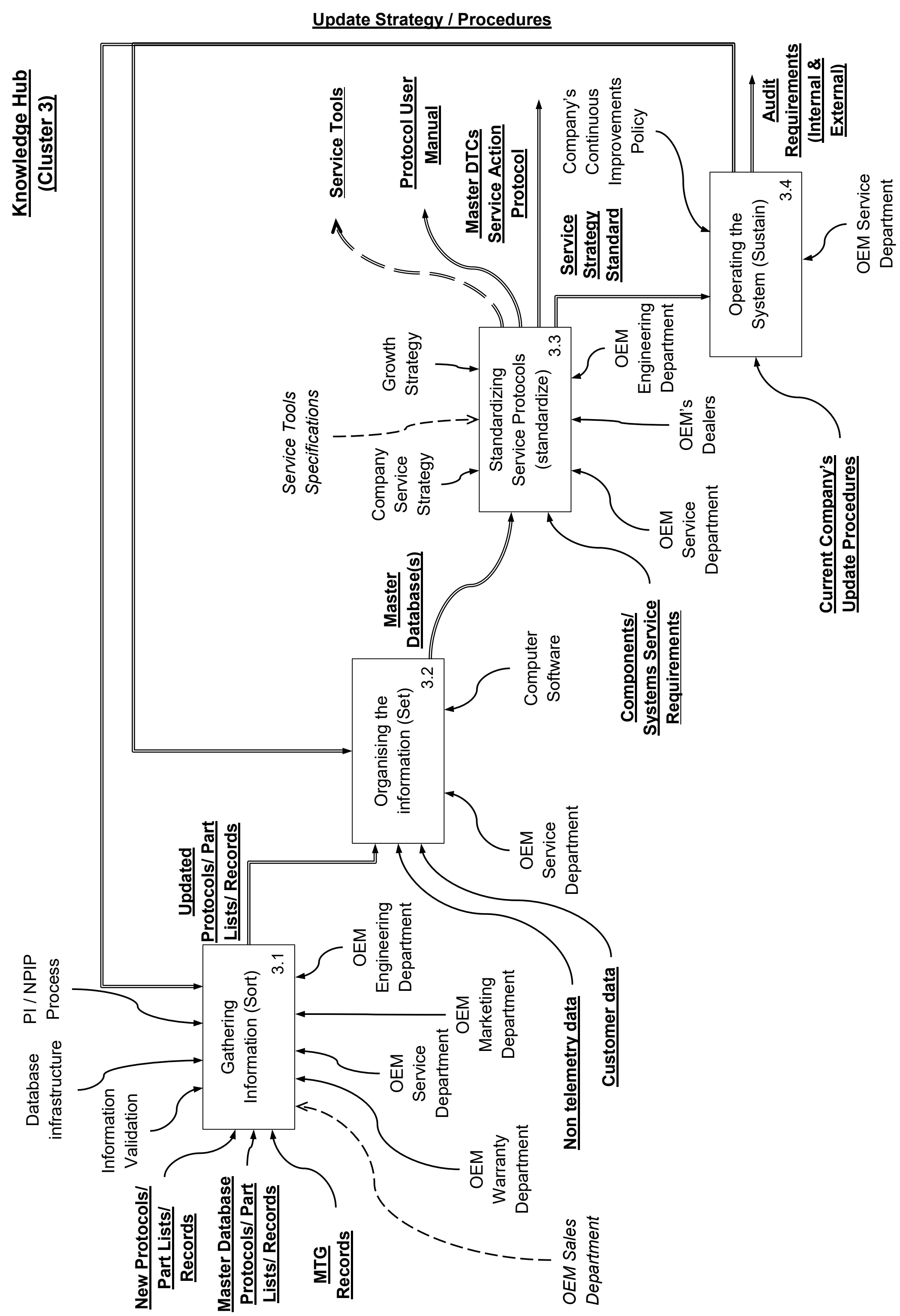
APPENDIX O ROAD MAP CLUSTER 1 – PRODUCT MONITORING (REVISED)



APPENDIX P ROAD MAP CLUSTER 2 – DATA MINING (REVISED)



APPENDIX Q ROAD MAP CLUSTER 3 – KNOWLEDGE HUB (REVISED)



APPENDIX R DTC-FTB SUMMARY REPORT FOR ENGINEERS

Data Range:	02/02/2015	Heavy Products										Descriptions							
Contact: Felix Ng (3393)										Ver. 20150108		Perforce Document Ver.139			Live Link Website		Service Master Help File Ver.20150113		Machine
UTA2-Type	Name	VIN	BU	LL Group	SPN	FMI	SA Hex	Activated Time	Deactivated Time	Inducement	DTC-FTB	Severity	SAE/ISO	JCB	Notifications	Status Level	DTC	FTB	Country
T4F RGF (UK & USA)																			
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 12:30:43	02/02/2015 12:32:48	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 12:30:43	02/02/2015 12:32:48	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 13:13:57	02/02/2015 13:14:56	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 13:13:57	02/02/2015 13:14:56	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 13:13:57	02/02/2015 13:14:56	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 13:13:57	02/02/2015 13:14:56	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 13:23:56	02/02/2015 13:26:55	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 13:23:56	02/02/2015 13:27:55	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 13:30:55	02/02/2015 13:35:03	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 13:30:55	02/02/2015 13:35:03	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 14:14:01	02/02/2015 14:18:01	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 14:14:01	02/02/2015 14:18:01	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 15:40:57	02/02/2015 15:41:57	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 15:40:57	02/02/2015 15:44:57	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 15:42:57	02/02/2015 16:08:56	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 15:45:57	02/02/2015 16:08:56	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 16:43:54	02/02/2015 16:46:54	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 16:43:54	02/02/2015 16:47:54	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 16:49:54	02/02/2015 17:07:09	No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 16:49:54	02/02/2015 17:07:09	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520296	2	0x27	02/02/2015 17:09:09		No	C131A-64	SERVICE	#N/A	Lever Lock Switches Plausibility Error	Do not Display		Lever Lock Switches plausibility error (only one lever lock switch has been registered when the lever was lowered)	Description update to be confirmed	UK
RGF	T4F HPRG2	JCBJS22FC0242 4862	HP		520278	5	0x27	02/02/2015 17:09:09	02/02/2015 17:14:08	No	C1307-13	SERVICE	#N/A	Controls Enable Solenoid Open Circuit	Health alert - C1307 - Please contact your JCB Dealer	Y	Required Update	Required Update	UK
T4F Endurance + Development (UK + Finland)																			
End. + Dev. (UK & FIN)	T4F HPRG1	JCBJS22FE0242 4861	HP		521066	19	0x00	02/02/2015 10:59:24	02/02/2015 11:07:28	No	U010A-88	SERVICE	Lost Communication With Exhaust Gas Recirculation Control Module "A"	CAN communication error: EGR CAN Fault	Do not Display		Lost communication with Exhaust Gas Recirculation (EGR) control module - Fault on the CAN communication network.	Bus off	UK
End. + Dev. (UK & FIN)	T4F HPRG1	JCBJS22FE0242 4861	HP		521080	19	0x00	02/02/2015 10:59:24	02/02/2015 11:07:28	Yes	U040D-96	Service	Invalid Data Received From Turbocharger/Supercharger Control Module "A"	CAN communication error: VGT hardware	Do not Display		Fault with Variable Geometry Turbochanger - Fault detected with the VGT electrical or mechanical system	VGT Actuator internal error	UK
End. + Dev. (UK & FIN)	T4F HPRG1	JCBJS22FE0242 4861	HP		521369	14	0x00	02/02/2015 10:59:24	02/02/2015 11:07:28	No	P2BAB-00	Operator	#N/A	EGR Warning Requested	Do not Display		Exhaust gas recirculation - An error has been detected with the exhaust gas recirculation control unit	EGR warning requested	UK
End. + Dev. (UK & FIN)	T4F HPRG1	JCBJS22FE0242 4861	HP		521458	0	0x00	02/02/2015 10:59:24	02/02/2015 11:07:28	No	P204F-9A	ACK CRITICAL	#N/A	Inducement Repeat Offence Active	Do not Display		Blocked filter - Clogged filter in the supply module or DEF leak on the dosing system	Component or system operating conditions - Engine ECU (Level 4 enacted)	UK
End. + Dev. (UK & FIN)	T4F HPRG1	JCBJS22FE0242 4861	HP		521332	19	0x3D	02/02/2015 10:59:24	02/02/2015 11:07:28	Yes	P2413-87	SERVICE	#N/A	Impeded egr fault data or bus off for egr faults from engine ECU	Do not Display		Impeded EGR fault data engine ECU - error with the exhaust gas recirculation valve.	Missing CAN message from ECU (impeded EGR fault data or bus off for EGR faults from engine ECU)	UK

APPENDIX S DAILY EXECUTIVE SUMMARY REPORT (OVERVIEW)

		Machine	Number	Current Status	Machine Clock Hours	Total hours with customers	Hours run in last 24hrs	Warranty Claims in last 24 Hours	Key Technical / Service Issues / Livelink Summary	Current Customer	Current Location	Notes / Customer Comments	Software	Head Unit	Other	MCn. Software (SCR)
	UK	Loadall - 541-70Ag+	PB10 (2343422)		542	408	4.4									
	UK	Loadall - 536-60 - 81kW	PB11 (2343719)		386	384	1.5									
	UK	Loadall - 560.80WM - 93kW	PB15 (2344014)		895	809	4.4									
	UK	Loadall - 560.80 - 108kW	PB18 (2344338)		490	436	4.6									
	UK	Loadall 535-140 (93kW)	PB12 (2343636)		597	556	6.4									
	UK	Loadall 541-70	PB17 2343889)		626	553	6									
	UK	Loadall 510-56	BR4 (2433104)		1399	1392										
	UK	Loadall 510-56	BR5 (2433106)		1358	1350										
	UK	Excavator - JS220 - 129kW	HPRG2 (2424862)		700	566	0.5									
	UK	Excavator - JS130 - 93kW	HPRG3 (2424002)		627	393	0.2									
	UK	Excavator - JS160 - 93kW	HPRG4 (2424603)		949	727	0.3									
	UK	Backhoe - 3CX - 81kW	BHL138 (2269573)		608	497	4.9									
	UK	Backhoe - 4CX - 81kW	BHL136 (2269379)		557	534	7.5									
	UK	Backhoe - 3CX - 81kW	BHL137 (2269474)		672	278	1.6									
	UK	Backhoe - 3CX - 81kW	BHL139 (2269633)		762	741	9.2									
	UK	Backhoe - 3CX - 81kW	BHL140 (2269721)		410	386	0									
	UK	Backhoe - 3CX - 81kW	BHL142 (2269634)		478	399	5.3									
	UK	TM320 - 93kW	RGF1 (1910875)		673	666	3.7									
	UK	TM320 - 93kW	RGF2 (2420804)		529	524	2.1									
	UK TOTAL Hours		17 Machines			11,598	114 62.6									
	NA	Backhoe - 4CX - 81kW	BHL 133 (2269101)		354	291	7.6									
	NA	Backhoe - 3CX - 68kW	BHL 134 (2269175)		709	668	5.2									
	NA	Backhoe - 4CX - 81kW	BHL 135 (2269270)		570	532	0.4									
	NA	Excavator - JS220 -	HPRG5 (2424863)		117	102	0									
	NA	Excavator - JS220 -	HPRG6 (2424864)		178	154	0									
	NA	Loadall 509.42 (81kW)	PB3 (2406844)		569	513	1.9									
	NA	Loadall - 510.56 - 81kW	PB4 (2436601)		543	469	0									
	NA	Loadall 510.56	PB6 (2436609)		414	340	5.7									
	NA	Loadall - 510.56 - 81kW	PB7 (2406871)		383	334	4.6									
	NA	Loadall - 512.56	PB19 (2436964)		389	350	1.9									
	NA	Loadall - 514.56 - 81kW - (Was S&M)	PB20 (2437012)		312	277	2.4									
	NA	Loadall - 510.56 - 81kW	PB23 (2437229)		588	581	4.7									
	NA	Loadall - 514.56 - 81kW	PB25 (2437230)		380	329	0									

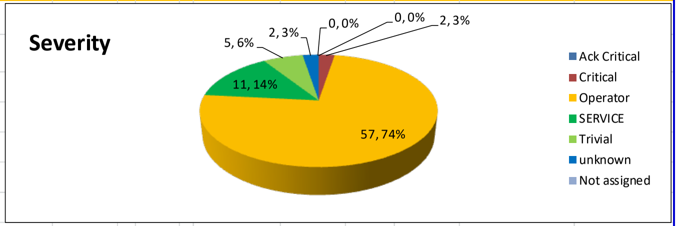
Confidential

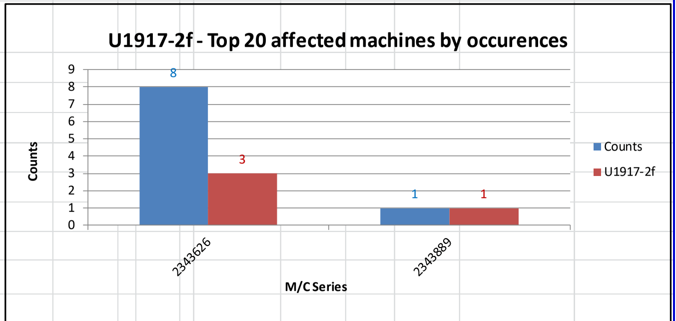
APPENDIX T DAILY DTC-FTB EXECUTIVE REPORT

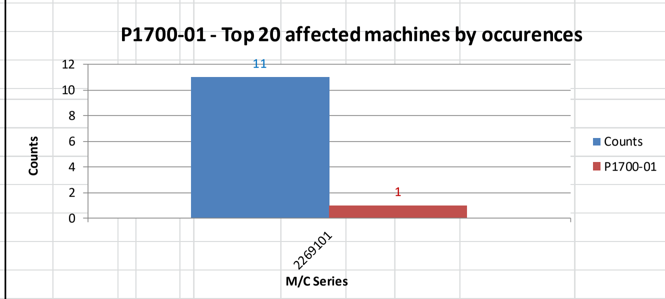
T4F RGF Diagnostic Code Summary Report - 31 May 15 (Period - 23th May - 30th May)

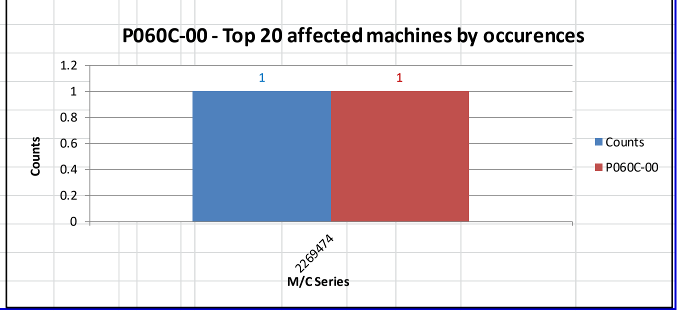
Model	Number of Machines	Number of machine active in Period	Total Number of hours
Backhoe Loaders	8	8	149.4
Loadall	14	13	205.4
Heavy Products	5	2	14.5
Earthmovers	2	2	83.1
Total	29	25	452.4

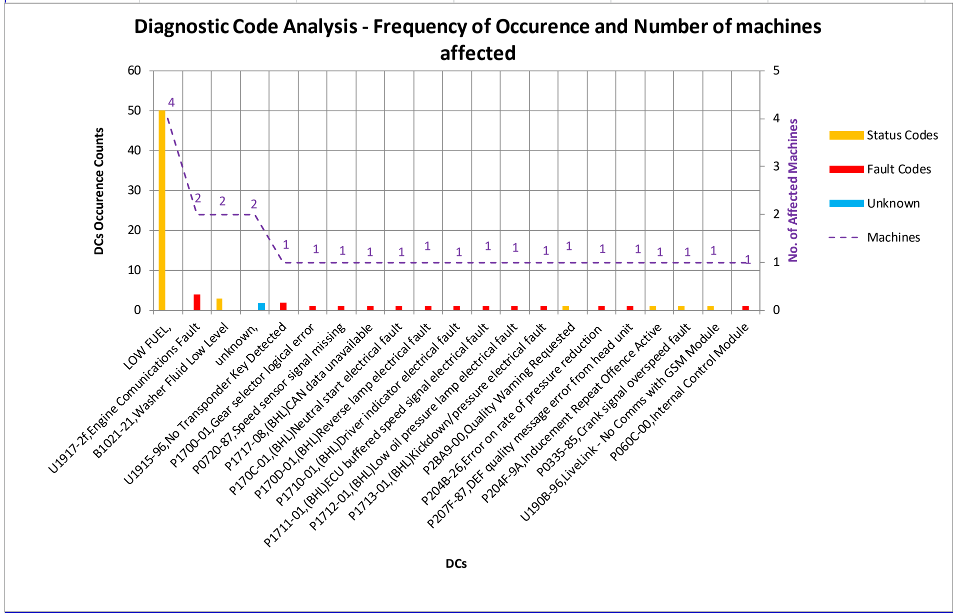
Model	Number machines producing DC in Period (Diagnostic Codes)	Number of DC in Period (Diagnostic Codes)	Number of DFC in Period (Diagnostic Fault Codes)	Number of DSC in Period (Diagnostic Status Codes)	Number of Inducement in Period (≥1min in Duration)
Backhoe Loaders	7	22	14	7	2
Loadall	5	54	4	50	0
Heavy Products	1	1	0	0	0
Earthmovers	0	0	0	0	0
Total	13	77	18	57	2





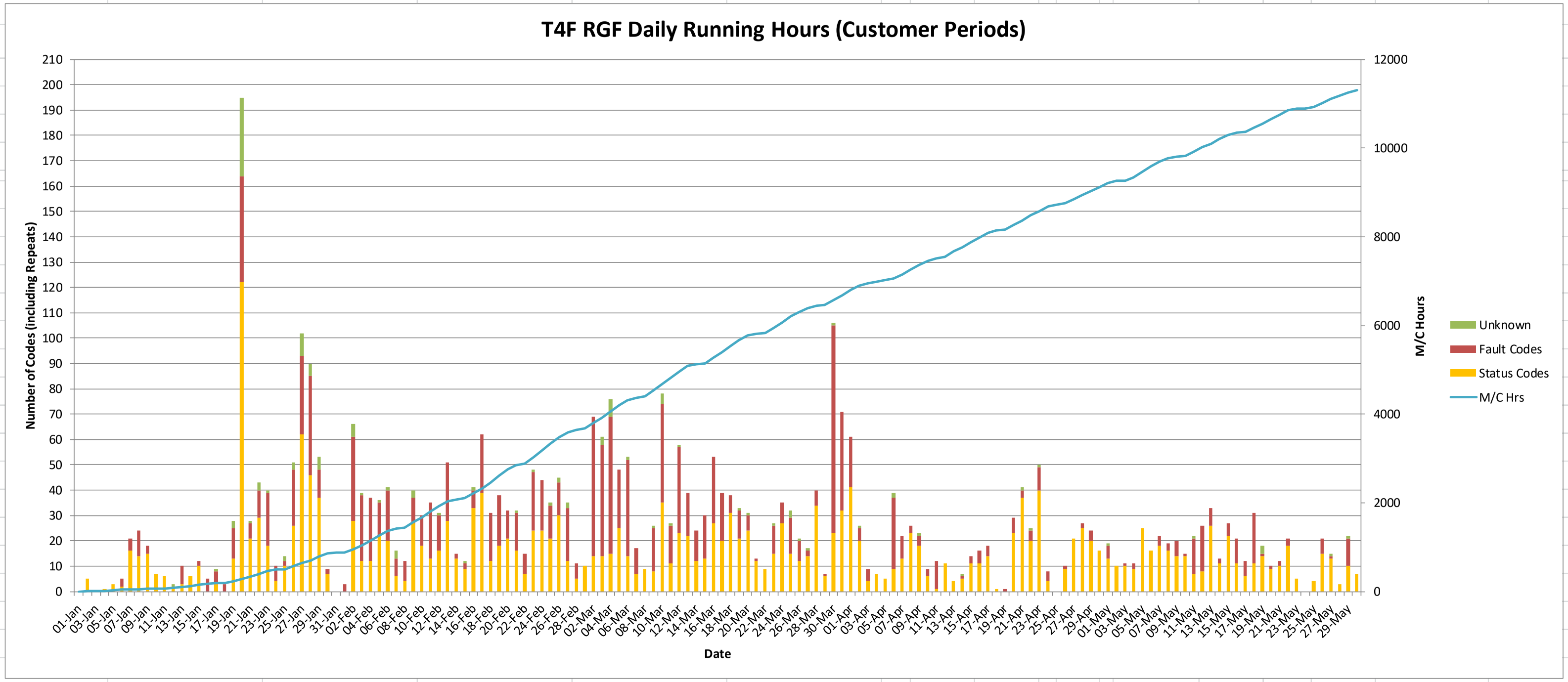




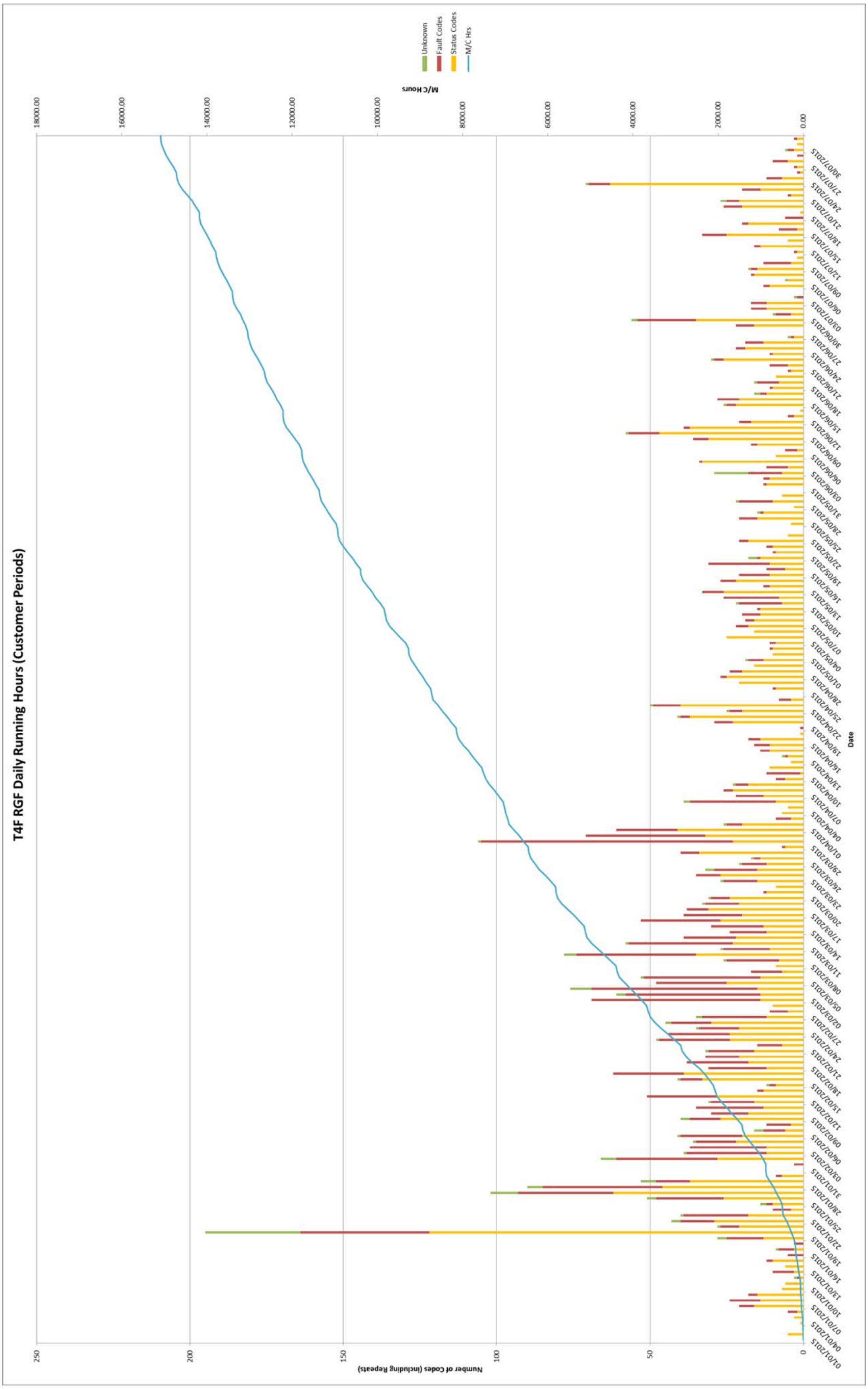


T4F RGF Diagnostic Code Summary Report - 31 May 15 (Period - 23th May - 30th May)

DTCs	Counts	JCB Description	ISO Description	Status	Machines	Severity	Inducement
LOW FUEL	50	(LDL)Low Fuel Level (Service Level)	(LDL)-N/A	Status Codes	4	Operator	Status Codes
U1917-2f	4	(LDL)Engine - Communications Fault	(LDL)-N/A	Fault Codes	2	Trivial	Fault Codes
B1021-21	3	(BHL)Washer Fluid Low Level switch activated	(BHL)Washer Fluid Level Low - Signal Amplitude Less Than Minimum	Status Codes	2	OPERATOR	Status Codes
unknown	2	unknown	unknown	Unknown	2	unknown	Unknown
U1915-96	2	(BHL)Transponder System - No Transponder Key Detected In Key	(BHL)-N/A	Fault Codes	1	OPERATOR	Fault Codes
P1700-01	1	(BHL)Gear selector logical error	(BHL)Gear selector logical error / Invalid gear selection - General Electrical Failure	Fault Codes	1	SERVICE	Fault Codes
P0720-87	1	(BHL)Output Speed Sensor Circuit - Missing Message	(BHL)Output Speed Sensor Circuit - Missing Message	Fault Codes	1	SERVICE	Fault Codes
P1717-08	1	(BHL)CAN data unavailable	(BHL)CAN data unavailable / Torque converter lock up disable - Bus Signal / Message Fa	Fault Codes	1	SERVICE	Fault Codes
P170C-01	1	(BHL)Neutral start electrical fault	(BHL)Neutral start electrical fault / HS 9 output fault - General Electrical Failure	Fault Codes	1	SERVICE	Fault Codes
P170D-01	1	(BHL)Reverse lamp electrical fault	(BHL)Reverse lamp electrical fault / HS 10 output fault - General Electrical Failure	Fault Codes	1	SERVICE	Fault Codes
P1710-01	1	(BHL)Driver indicator electrical fault	(BHL)Driver indicator electrical fault / LS 1 output fault - General Electrical Failure	Fault Codes	1	SERVICE	Fault Codes
P1711-01	1	(BHL)ECU buffered speed signal electrical fault	(BHL)ECU buffered speed signal electrical fault / LS 2 output fault - General Electrical Fa	Fault Codes	1	SERVICE	Fault Codes
P1712-01	1	(BHL)Low oil pressure lamp electrical fault	(BHL)Low oil pressure lamp electrical fault / LS 3 output fault - General Electrical Failur	Fault Codes	1	SERVICE	Fault Codes
P1713-01	1	(BHL)Kickdown/pressure electrical fault	(BHL)Kickdown/pressure electrical fault / LS 4 output fault - General Electrical Failure	Fault Codes	1	SERVICE	Fault Codes
P2BA9-00	1	(BHL)Quality Warning Requested	(BHL)Quality Warning Requested	Status Codes	1	OPERATOR	Status Codes
P204B-26	1	(BHL)Error on Defective pressure reduction	(BHL)Reductant Pressure Sensor Circuit Range/Performance - Signal Rate Of Change Be	Fault Codes	1	SERVICE	Fault Codes
P207F-87	1	(BHL)Aftertreatment 1 Diesel Exhaust Fluid Property	(BHL)Reductant Quality Performance - Missing Message	Fault Codes	1	SERVICE	Fault Codes
P204F-9A	1	(BHL)Inducement Repeat Offence Active	(BHL)Inducement Repeat Offence Active	Status Codes	1	CRITICAL	Status Codes
P0335-85	1	(BHL)Crankshaft Position Sensor A Circuit	(BHL)Crankshaft Position Sensor A Circuit	Status Codes	1	OPERATOR	Status Codes
U190B-96	1	(BHL)	(BHL)-N/A	Status Codes	1	TRIVIAL	Status Codes
P060C-00	1	(BHL)Internal Control Module Main Processor Performance	(BHL)Internal Control Module Main Processor Performance	Fault Codes	1	CRITICAL	Fault Codes



APPENDIX U FLEET PERFORMANCE GRAPH



APPENDIX V A CUSTOMERS' SATISFACTION BASED FRAMEWORK FOR CONTINUOUS DEVELOPMENT OF PSS (PAPER 1 – PUBLISHED)

Full Reference

Ng, F., Harding, J. and Rosamond, E., 2012. A Customers' Satisfaction Based Framework for Continuous Development of PSS. *Proceedings of the 4th CIRP International Conference on Industrial Product-Service Systems, Tokyo, Japan, November 8th - 9th, 2012,* pp. 239-244

Abstract

Customer satisfaction levels have been used by industry to provide valuable insight into the evaluation of products and service quality. However, the levels do not necessarily provide a full picture needed for a full evaluation. This paper analyses published academic research work and industry's views, and presents a framework that uses customer satisfaction as the main contributor towards the state of "total contentment", to measure performance and develop product service systems (PSS) within industry. Additional parameters such as customer loyalty and retention are included in the proposed framework, providing a full overview in how customers' "total contentment" can be determined.

Keywords

Customer Satisfaction; Product Service Systems; Product Improvements; Service Improvements

Paper type

Conference Paper

A Customers' Satisfaction Based Framework for Continuous Development of PSS

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Abstract
Customer satisfaction levels have been used by industry to provide valuable insight into the evaluation of products and service quality. However, the levels do not necessarily provide a full picture needed for a full evaluation. This paper analyses published academic research work and industry's views, and presents a framework that uses customer satisfaction as the main contributor towards the state of "total contentment", to measure performance and develop product service systems (PSS) within industry. Additional parameters such as customer loyalty and retention are included in the proposed framework, providing a full overview in how customers' "total contentment" can be determined.

Keywords:
Customer Satisfaction; Product Service Systems; Product Improvements; Service Improvements

1 INTRODUCTION

Various forms of product service systems (PSS) can be found within heavy industry due to the complex relationships between partners in the value chain. Customers, the hiring companies, buy a fleet of machines along with service packages from the original equipment manufacturers' (OEMs) through a dedicated dealer. Hiring companies lease their machines to their customers, (contractors), according to their job requirements and ensuring the integrity of the machines. Finally the end-users are hired by the contractors to perform the tasks with the machines. Later in their life cycle, machines tend to be sold off to other owners, who may obtain another service pack from the dealer, machines are then likely to have a completely different pattern of usage and applications. Baines argues that PSS is a competitive proposition, and can refer to the need for customer satisfaction (CS) [1]. As service requirements and product usage vary hugely throughout the machines' life, assessing CS levels in each stage would not only allow OEMs to understand the performance of the product in different conditions, but may also help to improve PSS because the service provider has the incentive to use and maintain equipment properly, increasing both efficiency and effectiveness [2].

Both industrial and academic researchers are starting to analyse the relationships between products and their customers, quantifying how the level of fulfilment of customers' requirements and needs by products can be measured or, in other words how the satisfaction of customers can be measured or assessed.

2 BACKGROUND

2.1 Literature Review

A number of ways have been reported to successfully quantify the true meaning and identify the real value of CS. In this section, the definitions of CS are discussed based on two sources, i.e. academic publications and industrial publications, (e.g. industrial magazines, interviews with engineering managers, etc.) This paper deliberately examines views from both the academic and industrial worlds, in an attempt to create a framework that has a high commercial readiness value.

2.2 What is Customer Satisfaction (CS)?

CS is generally defined as, the extent to which customers are happy with the product and/or service provided by a business [3]. However, definitions vary depending on the nature of the products. A specification of CS was defined by Eugene who developed a theoretical framework;

$$\text{Profitabilty}_t = f_3(\text{Satisfaction}_t, \xi_{3t}) \quad (1)$$

$$\text{Satisfaction}_t = f_2(\text{Quality}_t, \text{Price}_t, \text{Expectation}_t, \xi_{2t}) \quad (2)$$

In equation 1 Eugene claimed, profitability at any given time (*t*) is a function of satisfaction [4]. Satisfaction is the function of three factors: the quality and price of product or service and the customers' expectation at the given time. These equations include vectors of factors (ξ), such as environmental trends or historical dependent variables [4]. These factors cause variations which influence the satisfaction level through customers' experience on products/services. It is hard to understand and interpret satisfaction levels in a quantifiable and comparable form. The European Institute of Public Administration (EIPA) stated a number of difficulties in simply clarifying the concept of satisfaction: It is not static, but dynamic due to the accumulation of experience by customers hence customer expectations and perceptions of the same products/services will change over time [5]. It is very difficult to analyse how the mixture of experiences accumulates. Some products that are intangible can fulfil their function behind the scenes, making it harder for the customer to express the reason for their satisfaction.

Ultimately, without understanding the causes of satisfaction, companies may be blinded by the success of visible results, miss the core reason for satisfaction and hence not able to sustain the advantage. Perhaps the key to satisfaction is not just the fulfilment of customer's needs by products performing their desired functions. Fumiya mentions that a customer perceives satisfaction for a product or service when not only his requirements but also his values are fulfilled [6].

3 EXPECTATION AND PERCEPTION

Fonseca argues that CS can be viewed as the action of monitoring the quality of service delivered, thus measuring how well the organization is delivering the service [7]. EIPA argues that the main elements in achieving high CS are to understand expectation, i.e. what the customer expects to receive from the service, perception, and what the customers think they have received/gained from the services. Expectation can result from personal experience which will vary for different human beings [8].

3.1 Expectation

To satisfy customers, providers should consider contracts from the viewpoint of expectation, rather than only aim to complete the job in the shortest possible time [9]. The accounts commission of Scotland (ACS) stated that the five most common factors that influence the formation of personal expectations from a service are: personal needs, previous experience, word-of-mouth communication, explicit service communication and implicit service communication [10].

Personal needs are the key requirement a customer expects the service will provide [11]. It is essential to identify customers' needs before designing and offering the service. Customers are likely to have had similar services in the past. These accumulated experiences often set minimum standard that customers expect from a similar service [12]. Humans can have huge influence on each other, as propaganda and rumours can manipulate people to believe in certain facts, both consciously and unconsciously. In word-of-mouth communications, customers may hear gossip about the suppliers from other customers within the industry [13].

Explicit and implicit service communication usually comes in the form of propaganda, explicit service involves publishing material to the general public, e.g. TV advertisements or leaflets/brochures distributed in targeted market segment. Implicit service is a statement of how a reliable, successful business venture should look like being made by the business provider through a visible, general acceptance and perception within the particular society [8] [10].

Value/belief and views on government have been described and explained for public service sector [12], the nature of these views should also be relevant in the private sector, Dinsdale and Marsden also stated that image is more likely to be important for public services than in the private sector, as the absence of competitor services limits customers' choice.

3.2 Perception

The word perception is defined by the Cambridge dictionary as, "A belief of opinion, often held by many people and based on how things seem." Most satisfaction surveys conducted by companies are very much based on the perception of the customers, after they have received and used the particular product or service. However, the level of expectation of customers prior to receiving the product or service were often neglected, hence interpretation of the rating within a satisfaction survey is

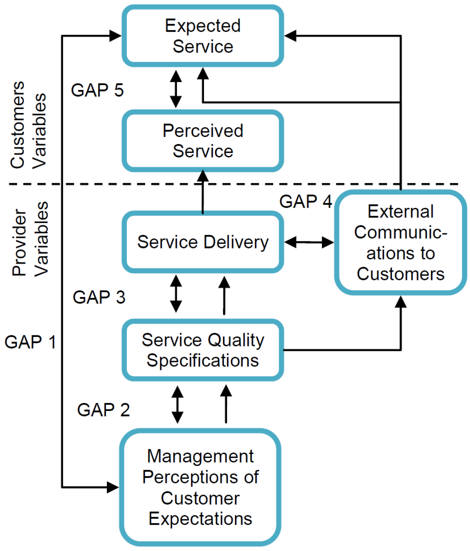

Figure 1 - Servqual Model [6].

generally difficult, and potentially biased within the particular region that the survey was conducted, making the results difficult to compare and analyse [14]. The Servqual model shown in Figure 1 is a service quality measurement tool that can be used to make the role of perceptions and expectations operational by including both service perception and expectation across a range of different service characteristics, which are believed to influence human perceptions and expectations towards a certain service. The model was developed in the 80s by Zeithaml, Parasuraman and Berry who classified the difference between perception and expectation as gaps, which can be analysed to identify the conditions needed to move between perception and expectation [15]. Hence companies can set targets and prioritise effort to improve satisfaction levels by applying resources to measure, manage and minimise these gaps. The model helps customer expectations to be understood and the results interpreted to give a valid rating.

Gap 1 describes the difference between customers' expectations and management perceptions. This is a result of marketing research operations not being prioritised or considered frequently enough, to allow management to capture and understand the wider and dynamic picture of customer expectations [16]. Increasing communication between a company and its customers, and decreasing the hierarchical layers of management can help to reduce the gap [8].

Gap 2 describes the commitment of the company / management board to clearly define their service specification based on their perception of customers' needs and requirements. A clear goal and objectives for the business would allow the standardization of approach and procedures, enabling the service offered to be more transparent and efficient.

Only a well trained service provider with the necessary skills and knowledge can deliver satisfactory services. Hence companies need to provide and monitor employees training programmes to suit individual needs. In lean manufacturing, a team leader board is often employed to address the issues identified by Gap 3. An employee skill matrix, showing the skill sets of each employee enables supervisors to organise training programs according to each job description.

Gap 4 identifies the content of external communication with customers, which must be transparent to allow the company to react as and when requirements develop.

Dimensions	Descriptions
Tangibles	The physical facilities and equipment available, appearance of staff, ease of understanding communication materials.
Reliability	Performing the promised service dependably and accurately.
Responsiveness	Helping customers and providing a prompt service.
Assurance	Inspiring trust and confidence.
Empathy	Providing a caring and individual service to customers.

Table 1 - The five dimensions for service quality [10].

In Gap 5, the difference between service provider perception and customer expectation can only be fully analysed if data has been gathered from the previous 4 gaps described above. Furthermore, the model suggests that the user should also incorporate the influence from the customer side, such as personal needs, word of mouth communication and past experience etc.

The model allows companies to understand and measure causes toward customer expectation and perception. Yet, it is not clear what attributes of products and services should be looked at to determine CS levels. Based on the model, the accounts commission defined five dimensions that are the core factors for measuring service quality. (See Table 1) These dimensions should be included when determining satisfaction level.

3.3 Behavioural Intentions

To improve product and service development, OEMs and service providers should focus on identifying the reasons behind CS. However, how can a fully satisfied customer be identified, as mentioned earlier, customers who claim to be satisfied are not necessarily fully pleased and return to the same OEM or dealer. Yap Sheau Fen describes service quality is an important driver of behavioural intentions, but its direct effect towards behavioural intentions is insignificant compared to its indirect effect through CS [17]. What is a behavioural intention? Zeithaml, Parasuraman and Berry presented a model in 1996 and stated that behavioural intentions can be seen as behaviour if a customer wishes to remain or defect to other providers or OEMs [18]. e.g. customers with positive behavioural intentions can often be confirmed by their level of repurchase intentions, and expression of their preferences for particular products/services. This can be seen as a sign of loyalty and satisfied customer [18]. Yap Sheau Fen's work, also suggested that as customer expectations change over time, practitioners are advised to measure their customer expectation and satisfaction regularly and handle complaints timely and effectively [17].

4 THE IMPORTANT OF CUSTOMER SATISFACTION IN THE CONSTURCTION SECTOR

Earthmoving equipments are the main elements of the construction industry. The adoption of PSS can be observed from most equipment sellers and buyers, both parties understand the complexity of the equipments and the nature of their applications, hence products are best to be maintained and repaired by trained service engineers. In this section, different industrial views have been examined to identify how PSS can be best applied and maintained through the measurement of CS.

4.1 The relationships

Generally in the construction industry, OEMs do not necessarily communicate with the end users directly, but through their dedicated dealers. As a result, dealers are seen as the providers of both products and services. Yet OEMs still play a vital part in manufacturing the products, providing spare parts and training dealers' service engineers. To customers, dealers are the OEMs representative; as a result the performance of the dealers can directly make a huge impact on the OEMs reputations, and ultimately the life and death of the OEMs. To evaluate the effectiveness and performance of PSS, and identify areas to improve, the performances of both products and services have been evaluated.

4.2 Being Competitive in the real world

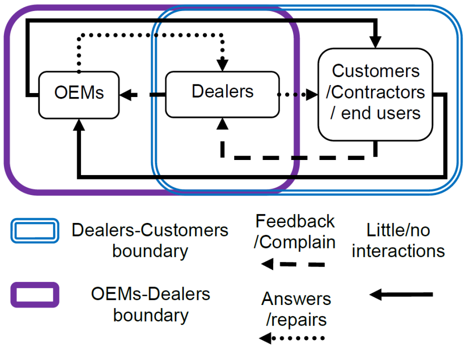

Figure 2 - Typical OEMs, dealers and customers relationship.

High product performance is a very important factor to satisfy the customers' needs. Irvine Alpert, the executive vice president of Onvia, an American government business intelligence company, said it is critical to have an ongoing program that gathers customer value and satisfaction data, in order to manage a sustainable competitive advantage [19]. Joanne Costin, the founder of Costin Custom Communications, a marketing / public relations company, suggested conventional wisdom holds that one unhappy customer tells ten to fifteen others whereas one happy customer only tells five [20]. This confirms ACS's claims [10], known as "word of mouth communication". Within a PSS, service is generally delivered as a form of after sales service, which can be useful for capturing service feedback from customers. Mary Amon, controller of Fillmore Equipment, suggested that feedback gives opportunities to respond to issues that might otherwise not get resolved and turn bad situations into good [20]. Most customer surveys by dealers/OEMs give their customers an opportunity to voice complaints and make suggestions on both products and services. It is an effective but simple idea to gain valuable information for planning strategic goals, yet it is not common practice across industry. Mary Szabo, program manager for Napervill-based Strategic Feedback, a research firm specializing in CS research for dealerships, suggests some dealers/OEMs simply do not want to know how they are doing at the customers' end [20]. Al Morgan, president of Morgan Business Associates, a consulting and training firm, says dealers are just too occupied to spend their resources collecting and processing customer feedback [20]. Although some dealers like Wilson Equipment Co, do commit resources to their feedback process, too little time is given for analysis. Morgan also suggested that the rate of customers moving to competitors should not be neglected, as he estimated that dealers lose about 10% of customers per year, of which 65% left due to CS related reasons [20]. Ron Slee, the president of R.J. Slee & Associates, suggested that a company's ability to make profit will be short-lived unless it provides CS [21]. He also suggested that satisfaction can be measured through several approaches; the change of sales from one period to another, survey format to customers or measuring both parts and service markets capture rates [21].

Leigh Condon, chairman and founder of Strategic Feedback, encourages dealers to create a culture to actively respond to both positive and negative comments made by customers [20]. Furthermore, the collected results should be compared to external data. OEMs and dealers can then assess their performance against the rest of the market to increase their competitiveness [20].

The parts and service department of Nortrax, North America's largest dealer for John Deere, was announced by Strategic Feedback to be the 2010 dealers of the year for outstanding Customer Satisfaction. Bill Pyles, the vice president of service for Nortrax in North America, says they measure company response time to fulfil customer requests as a metric to determine CS. Randy Woodford, a service manager with 35 years' experience, believes the attitude of sincerely caring about customers' problems, allow customers to know that their needs are being taken care of. It is also Nortrax's policy that negative comments are sent to the related branch and contact is made with the customer within 48 hours. Mistakes will be made no matter how much preparation has been done, but the difference is that mistakes will be attended to and fixed immediately [22].

4.3 Customer Loyalty

For Barry Himmel, the senior vice president for Signature Worldwide, a service consultant company for the equipment industry, knowing whether a customers is satisfied or not is only the first step towards a larger goal; customer loyalty [24]. New customer behaviour research proves that customers who are merely satisfied are not necessarily loyal. Kristin Rockwood, director of sales of Strategic Feedback, expressed customer experience as the building blocks towards loyalty. As Ron Slee suggested earlier, customer survey is a common tool used by companies to assess their customers' satisfaction

Dimensions	Descriptions
Responsiveness	Up-to-date important information accessible by customer contact personnel, to be reactive to customers' needs.
Price	Matrix pricing, price accounting to the tasks' complexity, skill and tools requirements.
Availability	Parts availability and service capacity to customer needs.
Consistency	Same level of service exhibited by all providers at all times
Quality	A promise of workmanship that exceeds the guarantee of warranties.

Table 2 - Customers' interests (Product Support Opportunities Handbook). [23]

level in their product and service, yet research shows that typically 85% of respondents say they are simply "somewhat satisfied" or "completely satisfied", so is this a cause for celebration [24]? What are the 15% of dissatisfied respondents, dissatisfied with? Are these reasons to be dissatisfied contagious and can they spread to the other 85%? Does this mean that the 85% partially satisfied respondents will remain loyal or will move onto competitors, based on comments from their friends, i.e. the world-of-mouth communication? Can customers who stay loyal to the brand and are not moved by others' comments, be seen as above satisfaction, and in total contentment? The rest of this paper will focus on the clarification of this level of absolute customer loyalty.

The Product Support Opportunities Handbooks published by the Association of Leaders in Equipment Distribution (AED), uses statistics of contractors' buying patterns, generated via research-based methods every year. In its 2001 and 2007 (Table 2) versions, it states that customers are interested in five dimensions of excellence from OEMs and service providers: price, responsiveness, price, consistency and quality [23].

5 THE REQUIREMENT FOR A SATISFACTIOM BASED FRAMEWORK

General PSS is a system that includes and integrates products, services, support networks and the necessary infrastructure to offer services such as maintenance, recycling, recovering and software/hardware update [25]. Both elements, products and services, must synchronize in harmony with each other to create successful relationships. End-users (e.g. customers) experience both the performance of the products and the quality of the services. Hence understanding the state of "**total contentment**", would allow companies to: 1. Evaluate products and services in real life scenarios. 2. Evaluate the performance of service providers and the quality of their services. 3. Assess the harmony between the product and service and hence determine the flexibility of the service package being delivered according to actual product conditions.

According to academic literature, to find the best performing products and the best delivery services model to follow, three elements have to measured together; service quality, satisfaction and behavioural intention.

5.1 The Product and Service Attributes

Academia and industry agree on a number of issues relating to CS. However, there are other views on which they appear to disagree. These are now discussed and evaluated further, to determine whether they are valid for the framework.

The effect of "**Word-of-mouth**" has been discussed previously by both Academics and Industrialists. It defines customers' expectations, and is agreed to be an important factor to determine how well the product and service satisfy customers. "**Personal needs**", "are conditions or states necessary to customers' physical and psychological well-beings" [26]. Industry interrupts this dimension as "**Availability**", which does not only include the availability of parts and service engineers, but also other items such as information that enables the further clarification for the internal understanding of requests from customers [23]. Academics and industrialists agree on the importance of knowing customers' experience and meeting their needs and both agree that this cannot be neglected as it has consequences on levels of expectation from the service and customer retention,

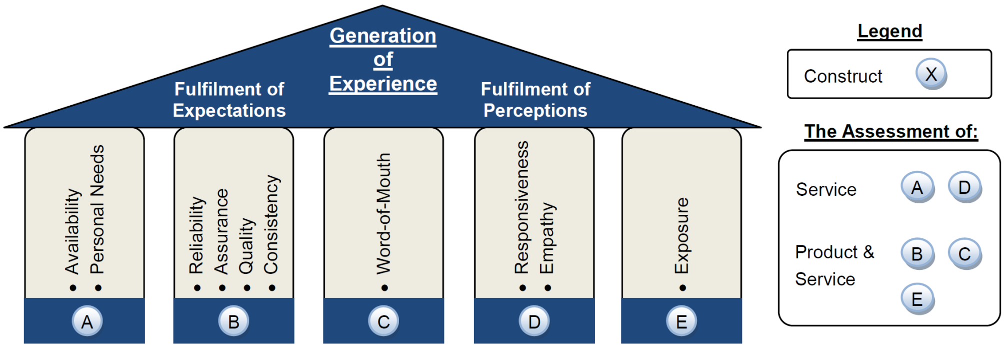

Figure 3 - The Conceptual Framework.

Mont also suggested that one of the main goals of PSS should be satisfying customer needs [27].

The two sets of dimensions that were identified by the product support opportunities handbook and ACS contain the determinants from both views, used by customers on service quality that are similar to each other. Although, both mentioned "**Responsiveness**", this was interpreted differently. One describes it as speed in resolving customers' problem, with willingness and readiness to match customers' needs, e.g. scheduling service time [8][10]. Ron Slee, also mentioned the internal responsiveness by the service providers or OEMs, e.g. a system that records and communicates all customers' related histories [23], in order to respond to the specific individual needs and expectations. The handbook identified "**Quality**" (Table 2) which can be expressed as the reliability and the integrity of the work completed, and should be guaranteed for its acceptable lifespan. "**Assurance**" is described as trust and confidence of the customers in their service provider that the service quality would be delivered. With this similarity, these two views can be categorized under the same umbrella. Furthermore, "**Reliability**" can fall into this umbrella, as well as the "**Consistency**" (Table 2) which means that a stable and non-fluctuating level of service performance will be exhibited by the provider to all customers, whereas "**Reliability**" is defined as performing the service dependably and accurately. However if the assumption of the level of service to be delivered is at an acceptable level, and with a high level of repeatability, these three dimensions can be classified as one construct in the framework.

Taking the dealer of the year, Nortrax, who focused on sense of urgency with a high level of care. This is very similar to the servqual's dimensions of "**Empathy**" and "**Responsiveness**", which require a devotion and sense of urgency towards matching customers' needs. Hence these dimensions should be considered in one construct.

The final construct for the framework comes from a view expressed by industry only. This was suggested by Leigh from Strategic, the exact level of service may not be assessed simply by comparing results with internal data. Comparison also needs to be made with the performance of other competitors. This framework construct will be called "**Comparison**".

Competitive pricing is a weapon used by industry to win business from their competitors. The Product Support Opportunities Handbook puts "**Price**" as one of the most common customers' interests for both products and services, however Ron Slee suggests that customers are beginning to put responsiveness before price. What customers are looking for are not just low prices, but a fixed quote before any product or service is to be sold or delivered. Hence price does not fit well into the main purpose and approach of the framework.

"**Tangible**" is defined as the physical facilities and equipment availability, the appearance of staff, and the ease to understand communication materials [8][10]. Barry from Signature Worldwide mentioned not only the physical appearances of the staff and the company, but also the exposure of the service and the system used to offer it. This part of the dimension also includes some elements of implicit and explicit service communications, but these have already been included and classed with four other elements, therefore, a new construct should be created and named as "**Exposure".**

6 THE CONCEPTUAL FRAMEWORK

A conceptual framework was put together using the constructs created in the previous section. The framework, Figure 3, is designed to allow OEMs or service providers to use as a guideline to identify the best practice being delivered to the customers, which results in the generation of positive experience and fulfilment of both expectation and perception, hence the outcome of full loyalty and total contentment from customers. The pillars represent the construct categories created earlier in this paper. The framework is not a satisfaction capturing tool, but rather a manual to put such a tool together for capturing vital information to identify the contentment level of the customers. The framework can be adapted into a number of different survey forms, including face-to-face interview, self-completion, telephone or web-based questionnaire. Alternatively a customer panel can be adapted to better suit the business culture of particular OEMs or service providers. A customer panel is a group of customers of a particular product or service, representing the entire customer population. Each construct is designed to capture the information for assessing either or both product and service. Therefore no matter which method is used, the format should remain the same. As mentioned, the identification of customers' expectations and perceptions are most important, as these provide a baseline for CS and the generation of negative or positive experience for each construct. Some constructs may identify a mixed generation of positive and negative experience, so it is critical for the OEMs or service providers to review the constructs results individually for each particular customer. These constructs do not have direct relationships with each other, hence they should each be treated as separate categories. The information generated should help the OEMs and service providers to access the quality of the service and product used by users with various backgrounds.

7 DISCUSSION AND CONCLUSION

This paper has discussed and compared the views of both heavy equipment industry and academia on identification and assessment of CS within industry. The importance of some elements of the subject was agreed by both parties, however there are few points on which both parties do not necessarily agree or which they were interpreted differently. It was discovered that merely assessing the level of satisfaction does not fully reflect the population's expectation and perception, but customer loyalty to the brand is a gesture of total contentment with their experience.

The conceptual framework created in this paper is designed to provide guidelines for OEMs or service providers in creating tools or methods for capturing information and practice which will result in total contentment from customers toward the particular product or service they receive. This framework does not offer solutions to increase CS or contentment levels directly, but heavily depends on the users to fully utilise the captured and categorised information.

8 ACKNOWLEDGMENTS

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APPENDIX W AN ECO-APPROACH TO OPTIMISE FUEL EFFICIENCY AND PRODUCTIVITY A HYDRAULIC EXCAVATOR (PAPER 2 - PUBLISHED)

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Abstract

The depletion of fossil fuel and the ozone layer has been a global concern for decades. The International Organization for Standardization has published earth-moving machine sustainability standards for the industry to provide information to satisfy their customers' interests in their construction projects. Furthermore, steeply rising energy prices and the collapse of financial institutions in recent years have sparked demand for ways to improve individual energy efficiency.

Original equipment manufacturers of earth-moving machines must address sustainability requirements, as well as remaining competitive and they aim to do this by improving machine efficiency, adopting advanced fleet management systems, providing operator training courses etc. Clearly high fuel efficiency is important to reduce depletion of fossil fuels and damage to the environment. However, the objectives of achieving the highest possible productivity (m3/h) and improving fuel efficiency (kg/l) are often considered separately. Many equations have been formulated to measure a machine's highest possible productivity level, yet there is a lack of consensus between academia and industry sources on the terms which should be considered within such equations.

Perhaps more importantly, none have explicitly considered the relationship between fuel efficiency and productivity, and only scant consideration is given to the role of operators in achieving optimum productivity for fuel efficiency. Therefore, this paper presents an eco-approach to enable operators to achieve optimal productivity for fuel efficiency of a hydraulic excavator. Hydraulic excavators are primarily designed for excavating with a bucket. Their ease of use, versatility and high productivity have won them major segments of the construction equipment market, therefore the focus on hydraulic exactors in this paper is justifiable. The research presented in this paper has adopted an applied research methodology to collect measurable, empirical evidence through scientific experiments in order to test several hypotheses that focus on the reduction of GHG produced by construction machines. The research has examined two variables, engine speed and bucket cut depth, to determine their effects on productivity and fuel efficiency of a hydraulic excavator. The experimental results show that the combinations of various engine speed settings and bucket cut depths can increase productivity by 30% and cut greenhouse gas emissions by 24%, consequentially moving 62% more spoil every hour for every litre of fuel consumed. The results also suggest that identifying the correct bucket cut depth is the key to significant improvements in productivity and reduction in greenhouse gas emissions. The paper therefore concludes that adoption of an appropriate construction machine operation style can help reduce the greenhouse gas emissions associated with hydraulic excavators. Hence, educating operators to select the right engine speed and bucket cut depth is a cost effective approach to lowering the operational costs and carbon emissions through lower fuel consumption and greater machine longevity.

Keywords

Hydraulic Excavator, Productivity, Fuel Efficiency, Engine RPM, Bucket Cut Depth, GHG Emissions

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An eco-approach to optimise efficiency and productivity of a hydraulic excavator

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ABSTRACT

The depletion of fossil fuel and the ozone layer has been a global concern for decades. The International Organization for Standardization has published earth-moving machine sustainability standards for the industry to provide information to satisfy their customers' interests in their construction projects. Furthermore, steeply rising energy prices and the collapse of financial institutions in recent years have sparked demand for ways to improve individual energy efficiency. Original equipment manufacturers of earth-moving machines must address sustainability requirements, as well as remaining competitive and they aim to do this by improving machine efficiency, adopting advanced fleet management systems, providing operator training courses etc. Clearly high fuel efficiency is important to reduce depletion of fossil fuels and damage to the environment. However, the objectives of achieving the highest possible productivity (m^3/h) and improving fuel efficiency (kg/l) are often considered separately. Many equations have been formulated to measure a machine's highest possible productivity level, yet there is a lack of consensus between academia and industry sources on the terms which should be considered within such equations. Perhaps more importantly, none have explicitly considered the relationship between fuel efficiency and productivity, and only scant consideration is given to the role of operators in achieving optimum productivity for fuel efficiency. Therefore, this paper presents an eco-approach to enable operators to achieve optimal productivity for fuel efficiency of a hydraulic excavator. Hydraulic excavators are primarily designed for excavating with a bucket. Their ease of use, versatility and high productivity have won them major segments of the construction equipment market, therefore the focus on hydraulic exactors in this paper is justifiable. The research presented in this paper has adopted an applied research methodology to collect measurable, empirical evidence through scientific experiments in order to test several hypotheses that focus on the reduction of GHG produced by construction machines. The research has examined two variables, engine speed and bucket cut depth, to determine their effects on productivity and fuel efficiency of a hydraulic excavator. The experimental results show that the combinations of various engine speed settings and bucket cut depths can increase productivity by 30% and cut greenhouse gas emissions by 24%, consequentially moving 62% more spoil every hour for every litre of fuel consumed. The results also suggest that identifying the correct bucket cut depth is the key to significant improvements in productivity and reduction in greenhouse gas emissions. The paper therefore concludes that adoption of an appropriate construction machine operation style can help reduce the greenhouse gas emissions associated with hydraulic excavators. Hence, educating operators to select the right engine speed and bucket cut depth is a cost effective approach to lowering the operational costs and carbon emissions through lower fuel consumption and greater machine longevity.

Abbreviation: BCD, Bucket Cut Depth; BS, British Standards; CAT, Caterpillar Incorporated; CECE, Committee for European Construction Equipment; CH_4, Methane; DECC, Department of Energy and Climate Change; DEF, Diesel Exhaust Fluid; DEFRA, The Department for Environment Food & Rural Affairs; DPF, Diesel Particular Filter; EngD, Engineering Doctorate; GHG, Green House Gas; ISO, International Standard Organisation; JCB, J. C. Bamford Excavators Limited; KOM, Komatsu Limited; N_2O, Nitrous Oxide; NRMM, Non-Road Mobile Machinery; ODP, Ozone Layer Depletion; OEM, Original Equipment Manufacturer; PAR, Performance Ability Ratio; RPM, Revolutions Per Minute; SAE, Society of Automotive Engineers.

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Nomenclature

Descriptions/symbols & SI unit

Energy Consumption (E_{con})	kWh
Fuel Efficiency	kg/l
Productivity	m^3/h
Task Efficiency	kg/l
Density (P)	kg/m^3
Lower Heating Value	kJ/kg
Energy Consumption	kWh
Productivity	m^3/h
V_{cece}	m^3
$t^{exc}{}_{th,\ x}$	min
Fuel Consumption Rate	l/h

1. Introduction

Under the climate change Act (2008), a target has been set for the UK to reduce at least 80% of its Green House Gas (GHG) emission level in 1990 by 2050. 7% and 8% of the total GHG emissions come from non-road mobile machinery (NRMM) within the business and agriculture sectors respectively (Grummer et al., 2013). The Department of Energy and Climate Change (DECC) claims about 33% of total CO_2 emissions in England are from on-site construction activities (Green Construction Board, 2010), of which 26% of total carbon emissions are due to plant and equipment use such as excavators or backhoe loaders (Chiang et al., 2014). These emissions pollute the environment and have impact on acidification and ozone layer depletion (ODP) (Elduque et al., 2014), and correspondingly are harmful to people (Zhang et al., 2014). Among construction machines, excavators are used extensively within the UK construction industry, due to their ease of use, versatility and high productivity, compared to other construction machines (Edwards et al., 2001). Under the European Commission directive 2012/46/EU, NRMM OEMs are under constant pressure to reduce GHG emissions, yet the pressure to maximise excavator productivity has also increased (Patel et al., 2001). This is due, at least in part, to fuel duty increases: the price of red diesel (a low tax fuel for registered agricultural and construction vehicles) rose from £0.55 per litre (in 2010) to £0.70 per litre (in 2013) (Agriculture and Horticulture Development Board, 2013). Excavator operators therefore have a dual challenge, firstly to lower fuel consumption in order to reduce cost, but without compromising machine productivity (m^3/h), and secondly, to reduce fuel consumption such that GHG emissions will be reduced.

Most OEMs offer a range of machine modes on their machines to suit various task specifications (referred to hereafter as duties). A duty is a task which operators have to perform, such as tracking, trenching and loading (for example, an excavator can undertake over 15 different duties). A machine mode is designed to give customers and machines greater flexibility to deal with the challenges which commonly occur when performing various duties such as saving time, reducing fuel consumption or breaking through hard materials. However, such modes could be seen as restrictive to operators who have sufficient experience and expertise to manually adjust machine settings to optimise productivity and fuel efficiency.

The challenge of increasing excavator productivity while minimising fuel use is of growing importance for both industry and academic research. Tam attempted to use artificial neural networks to develop a quantitative model for predicting productivity (Tam et al., 2002). It is also important to the UK to reduce GHG emissions (Mao et al. 2014). The need to better understand the nature of productivity related to fuel consumption in this specific context is critically important. Therefore, this paper investigates a novel, eco-approach specifically for operators to optimise productivity and fuel efficiency whilst operating a hydraulic excavator. A new, and important, variable, bucket cut depth (BCD), has been used in this research as a result of the recommendations from industries and academics mentioned in Sections 2,3 and 4. In previous studies BCD has been treated as a constant (rather than variable) value, and its influences on the optimisation of productivity and fuel efficiency have rarely been the focus of research within the field. In this research, its influences were tested along with various RPM settings based on industrial standard technical specifications from the International Organization for Standardization (ISO), to determine the practical and scientific importance of BCD to both industry and academia.

2. The determinants of excavator productivity

A general definition of productivity is given by the association of input(s) and output(s) in the particular context, i.e. productivity = output/input, and this is the common formula adopted within the industry (Park, 2006). In the context of excavators, output has often been quantified in terms of the materials handled by machines; e.g. volume of spoil moved per operator-hour (Elazouni and Basha, 1996), or volumetric capacity of the bucket (Solazzi, 2010). This simplistic interpretation has been explored and expanded in various research projects reported in the literature and in practice, so this section explores some of the key factors that appear to determine the productivity of hydraulic excavators.

As stated in the International Organisation for Standardization's Technical Specification 11,152, earth-moving machinery — energy use test methods (ISO/TS 11,152), cycle time is defined as the amount of time it takes a machine to perform a repetitive segment of an operation, typically measured as the time it takes a machine to return to the same position (ISO, 2012). The fastest achievable cycle time of an excavator is arguably the most meaningful indicator of machine productivity for a given duty, but prediction is difficult and results may therefore be inaccurate. First, in a study of observed performance of construction equipment working in Egypt, Elazouni (Elazouni and Basha, 1996) concluded that two groups of issues affect productivity, i.e. identifiable or undetectable factors. The former are detectable before the duty starts and thus a planner could plan ahead to counteract the effects that may have a negative impact on productivity (e.g. soil/ground conditions, work-space restrictions and hauling distance). In contrast, undetectable factors do not emerge until the duty has commenced (e.g. weather conditions, site management effectiveness and downtime) (Elazouni and Basha, 1996). Cycle time (in seconds) was considered to be an important unit in the measurement of productivity factors, but to fully account for these factors, a performance ability ratio (PAR) value was introduced, which is the ratio of the predicted productivity to the actual productivity, in order to judge the effect of the operator on productivity (Alfeld, 1988).

An alternative approach, based on data from machine performance handbooks from OEMs, was taken by Edwards and Holt (Edwards and Holt, 2000), who developed a productivity prediction model, ESTIVATE, which estimates excavation cost, based on the given cycle time (cycle/h) and productivity (m^3/h) of the excavator. Unlike the model of Elazouni (Elazouni and Basha, 1996), the cycle times were derived from OEM performance handbooks (notwithstanding criticisms of the accuracy of such data) (Lambropoulos et al., 1996), and a multiple regression equation was used.

$$Y = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n \quad (1)$$

Y is the cycle time under the influence of β
β is the partial regression coefficient, which varies with x
x is the particular independent variable

Based on previous work (Edwards and Holt, 2000) and evidence from OEM performance handbooks to support the significant relationship that these variables have with cycle time, three independent variables (x) were selected (machine slew angle, digging depth and machine weight) to model the dependent variable, cycle time (Y). Two further variables, excavation materials and site obstructions, were also used to estimate the maximum and minimum cycle times.

The effect of bucket capacity is also commonly considered in research on excavator productivity (Schabowicz and Hola, 2007). Panas and Pantouvakis (Panas and Pantouvakis, 2010) identified a number of operational coefficients, such as dig depth, slew angles, bucket capacity and machine weight and used data from a construction site to develop a cost prediction system. Interestingly, this included a value for the power requirement by the excavator to overcome the resistance of the dig (Lambropoulos et al., 1996), but understanding the optimum relationship between bucket characteristics and output is difficult. Different rated bucket capacity (heaped) definitions can affect the estimation of the total volume of material being collected by the same bucket. This is critical, as international standards, such as SAE (Society of Automotive Engineers), SAE J2754-2007 and BS (British Standard), BS 6422:1983, as shown in Fig. 1, examples of various industrial standards definitions of heaped angles, have defined the angles differently and these have since been adopted within different countries. In the research reported in this paper BS 6422:1983 has been adopted.

Although some think that it is good for productivity if peak volumetric fill is always achieved, others disagree, suggesting that to minimise cycle time operators tend to fill the bucket to only 80% of capacity which results in more passes than would be required if the bucket was always filled to 100% (Fiscor, 2007). Spinelli et al. (2009) points to the "Piece-Size Law" to show that productivity increases at a decreasing rate with the increase of the piece size, up to the optimum (Spinelli et al., 2009). Yet as piece size increases beyond the optimum, productivity will fall as the demand on the machine will increase due to the weight of the load. The productivity value therefore exhibits a parabolic behaviour against piece size (m^3), see Fig. 2, the piece-size law. However, the graph assumes maximum engine and pump output, and overlooks additional fuel consumed as a result, so this approach is arguably flawed in both cost and environmental terms.

Indeed, fuel efficiency is the third and final point to cover here. Elton and Book (2010) defined fuel efficiency as a measure of how much fuel a machine uses to complete a certain task, which can be treated as a way to measure task efficiency (Elton and Book, 2010). Task efficiency is the measure of input required to achieve a particular amount of output. In this experiment, task efficiency is measured as the amount of soil moved per unit of fuel (kg/l) (Elton and Book, 2011).

Fuel consumption of a diesel engine is determined mainly by engine torque and RPM settings at a given time, a certain amount of fuel is injected into the combustion chamber for combustion, hence the higher the RPM setting is the greater the amount of fuel that will be consumed. The Department for Environment Food & Rural Affairs (DEFRA) stated that every litre of diesel fuel combusted will produce 2.67 kg CO_2e GHG emission, hence the more fuel consumed the more GHG emission will be produced. Fig. 3 shows an example of an engine fuel map (Miller, 2010); note that the lowest RPM does not necessarily give the lowest fuel consumption. RPM is often set to its maximum level and changes rarely throughout jobs, as high RPM will speed the machine up, complete the job more quickly and provide sufficient hydraulic power for most duties, however more fuel will be burnt as a result.

Under the Companies Act 2006 (Strategic Report and Directors' Report) Regulations 2013, UK companies are required to report their GHG emissions. DEFRA have derived GHG conversion factors to quantify GHG emissions such as CO_2 (kgCO_2/litre), CH_4 (kg CO_2e/litre) and N_2O (kg CO_2e/litre) produced from combusting various fuel types (Hill et al., 2012).

Gazi et al. (2012) claims that the environmental impact of GHG that is generated by diesel fuel, with the exception of CO_2, is less than 1% of the total amount of GHG generated. The total CO_2 emissions of a certain amount of work done can be found by (Gazi et al., 2012):

$$CO_{2\text{emission}} = E_{CO_2} \times (3600 \times n_{th} \times E_{con}/p \times LHV) \quad (2)$$

(E_{CO_2}) is the diesel combustion CO_2 emission factor
(n_{th}) is the thermal efficiency of machine
(E_{con}) is the energy consumption over certain work done (kWh)

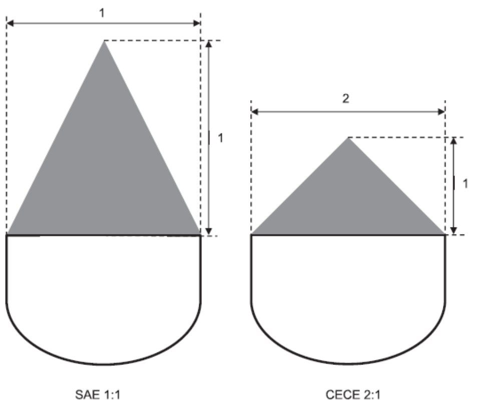

Fig. 1. Examples of various industrial standards definitions on heaped angles.

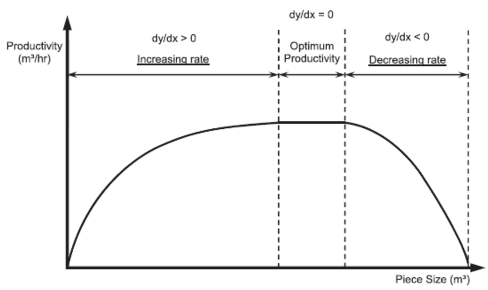

Fig. 2. The piece-size law.

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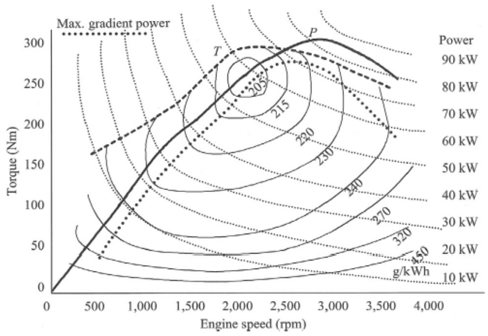

Fig. 3. Engine fuel map.

(P) is the density of diesel fuel (kg/m^3)
(LHV) is the lower heating value of diesel fuel (kJ/kg)

As stated in Fig. 3, engine fuel map, engine torque has a direct influence on how much fuel is consumed. The engine torque value can vary dramatically for an excavator when performing any particular duty. This is due to the excavatability of the materials being extracted, i.e. the resistance force being exerted on the bucket at a given time. The hydraulic pumps will need to provide varying degrees of hydraulic fluid volumetric flows and pressure to the rams to generate the necessary force to extend and retract the bucket, dipper arm and the boom against a given load, hence torque can vary. The highest pressure experienced during a trenching duty is when the bucket is forced into the ground, dragged towards the machine and breaks through the surface (Ng, 2012), as shown in Fig. 4, engine torque behaviour during trenching. As the pump is working harder to generate the pressure that is needed, the engine will equally need to consume more fuel to generate the torque in order to support the pump.

3. How the OEM industry determines productivity

Having identified some key determinants of excavator productivity and overviewed the nature of the relationships between them, it is now pertinent to consider how OEMs interpret these parameters and communicate what they see as optimum fuel saving productivity to their customers and operators. Some industry bodies have attempted to model excavator productivity, and thus synthesise the factors described in the previous section. For instance, in 1983, the Central Association of the German Building Sector (Zentralverband des Deutschen Baugewerbes) and the German Federation of the Construction Industry (Hauptverband der Deutschen Bauindustrie) published the BML handbook (Handbuch BML: Daten für die Berechnung von Baumaschinen-Leistungen) (Zentralverband des Deutschen Baugewerbes (Central Association of the German Building Sector), Hauptverband der Deutschen Bauindustrie (German Federation of the Construction Industry), 1983), which suggests the following to calculate the hourly productivity of a fleet of excavators ($Q^{exc}{}_{eff,BML}$), in units of (m^3/h):

$$Q^{exc}{}_{eff,BML} = 60 \times n_{exc} \times \left(V_{cece} \times f_{fill}\right) \Big/ t^{exc}{}_{th,BML} \times f_{swing} \times f_{depth} \times f_E \qquad (3)$$

(n_{exc}) [−] is the number of the excavators within the fleet
(V_{cece}) [m^3] is the rated capacity (heaped), which dictates the height of the piled material. Different OEMs have adopted a standard defined by the Committee for European Construction Equipment (CECE), to determine heaped angle ratio, which dictates the height of the piled material as shown in Fig. 1, examples of various industrial standards definitions on heaped angles.
(f_{fill}) [−] is the coefficient which describes the actual volumetric coverage of the spoil to the buckets' nominal capacity.
($t^{exc}{}_{th,\,x}$) [min] is the theoretical cycle time of a given excavator (this will vary according to engine size and weight), based on the bucket's nominal capacity, soil types and soil excavatability (Panas and Pantouvakis, 2010). The attributes that affect theoretical cycle time (f_{swing} and f_{depth}) are considered separately.
(f_{swing}) [−] as applied in Equation (3), is the slew angle coefficient that describes the amount of rotation of a hydraulic excavator above the tracks or wheels, involved in a duty, as shown in Equation (4). Based on OEMs performance handbooks, it is accepted that the larger the slew angle is, the longer it will take the excavator to complete the task. BML specified two coefficients representing the fixed slew angles of 45° and 180°.

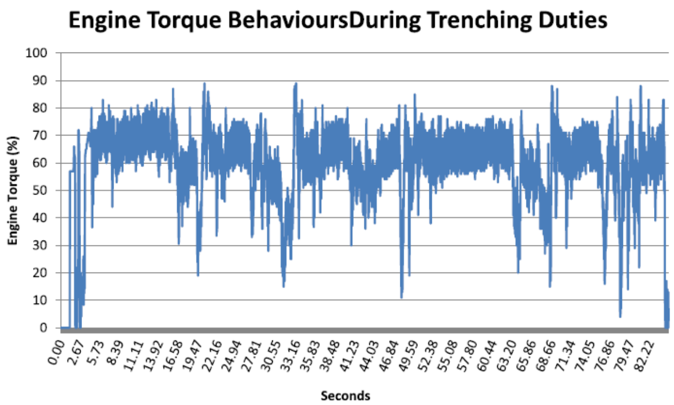

Fig. 4. Engine torque behaviour during trenching.

Similarly Komatsu Ltd. calculated a 3–6 s difference between the two slew coefficients (Komatsu Limited, 2009); Caterpillar Inc. quantified five sets of slew angles for their cycle time scale (Caterpillar Inc, 2011).

$$f_{swing} \approx 1.754 \times a^{-0.1258} \quad (a \in [45^\circ, 180^\circ]) \tag{4}$$

(f_{depth}) [−], digging depth coefficient describes a proportion of the maximum vertical distance that the bucket can reach below the horizontal line of the tracks/wheels. Here, excavatability is described in terms of the properties of the excavated material and the vertical distance (h_d), the latter of which can affect productivity by 20% in extreme cases (Panas and Pantouvakis, 2010). OEMs often interpret (f_{depth}) as a percentage.

(f_E) [min/min] is the efficiency coefficient. It is a factor that indicates the proportion of the hour that the excavator has worked. The factor is calculated by the following equation;

$$f_E = (60\ \text{minutes} - \text{Stoppage Time})/60\ \text{minutes} \tag{5}$$

Equation (3) is helpful, but in the intervening 30 years since its publication, most OEMs have used the above to derive their own, broadly similar, ways of quantifying excavator productivity. Equation (6) (Caterpillar Inc, 2011), Equation (7) (Komatsu Limited, 2009) and Equation (8) (J C Bamford Excavators Limited, 2007) are examples of productivity equations used by the leading global OEMs within the industry:

$$Q^{exc}{}_{\text{eff,CAT}} = 60 \times n_{\text{exc}} \times \left(V_{\text{cece}} \times f_{\text{fill}}\right) \Big/ \left(t^{exc}{}_{\text{th,CAT}} \times f_{\text{con}}\right) \times f_E \tag{6}$$

$$Q^{exc}{}_{\text{eff,KOM}} = 60 \times n_{\text{exc}} \times \left(V_{\text{SAE}} \times f_{\text{fill}}\right) \Big/ \left(t^{exc}{}_{\text{th,KOM}} \times f_{\text{con}}\right) \times f_E \tag{7}$$

$$Q^{exc}{}_{\text{eff,JCB}} = \left(V_{\text{SAE}} \times f_{\text{fill}} \times t^{exc}{}_{\text{th,JCB}} \times f_E\right) \Big/ f_{\text{con}} \tag{8}$$

The key difference between these equations and the BML Equation (3) (Zentralverband des Deutschen Baugewerbes (Central Association of the German Building Sector), Hauptverband der Deutschen Bauindustrie (German Federation of the Construction Industry), 1983) is that in Equations (6)–(8) a conversion coefficient (f_{con}) has been included, however each OEMs defines their factor in a different manner:

- Caterpillar Inc. includes operator skill/efficiency coefficient and machine availability;
- Komatsu Ltd. includes a percentage of the actual dig depth against the maximum with the dump conditions; and,
- J C Bamford Ltd. includes a percentage of actual dig depth against the maximum with the swing angle.

4. The relationship between fuel consumption and productivity

All of the above OEM equations for productivity and much of the related academic research essentially appear to be grounded in temporal (i.e. rate of excavation) and volumetric (i.e. bucket capacity) constructs. Exploration of other factors appears limited; for example only one of the equations above includes an explicit coefficient for operator behaviour. Moreover, most academic research in this area appears to have been conducted under the assumption that the machine will be set to perform at its maximum capability, however, as explained earlier, under such conditions, more fuel will be consumed and GHG emissions will be generated at the peak rate, which in most cases will add unnecessary cost and emissions to the environment. Furthermore, overloading (or peaking out) the engine will only expose the engine and the structure to unnecessary stress, significantly decreasing components' life expectancy (Doosan Equipment, 2013) and therefore causing further strain on the environment. In addition, the majority of the extant literature on excavator productivity overlooks fuel efficiency as an important component in the perceived productivity of a machine, from the perspective of the operator. The cost of fuel is acknowledged as a concern in the industry (Agriculture and Horticulture Development Board, 2013), hence its omission also seems unwise.

In response to the above, it is therefore appropriate and timely to seek out ways to achieve cleaner productivity, and hence lower GHG emissions. Such an initiative would benefit the user, in terms of lower fuel costs, benefit hire companies, in terms of increased machine longevity, benefit the OEM, in terms of potential competitive advantage and benefit the environment in terms of reducing the total GHG emissions from NRMMs. The need for new methods to aid the selection of an appropriate machine for specific operational parameters has already been identified (Edwards et al., 2001), for example, minimising movement of the excavator and maximising the available tear-out forces (Singh, 1997), i.e. positioning of the excavator, positioning of the dump truck and digging technique. In previous sections, operators are often mentioned to be one of the main influences on productivity and fuel efficiency, and this claim has been further strengthened by the factors used within the productivity equations, such as f_{swing}, f_{depth} etc. These factors are influenced by the operator, and are not controlled by most machine models available on the market, but operators are rarely a research focus for productivity or fuel efficiency improvement. Therefore, there is an incentive to create new ways of understanding that can be easily followed by the operators to achieve the optimal fuel efficiency and productivity.

Operators have always been the key to achieving high productivity and fuel efficiency for different duties. As a result, some OEMs are now offering training programmes to operators to enable them to use machines more efficiently. Most construction machines found working on site are hired by the contractors from a rental company and the contractor's aim will be to complete the job quickly and cheaply (by minimising the fuel and hiring period cost). Therefore some contractors are more willing to hire trained operators in order to reduce total costs. As stated in the Sustainability report in Rental Industry from the European Rental Association, an average of 10%–15% savings on fuel cost can be achieved as a result of these programmes (Aldeano et al., 2012). Volvo Construction Equipment Division states that a well-trained operator can potentially achieve a 5%–25% fuel reduction by adopting an environmentally friendly operating style, such as not over working the engine, without reducing their productivity level (Volvo Construction Equipment Press Information, 2010). Komatsu claims a 23% fuel saving can be achieved by just lowering engine power by 25%. Despite this change, fuel efficiency increases by 14%, which is equivalent to a 23% decrease in fuel consumption as a result, however productivity and cycle time suffered a 12% and 11% decrease respectively (Komatsu Limited, 2009). Hence, although these reports do support the claim that lower fuel consumption results from lower engine speed, the relationship with productivity levels is less well understood.

Based on the previous discussions on key variables related to excavator productivity, the focus of this research is to explore how to jointly improve both fuel efficiency and productivity in hydraulic excavators. An investigation has been conducted to test whether RPM and a new variable, bucket cut depth (BCD – see explanation in following section) have a direct effect on fuel efficiency and productivity of an excavator. The results provide the underpinning performance data for operators to learn how to reduce fuel consumption, whilst maximising productivity, using RPM and BCD as independent variables.

This research aims to answer the following question with a view to developing a better understanding of the variables involved:

4.1. *Do RPM and BCD (as independent variables) have a direct effect on both productivity and fuel efficiency on a hydraulic excavator?*

In order to answer this question, the following research objectives were identified and explored under controlled conditions (as explained in the following section):

1.) To investigate the relationship between RPM, fuel efficiency and productivity.
2.) To investigate the relationship between BCD, fuel efficiency and productivity.
3.) To interrogate the above results and develop a productivity map for a hydraulic excavator under a given set of circumstances.

5. Experimental design

The core parameters and procedures for the experiments conducted in this research were selected in accordance to ISO/TS 11,152, earth-moving machinery – energy use test methods. Most of the variables discussed in Sections 2,3 and 4 for measuring productivity and fuel efficiency will be used. New variables were introduced based on the recommendations stated in previous sections, and detailed explanations can be found in this section. The control of these variables, e.g. swing angle, to ISO standards is extremely important as not only can it affect the outcome of the findings, but it is also essential to ensure the integrity of both the commercial and scientific results provided by this research.

One of the most common duties for excavators was selected, in which spoil has been excavated and placed into a 16 tonnes dump truck. A total of 16 sets of experiments (each of 10 cycles, as determined by the size of the dump truck) were conducted by an experienced operator (with over 25 years of experience), using a 22 tonne class excavator, in the same location and material conditions. Spoil was collected in the dump truck and weighed to quantify the amount of spoil collected by volume and weight. At the end of each 10th cycle, all conditions were reset for the next set of experiments. Each set of experiments was carried out using a different combination of the independent variables. Each set of the experiments was repeated once to obtain an average and to ensure the accuracy of the result. Dependent variables were collected with a stopwatch; videos of the duty were recorded for data validation purposes. Extracted materials were loaded into a dump truck and weighed using calibrated weight pads. Care has been taken that all the experiments were carried out with academic rigour and also, to ensure the findings are suitable for use within commercial contexts, the experiments have been conducted in accordance with ISO/TS 11,152.

5.1. *Independent variables (RPM and BCD)*

To address the issue of buckets being utilised at less than 100% capacity to achieve shorter cycle times (Fiscor, 2007) and to establish whether maximising the bucket capacity in each dig does or does not have a positive effect on productivity (m^3/h), a new factor is introduced here, i.e. bucket cut depth (BCD). This is not the same as (f_{depth}), mentioned previously.

As shown in Fig. 5, side view of a construction bucket, BCD is given as a percentage, between 0% when the bucket is skimming on top of the surface (also known as grading) and 100%, when the bucket is fully dug in. In this case, two cut depths were used, 50% and 100%; the 50% BCD will be described hereafter as BCD_{50}, and the 100% will be shown as BCD_{100}. Both values are used currently in the industry, with 100% being the more common. Furthermore, to ensure that the results reflect only BCD's effects, all other factors shown in Equation (3) had to be controlled and fixed. Hence:

- (n_{exc}) is constant, as the same machine was used throughout the experiment;
- (V_{CECE}) is constant, as the same bucket was used (a general purpose bucket, measuring 1500 mm wide, with 1.19 m^3 capacity);
- (f_{fill}) is constant, as the same material was used throughout the experiment; based on the material properties used, the fill factor should remain between 95% and 110%. The same operator was asked to perform the same duty with the same machine therefore the theoretical cycle time should also remain constant.

Four sets of RPMs were used, based on the findings from previous experimental results (Ng, 2012).

5.2. *Dependent variables (cycle time, fuel consumption and output)*

Cycle time is a basic metric for loading performance, measuring the time taken for an amount of spoil to be moved into a dump truck, by an excavator. The cycle time is defined as the time taken from the start of one cycle to the start of the next (Hall, 2003). The total cycle time for ten cycles was recorded for each RPM setting and BCD.

Fuel consumption is the amount of fuel used, in litres (l), to conduct the required duties within the specific time span. It was measured by an external mechanical fuel meter (JPS engineering FMS 4, 12DC volt.), which is classified as a direct method for fuel flow measurement in ISO/TS 11,152. The fuel consumption was also measured by on-board fuel sensors, taking readings at every 1 s and broadcast onto the excavator's on-board CAN bus network.

Output is the amount of material that is moved within a specific number of cycles, measured in kilograms. The material was loaded into a dump truck and weighed at the end of each 10th cycle.

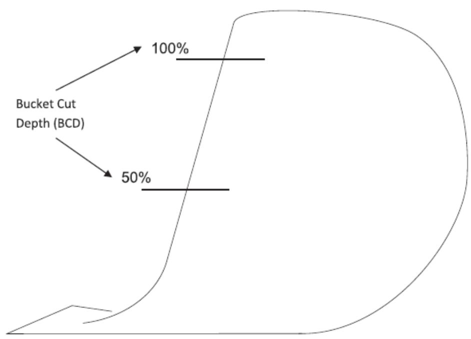

Fig. 5. Side view of a construction bucket.

5.3. Controlled factors (materials, swing and others)

To ensure the repeatability of the experiment, additional parameters were set as constants. Loose dry sand (Caterpillar Inc, 2011) stored in outdoor conditions was used and all experiments were conducted in similar weather conditions to ensure the composition of the material remained within an acceptable tolerance.

The angle of slew was set to 90°, and the excavator slewed only to load material into the dump truck and then returned to the dig area. Other factors such as the excavator, the dump truck, weight pads, operator, hydraulic system temperature, hydraulic oil levels, engine oil levels, digging style and data collection method remained the same throughout.

Further details about the experimental design:

- Swing angle: set to 90° with a tolerance of ±5°; this is due to the nature of loading a dump truck, and is an acceptable practice.
- Dig depths: 100% BCD: 1.317 m, and 0.6585 m for 50% BCD, hence the minimum and maximum f_{depth} will be 10% and 20% respectively. Based on the definition of f_{depth}, no effect will been seen on productivity if the operator is achieving anything less than 40% of the maximum dig depth (Panas and Pantouvakis, 2010).
- Finally (f_E), the efficiency coefficient, will remain as 1, i.e. based on the assumption that each cycle is 100% efficient.
- Therefore, based on the BML productivity formula (Zentralverband des Deutschen Baugewerbes (Central Association of the German Building Sector), Hauptverband der Deutschen Bauindustrie (German Federation of the Construction Industry), 1983) and performance data provided by the OEM, the maximum productivity of the excavator should range between 341.81 m^3/h, and 395.78 m^3/h.

6. Results and analysis

The findings presented here are based on results collected from the experiments conducted as described in Section 5. For commercial reasons, it not possible to present the raw data, therefore all results are expressed in terms of a percentage gain. This allows the authors to present and discuss the results without compromising consistency or revealing commercially sensitive data. Percentage gain is used widely in the industry to describe the amount of fuel saved in vehicles or machines, so this method is deemed to be acceptable.

Table 1 provides an example of how the collected results were recorded. It shows the averaged results of four engine RPM settings and two BCDs.

Some initial analyses can also be found in the table, whereby percentage values are used to clarify the differences between the results. For example, "Percentage gain overall" indicates the amount of gain as a percentage from the least desirable result collected. By selecting RPM as a constant variable, any clear variation in the results between the two BCDs can be observed. The last three values at the bottom of the table show the highest percentage gain among the eight values and the maximum percentage gain for each BCD across the range of RPM used in the experiment. Table 1 is representative of six similar tables that were created, i.e. for: fuel consumption (l), cycle time (s), output (kg), productivity (m^3/h), fuel efficiency (m^3/l) and fuel consumption rate (l/h). The following Sections describe the outcomes of the experiments.

6.1. Engine speed vs. productivity

Fig. 6, the combined effect of bucket dig depths (BCDs) and engine speeds on productivity, shows how the productivity values

Table 1
Results table example.

Fuel Consumption (Litre)		Engine RPM			
		1500	1600	1700	1800
Bucket Cut Depth (BCD)		Seconds			
	BCD_{50}	28	25	24	22
	BCD_{100}	34	30	27	24
		Overall Percentage Gain			
	BCD_{50}	17.65%	26.47%	29.41%	35.29%
	BCD_{100}	0.00%	11.76%	20.59%	29.41%
		Percentage Gain of BCD_{50}			
	BCD_{50}	17.65%	16.67%	11.11%	8.33%
Max. percentage gain between					
Overall		35.29%	BCD_{50}	21.43%	
			BCD_{100}	29.41%	

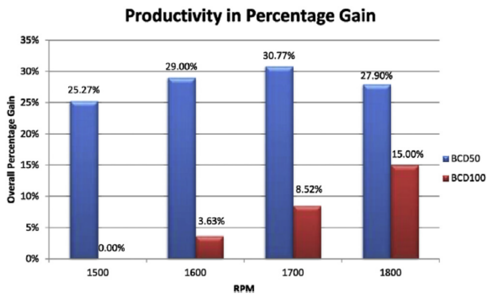

Fig. 6. The combined effect of bucket dig depths (BCDs) and engine speeds on productivity.

measured in m^3/h were generated due to the effect of the two BCDs and four RPM settings.

The four highest productivity values were all achieved by BCD_{50} (50% cut depth), which showed a 25%–30% increase from the lowest recorded productivity achieved at 1500 RPM by BCD_{100}. BCD_{100} achieved a maximum 15% increase at 1800 RPM, and the pattern suggests that its gain would increase with higher RPM. Perhaps of greater significance is that BCD is clearly shown to influence productivity; there is only a 5% fluctuation in productivity rates across the RPM range of BCD_{50}, whereas a much higher, 15%, fluctuation occurred for BCD_{100} (100% fill level). These results indicate that a deep dig with higher RPM does not necessarily give the best productivity rates.

6.2. Fuel efficiency vs. engine speed

As mentioned earlier, fuel efficiency is a measure of how much spoil is removed per unit of fuel (kg/l). Fig. 7, the combined effect of bucket dig depths (BCDs) and engine speeds on fuel efficiency, shows the increases in fuel efficiency compared to the lowest recorded value in this data set, i.e. 1700 RPM for BCD_{100}.

Similar to the findings in ý6.1, the highest fuel efficiency values were achieved by BCD_{50}. Results showed up to 23.5% less fuel consumed for every kg of spoil moved by BCD_{50} at 1600 RPM. However, a much larger variance of 17% in fuel efficiency across the RPM range of BCD_{50} can be observed. A gain of only 5% was observed with BCD_{100} across the four RPM values. Based on this test, working at BCD_{50} continuously shows benefits by reducing the amount of fuel required to complete the job, i.e. it uses less fuel to move a unit amount of material.

6.3. Fuel consumption rate vs. engine speed

Fuel consumption rate (l/h) is often used to measure the fuel efficiency and running cost of any products that are powered by a combustion engine. However this can be misleading. Indeed, Fig. 8, the combined effect of bucket dig depths (BCDs) and engine speeds on fuel consumption rate, shows that BCD_{100} reduced its percentage gain as RPM settings increased, and shows that BCD_{100} recorded the lowest fuel consumption rate. Although the rate is lower with BCD_{100}, if given the time duration period, BCD_{50} would have moved on average 30% more spoil with 26% saving on the cost of labour, machine rental costs and 25% of fuel cost.

If compared to the productivity value calculated earlier based on the productivity formula and data given by the OEM (341.81 m^3/h, to 395.78 m^3/h), the observed values were much lower, i.e. decreases of 19% and 28%, for BCD_{50} and BCD_{100} respectively.

6.4. Output vs. fuel use (m^3/hl)

Compared to the lowest performance, recorded by BCD_{100} at 1600 RPM, Fig. 9, the combined effect of bucket dig depths (BCDs) and engine speeds on spoil moved per hour per litre, shows the percentage gain for amount of spoil moved per hour spent and litres of fuel consumed for the range of RPM used in this paper.

The graph clearly shows BCD_{50} has a major advantage over BCD_{100}. The data are shown in units of (m^3/hl) which combines the importance of both productivity and fuel consumption into a single entity, hence achieving one of the aims of this paper. The results show that BCD_{50} can increase the amount of spoil being moved by 40%–62.9% over BCD_{100}. In industry terms, if a job is required to move 10,000 m^3 of spoil, based on the current red (in the web version) diesel price of £0.70 per litre (Agriculture and Horticulture Development Board, 2013), at a work site operating a 24 h shift, under such conditions if the right RPM and BCD were used, the operator would be able to achieve the same task using 24% less fuel, lower GHG emissions and 11 h faster, thereby saving £140 of fuel (at 2013 prices), without taking into account the savings from labour and machine rental costs.

6.5. (ProductivE+) – A map for cleaner productivity

The next stage is to visually present the data to clearly show the relationships between the independent variables (RPMs and BCDs) and the dependent variables (cycle time, fuel consumption and output). This has been done by combining the results into a map which in future will be referred to as the ProductivE + Map. The

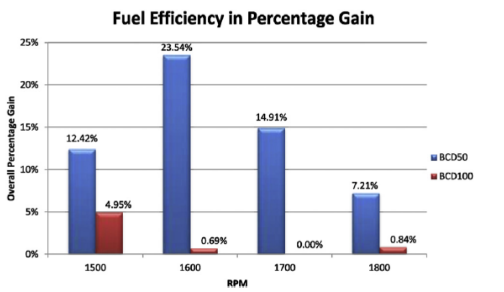

Fig. 7. The combined effect of bucket dig depths (BCDs) and engine speeds on fuel efficiency.

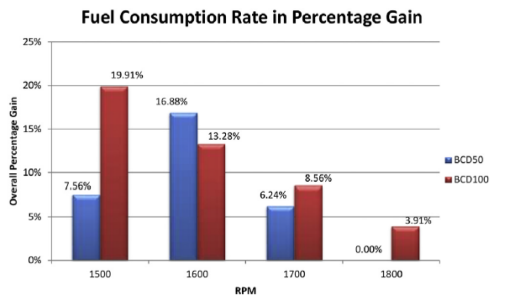

Fig. 8. The combined effect of bucket dig depths (BCDs) and engine speeds on fuel consumption rate.

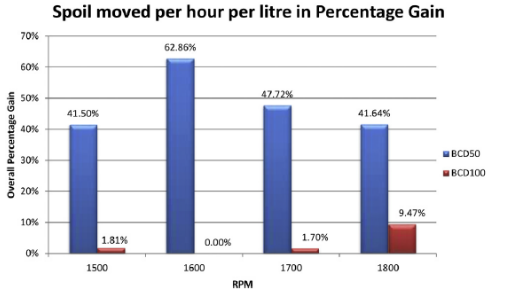

Fig. 9. The combined effect of bucket dig depths (BCDs) and engine speeds on spoil moved per hour per litre.

purpose of synthesising the data is to assist operators, in real-time, to understand that by limiting the machine end speed to a minimum they can cut down fuel consumption and GHG emissions, yet still increase productivity. Fig. 10, the ProductivE + map shows the data in a topographic format, demonstrating the effect of RPMs and BCDs on cycle time, fuel consumption and output.

To simplify the map, cycle time and output were combined into one unit: productivity (m^3/h, which is recognised by both industry and researchers). The fuel consumption pattern is laid over productivity to make clear the unexplored relationship between these variables. RPMs are on the x-axis, BCDs (%) on the y-axis and two variables, fuel consumption (litres) and productivity (m^3/h), on the z-axis. The dependent variables are shown as a percentage gain in 5% intervals. Two different coloured lines in the map describe the behavioural pattern of the dependent variables. Fuel consumption (litres) is represented in blue (in the web version) and productivity (m^3/h) in red.

The purpose of developing a full database from the ProductivE + map is to identify the maximum possible productivity and fuel efficiency of a particular excavator for a particular job and working environment. It is the first step towards the creation of guidelines on how to achieve cleaner productivity which can help operators in selecting the right RPM and use the correct BCD. As mentioned earlier, OEMs are pressured to offer operators more information to use the machine to achieve higher productivity at lower cost, the ProductivE + map will form a critical part of such information. Without the need to always rely on a low emission catalyst such as Diesel Exhaust Fluid (DEF) or technology such as diesel particular filter (DPF), OEMs can configure their machines' fuel and engine speed management system by referencing the particular engine torque map. Aided by torque sensors in the engine, the speed can be automatically adjusted to lower fuel consumption and GHG emission. However results also show operator preference (in terms of BCD level) has a significant impact on productivity level, therefore the ProductivE + map does not only include the engine torque map but also guidelines for the operators to increase productivity and fuel efficiency by using the correct BCD levels. There are third party positioning systems on the market which monitor BCD levels, and such technology can be integrated with the ProductivE + map in order to assist the operators to achieve the highest fuel efficiency, without compromising productivity. ProductivE + can be used as a database to support an automated system built into the excavator. The system could then adjust engine speed and the bucket dig depth when excavating, and by default set the machine to

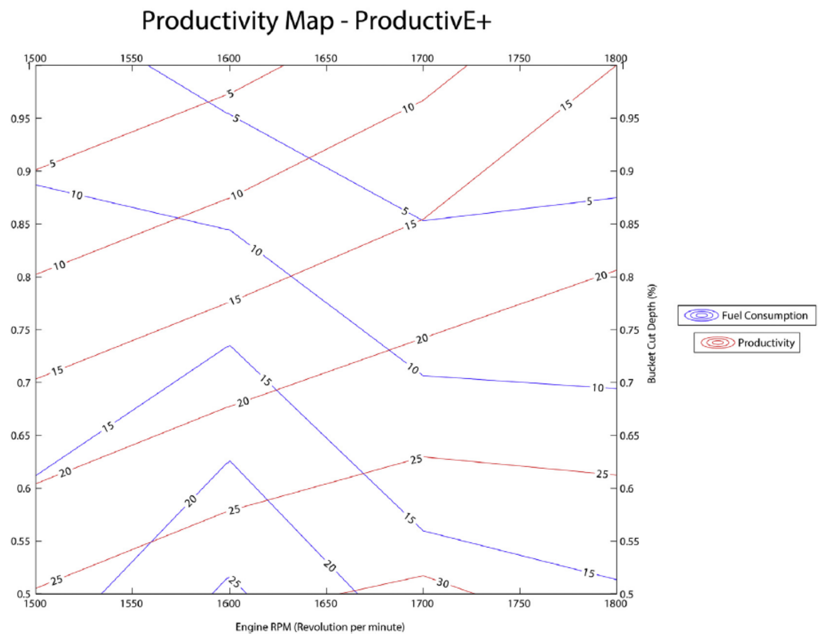

Fig. 10. The ProductivE + map.

1660 RPM and BCD to 50% to achieve the best possible productivity and fuel consumption rate. However, the operator should also be given the opportunity to use their judgement and experience and therefore should be given the option to shift the focus to either low fuel consumption or high productivity without compromising hugely on each other. This approach in using technologies for cleaner environmental impact offers multiple benefits in emission and cost savings, as mentioned in Section 6.4, and also in waste reduction, etc (Dovì et al., 2009).

However, the limitations of this research should also be noted. The results are valid for the particular parameters specified in Section 5 and the range of RPM and BCDs used was based on earlier experimental results, to locate the optimal machine setting for the particular working duty. If the ProductivE + map needs to be made compatible for the wider range of excavators, powered by different engines and hydraulic system configurations, more empirical measurements will be needed. Therefore, further work would be required to extend and create the required understanding of the behaviour of different excavators under different circumstances. Hence, other potential independent variables should be explored and a greater range of BCDs and RPMs settings should be tested. For example, different excavators and types of duties should be tested to create maps for different job tasks, although some of course may be common. Finally, the operator who participated in this experiment had more than 25 years of experience. As not all operators will exhibit the same level of experience or style, additional characterisations based on different operators' skill sets might also be considered.

7. Conclusion

While productivity is a well-researched area within operations research, a review of literature and industry guidance identified a gap in respect of fuel efficiency and productivity for hydraulic excavators. With concerns about fuel costs and a strong policy context invoking action towards reducing GHG emissions, there is growing concern that fuel consumption is not sufficiently reflected in physical and temporal measures of productivity. Moreover, the effect of operator behaviour on fuel consumption is often ignored or underestimated.

The relationship between fuel efficiency (kg/l) and productivity (m^3/h) in excavators was scientifically investigated using two new independent variables, RPM and bucket cut depth (BCD) within an experimental environment. It has been found that BCD and RPM settings can affect fuel efficiency and productivity of the operation of a hydraulic excavator. In addition, the results over ruled the existing, common perception that the highest RPM setting will achieve highest productivity. Conversely, low RPM settings do not necessarily consume the least fuel to complete the same task. The results also scientifically prove that a half-filled bucket (50% BCD) can have a maximum effect of 30% improvement on productivity (m^3/h), 24% saving on fuel efficiency (l/kg) and an overall amount of 62% more spoil moved per hour and litre of fuel consumed. The scientific results were further presented in a topographic map format and the ProductivE + data from this map could ultimately be used to identify the BCD and RPM required for a given excavator to undertake duties in the most fuel-efficient and productive manner.

This research responds to the need for companies to move towards cleaner productivity, by identifying an appropriate means to measure productivity and fuel efficiency as a single value. Operator training programmes should focus more on training the operators to select the correct engine speed and BCD, as an overarching strategy to improve productivity. The industry should use engine speed and BCD as variables to increase the accuracy of productivity equations. ProductivE + can be converted into a database to support innovative technologies or features such as "smart" bucket or auto engine speed, to maximise the potential to serve the development of a novel, intelligent system to automate excavators to improve their fuel efficiency and cleaner productivity resulting in lower GHG emissions.

Further studies are required to focus on other construction machines such as backhoe loaders, telescopic handlers etc. Work is also required to improve the accuracy of the data, by including other applications with the same amount of work by different operators with various experience levels.

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APPENDIX X IMPROVING HYDRAULIC EXCAVATOR PERFORMANCE THROUGH IN LINE HYDRAULIC OIL CONTAMINATION MONITORING (PAPER 3 – ACCEPTED)

Full Reference

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Abstract

It is common for original equipment manufacturers (OEMs) of high value products to provide maintenance or service packages to customers to ensure their products are maintained at peak efficiency throughout their life. To quickly and efficiently plan for maintenance requirements, OEMs require accurate information about the use and wear of their products. In recent decades, the aerospace industry in particular has become expert in using real time data for the purpose of product monitoring and maintenance scheduling. Significant quantities of real time usage data from product monitoring are commonly generated and transmitted back to the OEMs, where diagnostic and prognostic analysis will be carried out. More recently, other industries such as construction and automotive, are also starting to develop capabilities in these areas and condition based maintenance (CBM) is increasing in popularity as a means of satisfying customers' demands. CBM requires constant monitoring of real time product data by the OEMs, however the biggest challenge for these industries, in particular construction, is the lack of accurate and real time understanding of how their products are being used possibly because of the complex supply chains which exist in construction projects. This research focuses on current dynamic data acquisition techniques for mobile hydraulic systems, in this case the use of a mobile inline particle contamination sensor; the aim was to assess suitability to achieve both diagnostic and prognostic requirements of Condition Based Maintenance. It concludes that hydraulic oil contamination analysis, namely detection of metallic particulates, offers a reliable way to measure real time wear of hydraulic components.

Key words

Hydraulic Oil Contamination, Particle Sensors, Construction Equipment, Diagnostic, Prognostic

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Maintenance Strategy for Mobile Products

Introduction

Traditionally, products are designed and manufactured to meet customers' demands, but these can change dramatically over time. However, high value products such as construction equipment, trucks, buses and aeroplanes are expected to have long lifespans. These products are often bought in quantity as a fleet and are likely to be in service for 10 to 30 years or more. Product sales agreements often include a maintenance package and this is perhaps the most common and effective way to ensure that the products maintain a high reliability level [1]. Selling maintenance or other services together with the product in a bundle is known as a Product Service System (PSS). A PSS has been defined as a marketable set of products and services capable of jointly fulfilling a user's needs [2]. This manufacturing approach has been developed as a sustainable alternative to the conventional concepts of production and consumption for both manufacturers and consumers [3]. PSS aims to reduce the consumption of raw materials for manufacturing new products [4] by prolonging the life span of existing products [5].

However, it is very difficult to predict the maintenance that complex products such as construction equipment will require over many years, particularly when the conditions within which the product is working and the types of work being done are unknown. As a result maintenance has become an important part of operational budgets for OEMs [6], and companies seek to address this burden by reducing the complexity and uncertainty which currently exist in maintenance planning. Greater real time data acquisition and processing should enable them to conduct more accurate assessments of a product's condition in the field (i.e. before it is returned to the factory for maintenance and repair). Madenas stated that research into service and maintenance system development attracts little interest from researchers, and furthermore, this limited research tends to focus on the aerospace sector [7]. However, other industries with high data transactions, and significant warranty and maintenance costs, such as the automotive and construction industries, should also benefit from preventative maintenance schemes driven by real time data acquisition and processing. The research reported in this paper focused on a dynamic data acquisition technique that is typically used on mobile hydraulic systems (i.e. construction and mining machines). It draws on a 1,900-hour oil contamination monitoring study of a 22-tonne hydraulic excavator, to identify ways to improve maintenance regimes in hydraulic systems, namely through effective wear metal contamination detection.

Maintenance approaches

Maintenance is often perceived as being about fixing products that are no longer able to fulfil their designed functionality; this is also known as run to failure (RTF). British Standards define maintenance as: "The combination of all technical and administrative *actions,* including *supervision actions*, intended to retain an *item* in, or restore it to, a state in which it can perform a required function", [8]. The Maintenance Engineering Society of Australia (MESA) states that "Maintenance is the engineering decisions and associated actions necessary and sufficient for the optimization of specified capabilities", [9]. In this definition, "the optimization of specified capabilities" implies that the product's functionality should be delivered at a high level of performance and reliability.

Tsang stated that the primary objective of maintenance is to preserve system functionality in a cost-effective manner [10], yet maintenance has been described as an expensive and daunting element of support required throughout the product lifecycle of any given system [11]. Kelly went even further by suggesting that maintenance should achieve the agreed output level and operating pattern at a minimum resource cost, and within the constraints of the system's condition and safety [12]. In summary, maintenance must ensure the required reliability, availability, efficiency, and capability of a physical product [13].

Condition-based maintenance (CBM) is a philosophy for maintaining engineering assets based on non-intrusive measurement of their condition and maintenance logistics [14]. The R & D manager of Southwest Research Institute (SRI), Susan Zubik, stated that the aerospace industry considers CBM to be a maintenance philosophy to actively manage the health condition of assets in order to perform maintenance only when it is needed, and with the least disruption to the equipment's uptime (Zubik 2010). CBM is designed to prevent the onset of a failure [10], hence equipment condition is assessed by inspection and diagnosis, and maintenance actions are performed only when necessary [15]. The United States Air Force (USAF) defines CBM as a set of maintenance processes and capabilities derived from real-time assessment of weapon system conditions obtained from embedded sensors and/or external test and measurement using portable equipment [16]. Diagnostic and prognostic are two important components in a CBM programme, where diagnostic deals with fault detection and prognostic deals with fault and degradation prevention before they occur [17]. Previous studies confirm that machine components, data acquisition from sensors, data extraction, transformation and analysis are all key aspects of prognostic maintenance [18].

Rausch (2008) noted several common monitoring methods, such as vibration analysis, process parameter modelling, tribology, thermography and visual inspection. Sensors are often embedded into critical parts of the system to obtain data relevant to system health [1]. For example, Rolls Royce uses Engine Health Management (EHM) to offer its "Power by the Hour" monitoring service. There are about 25 sensors fitted permanently on a Rolls Royce Trent engine, which provide data (i.e. pressure at various locations of the engine, turbine gas temperature and cooling air temperature) [19]. With such real time data, OEMs can diagnose the condition of products whilst still operational in the field. Analysis techniques include neural networks and probabilistic-based autonomous systems for real time failure prognostic predictions [20].

CBM is initiated based on the state of the degrading system, and therefore components are only replaced when the level of degradation has reached a critical level. As a result, unscheduled down time of the equipment can be minimised. Furthermore, the ability to predict the time to a components' failure, means that Life Cycle Cost (LCC) may be greatly reduced because the life of the components and equipment can be utilised fully. OEMs or service providers can therefore also plan their service schedules more accurately, by knowing exactly what is required for the maintenance [20].

Challenges within Maintenance

Uncertainties about the current condition of products operating in the field make it extremely difficult for OEMs to plan maintenance schedules efficiently and cost effectively. This results in greater risks of under-maintaining products, which can lead to failure and longer, unscheduled down-times, both of which are unacceptable to customers. To reduce such uncertainties, accurate product data, particularly related to product use, needs to be acquired and processed to determine the frequency and types of maintenance/service required. Scheidt categorizes data as static and dynamic life cycle data [21]. Static data includes product information created during the product design phase, such as the product specification, Bill of Materials (BOM) and service manuals. Dynamic data is collected during the product's operational phase, commonly whilst it is being used by customers (rather than by the OEM), and consists of data such as usage patterns, servicing actions, environmental working conditions and components' wear rates. The data is typically stored in an on-board data logger and processor. OEMs also use questionnaires to capture product performance, patterns of use and customer satisfaction levels. Some larger OEMs invite their dealers and customers to a week-long conference to share their product experiences [22]. Although a large amount of first-hand feedback on the products' performance can be gathered in this way, this type of information becomes out-of-date rapidly, and is can be subject to error, ambiguity and subjectivity.

It is challenging for OEMs to collect accurate and useful real time (dynamic) data from a product. When products are designed, assumptions are made that they will be used in particular conditions and methods, as stated within the design specification, however, some customers (users) may misuse the products, thereby reducing operational lifespan. In the construction equipment industry, products are often subjected to unorthodox harsh usage and inadequate daily maintenance care, which can lead to accelerated wear on components, shortening life expectancy. To address this, OEMs may consider monitoring real time usage of the product, as per the aerospace industry. Monitoring systems enable service providers to schedule necessary maintenance immediately an abnormal event is detected. Any relevant real time data can also be extracted and analysed to determine the work and parts that are required [23]. However, data monitoring systems which involve the generation, processing and management of the product usage data are complex and expensive, and may even exceed the cost of the components that are being monitored. Bill Sauber, Volvo Construction Equipment North America's manager of remote technologies, stated that OEMs have a tendency to assume that if more dynamic, real time operational data are collected, more information will be captured. However, this data will mostly be just noise. Johnathan Metz, technology application specialist from Caterpillar also suggested that customers are likely to be overwhelmed by the sheer quantity of data, and its irrelevance to customers' needs [24]. Hence, if there is no system in place to analyse collected data in a timely manner, only limited value will be gained [25]. Therefore, to be cost effective and competitive, it is very important for construction equipment OEMs to design the monitoring systems as part of the overall product design. To do so, it is necessary to understand how the product's condition will be affected under different modes of operation, and how such changes in condition may be detected. This is critical such that monitoring systems, including the location and number of sensors can be designed to maximise the useful knowledge they can provide through real time data analysis, yet minimise costs incurred by sensor installation and operation. The remainder of this paper presents an assessment of the suitability of mobile inline particle contamination sensors for CBM, which was undertaken through a 1,900 hour oil contamination monitoring study.

Monitoring Hydraulic Systems to Predict Faults

Construction industry OEMs such as Caterpillar Inc. (CAT), Komatsu Ltd. and J C Bamford Excavators Ltd. manufacture heavy equipment for various industries, such as backhoe loaders, wheeled loaders and hydraulic excavators for handling bulky and heavy materials for various industries. More than 45% of the world's construction machines are hydraulic excavators [26], because of their high productivity and ease of operation compared to other construction machines [27]. Most excavators are powered by a combustion engine. Unlike a conventional automobile, the generated power of the engine is transmitted to drive the hydraulic pumps which provide the flow within the hydraulic system (Figure 1). Hydraulics is the science of transmitting force and/or motion through the medium of a confined liquid, and power is transmitted by pushing on this confined liquid. Pumps are installed to propel the oil around the circuit and, at times, pressurise it.

Valve blocks are often used to control the flow and direction of the oil. These are metal castings in which oil-ways or galleries are intersected by valve spools, the number of which depends on the number of services to be controlled. Failure of control valves can cause a loss of production which is many times more expensive than the cost of prevention [28]. The primary structural components of an excavator, such as the boom, dipper arm, bucket and slew motor are moved by hydraulic rams. Hydraulic rams convert fluid power into linear force and motion. The linear force generated by a hydraulic ram is a product of system pressure and effective area, minus system inefficiencies.

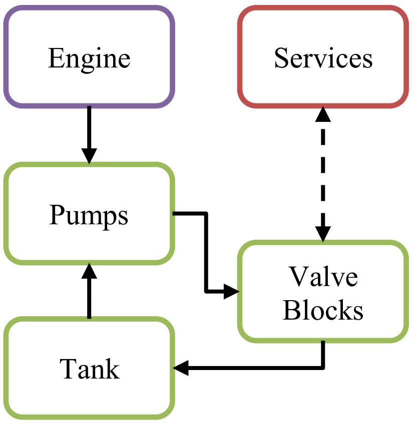

Figure 1 - Typical Hydraulic system (simplistic)

The complexity of off-highway excavators' hydraulic circuits and the tough working conditions they must endure, means that the reliability of such systems is always a serious consideration [29]. Analysis of hydraulic system operations indicates that the reliability of the system and its components will depend on a large number of factors [30], including pressure, flow, temperature, viscosity and particulate contaminants [31]. Dave Douglass, the director of training and education of Muncie Power Products, Muncie Inc. claims 70% - 90% of hydraulic system failures can be attributed to contaminated oil [32]. The National Research Council of Canada also found that 82% of wear problems are attributable to particle-induced failures such as abrasion, erosion and fatigue [33]. The National Fluid Power Centre (NFPC) also argues, in one of their oil contamination management courses, that failure to address and effectively manage contamination will lead to expensive downtime and short component life [34]. CAT Ltd maintains that the concentration of wear particles in oil is a key indicator of potential component problems. Hence, oil analysis techniques for condition monitoring offer significant potential benefits to operators [35]. For clarification, Ingalls and Barnes, president of TBR strategies and vice president of reliability service for Des-Case, defined oil contaminants as dirt, water, air, wear debris and leaked coolant [36].

Hydraulic circuit contaminants affect the performance and life of hydraulic equipment, leading to one of three types of system failure:

- Degradation: clearance-sized particles interact with both faces, often causing abrasive wear, corrosion and aeration issues. [37]
- Intermittent: contamination causes temporary resistance on the valve spool or prevents the poppet valve from moving. Although particulates are likely to be washed away by repetitive movement of the spool, only complete removal will ensure that this failure will not happen again [38].
- Catastrophic: this happens suddenly when a few large particles or a large number of small particles cause complete seizure of moving parts [39].

There are many different types of contaminants that can lead to system failures, of which moisture is probably the most common [40]. In general, there are three main sources of contaminants in hydraulic systems:

- Built-in contaminants, also known as primary contamination, are from manufacturing, assembly and testing of hydraulic components [41].
- Ingressed contamination often occurs due to insufficient sealing of the systems, such as rams [42], or insufficient filtration on the breather cap of the oil reservoir [39]. Machines used in mining industries tend to have a high level of silicon, dirt, [43] and water in hydraulic systems. Contamination can also be introduced during maintenance, especially when refilling hydraulic oil, if environmental contamination is not taken into consideration [38].
- Generated contamination, also known as abrasion, is caused by contact of hydraulic components during use and is not always avoidable [44].

The International Standard Organization (ISO), standard ISO 4406, “Hydraulic fluid power—Fluids—Method for coding the level of contamination by solid particles”, introduced a standardised way for determining the amounts of particles of sizes, 4 µm, 6 µm, and 14 µm per millilitre of fluid [45]. A scale of ISO code numbers is used for each particular size to represent the quantities of a specific range of particulates, e.g. ISO 20 represents any counts from more than 5000 to 10000 particles per millilitre. ISO 21 represents any counts from more than 10000 to 20000 particles per millilitre. A step ratio of two is generally used through the scale.

Most fluid analysis results are now shown according to ISO 4406. Hydraulic component manufacturers (such as Bosch Rexroth and Parker Hannifin) recommend a range of acceptable contamination levels for various types of systems, based on internal clearance, dirt sensitivity and operating methods of the components [46], [47]. Components such as pumps and valve blocks which operate in high pressurized systems with low clearance tend to require a higher level of cleanliness. Bosch Rexroth recommends that a level of cleanliness should be achieved based on the system requirements. For example, most modern hydraulic systems equipped with directional valves and pressure values should maintain a 20/16/13 level, whereas systems equipped with vane pump, piston pumps and piston engines should maintain a 19/14/11 level due to their smaller fitting tolerance on the components [48]. Not only are these components critical to the provision of the primary functionality of an excavator, but they are also some of the most expensive components in these products. Therefore, a filtration system is often incorporated in the hydraulic system to maintain an acceptable level of contamination in the oil.

Particle counters can be used to count the number of particles in a fluid system. These counters can be magnetic, optical or pressure difference depending on the application [49]. Most advanced automatic particle counters use laser-scattering, in which a laser projects perpendicularly through an oil passage within the counter onto a photocell detector. Size and quantity of the particles are measured by the different energy levels recorded by the detector, due to the particles' sizes in the oil [50]. Inline particle counters allow real time data to be collected during the usage of the machine; a temporary breach into the system is not required, so cross-contamination due to external environmental factors is prevented [51]. However, reliability is questionable, as accuracy is often affected by aeration due to pressure differences, giving false readings. Despite this, large excavators (typically over 100,000 kg operating weight, such as the Hitachi EX5500-6), will have integral contamination sensors [52]. Operators are alerted if excessive contamination is present, indicating the need to change the filters and oil. Figure 2 shows a typical setup of contamination sensors on a Hitachi hydraulic working machine [53]. That said, OEMs or service providers would still normally conduct an elemental analysis of an oil sample, before committing to changing the filter or oil.

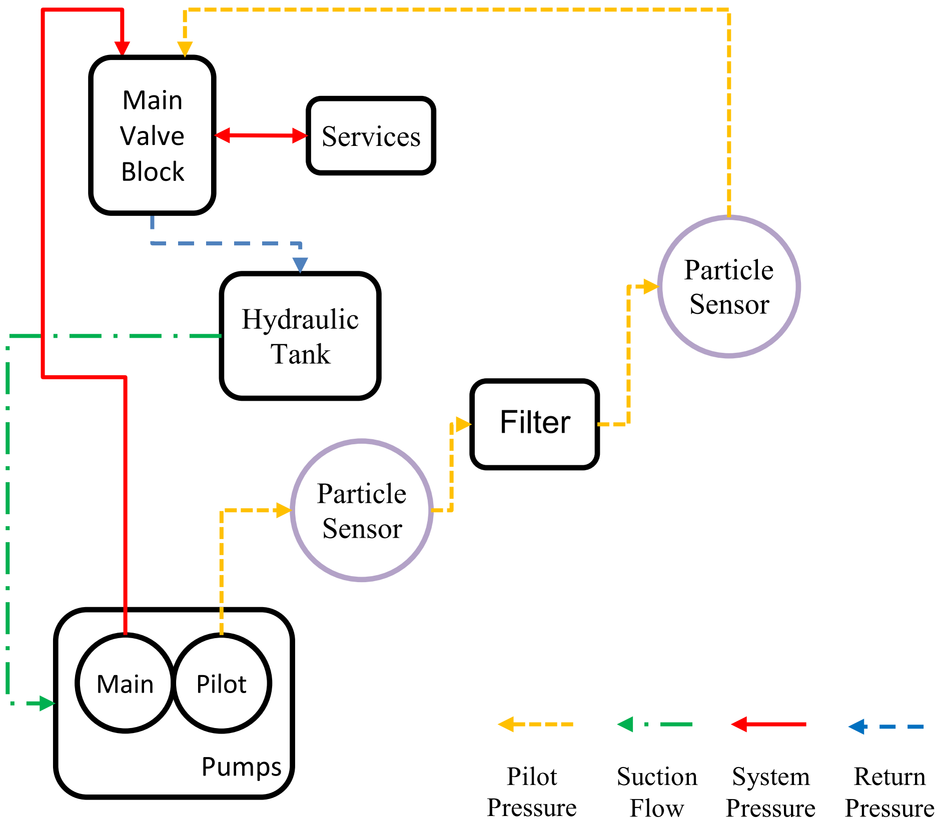

Figure 1 - A typical contamination sensors set up on a Hitachi machine

For construction machines, oil samples are typically taken by service technicians during a periodic service. These are either tested immediately by portable particle counters, providing quick and easy information on the cleanliness of the oil according ISO 4406, or are taken to an oil analysis laboratory for a more comprehensive elemental analysis. Inductively-coupled Plasma/Optical Emission Spectrometry (ICP/OES) is regarded as one of the most powerful and popular element analysis tools [54] because it measures 21 elements in the periodic table [55]. ICP/OES produces particles per millilitre (ppm) values for wear metals, contaminants and oil additives, by element type, at an accuracy level between 0.5% and 5% [56]. ICP/OES can analyse samples of at least 1ml [57], so is commonly used in fuel and oil analysis.

Metallic particles, also known as wear debris, are commonly considered to be the most damaging particles for components within hydraulic systems. Wear debris varies in shape and size, and is generated by components grinding against metallic built-in contamination or other generated wear debris. The cause and origin of the wear debris can be identified from its shape, size and colour. Based on such information and knowledge, a maintenance team can narrow down the problem to a single component and conduct maintenance or repairs before failure [58].

Hence, a monitoring system to enable CBM for hydraulic excavators, should enable samples to be taken and analysed from the hydraulic system, but from where should the samples be taken to accurately reflect the system's contamination level at a given time? British Standard (BS), BS5540: Part 3, "Evaluating particulate contamination of hydraulic fluids", specifies the procedures for obtaining bottle samples of hydraulic fluid from fluid power systems and containers for subsequent processing and evaluation by two approved methods; sampling valves and static sources [59]. Bottles should be clean enough to achieve less than 500 particles above 5 µm and volume of the sample should be at least 150 ml to ensure a large enough sample for elemental analysis. The contamination level in a given sample however is determined by the location at which the sample was taken; this should be at a point of turbulence, to ensure that contaminants are not settled and are well-mixed. Furthermore, the type of fluid flow in pipes is defined by the size of the Reynolds number (Re), which is calculated by:

$Re = \rho v D/\mu$ [60]

Where ρ is the density of the fluid, v is the velocity of the fluid, D is the diameter of the pipe and μ is the viscosity of the fluid.

If bottle samples are taken, a permanent valve type sampling point should be installed at a location at which filters or external pumping systems will not affect sample consistency. Before taking a sample at least twice the volume of the sampling line should be bled off. Finally, during sampling the flow rate should not be disturbed, as this may release trapped contamination [61]. Finning International Inc. the world's largest CAT Ltd dealer, like many other OEM dealers, further recommends that the system should be running for at least 15 minutes to ensure most oil is flushed through, and that the temperature is increased to the operating norm [62]. Aeration is no longer a concern with this type of sampling as samples are tested via ICP/OES, which greatly reduces the chances of inaccurate results due to aeration in the samples. However, the chances of cross-contamination may still exist which could lead to inaccurate results.

In closing this section, it is important to emphasise that hydraulic contamination can never be wholly eliminated. However, it can be controlled by taking precautions and installing filters of the correct grade. Although physical oil sampling has been adopted by most OEMs as a routine procedure during service intervals, test results are often used reactively. In addition, the interval periods are often too lengthy to capture the critical moment just before failure [16]. Furthermore, Lunt claims that offline laboratory oil analysis is becoming less acceptable, as maintenance strategies are developing more towards real-time decision making [63]. Hence, there is an arguably a need for OEMs to improve CBM programmes by addressing these concerns.

Research Method

The previous section identified that testing for the presence of hydraulic oil contamination within a hydraulic oil system can be used to determine the health status of its components and oil. As a result, a range of particle counters and oil sampling procedures have been developed by the industry to monitor hydraulic systems for oil contamination. Yet due to the harsh working environments, sophisticated particle sensors are used rarely in mobile applications such as excavators, and data generated by such sensors are scrutinised constantly by machine OEMs to determine whether accuracy and integrity is being affected by aeration. As a result, such sensor data tends not to be used to predict component faults and is therefore under-utilised in helping to extend the lifetime of an excavator and its components. Despite this, little work has been done to clarify causes and levels of inaccuracy, reduce uncertainties and increase understanding of monitoring information from hydraulic systems.

Therefore, this research focuses on current dynamic data acquisition techniques for mobile hydraulic systems. The main aim was to assess suitability of a mobile inline particle contamination sensor, to achieve both diagnostic and prognostic requirements of CBM.

To achieve the main aim of the research, three hypotheses were developed (as shown below), and tested through an experiment focusing on a mobile oil contamination particle sensor used within a typical mobile application working environment. All data collected were cross-validated by ICP/OES results, to check accuracy and reliability.

H_0: There is a difference between the levels and type of contamination generated by the two types of pumps in the machine.

H_1: The contamination level at the inlet to the main return filter is higher than at the outlet from the main pump.

H_2: Online particle sensors and ICP/OES have matching ISO code readings on the oil samples taken at a given time.

The experimental design consisted of three main tasks, to:

1. Conduct an empirical investigation on hydraulic contamination on a mobile application hydraulic excavator.
2. Understand the relevant technology and techniques in the data acquisition requirement for the generation and capture of dynamic data, which is the hydraulic oil contamination behavioural pattern.
3. Evaluate the suitability of oil contamination data for construction OEMs for diagnostic and prognostic.

Experimental Design

A 22 tonne excavator was selected and scheduled to perform a 2,000 hours simulated field endurance test. During the test, the machine underwent an hourly programme of mining and quarry duties, which included five different duties of excavating, tracking and lorry loading in specific ratios.

The machine was subjected to all standard service requirements set out by the excavator's OEM, and particle counters and an oil sampling system were installed. These were specifically designed for this research to measure contamination levels within the hydraulic system (see following sections for further details). The machine was subject to a routine service schedule, i.e. the main return filter was changed after every 500 machine engine hours, and the oil was changed at every 1000 machine engine hours. All return filters were collected and sent to the laboratory for filter debris and element analysis (to provide data on the quantities, sizes and types of trapped particulates).

Oil Sampling

Figure 1 - Particle Sensors and External Data Logger Installations

Particle counters were installed at the outlet from the main pump, the inlet to the main tank return filter and at the outlet from the tank (see Figure 4), in accordance with the literature. More than ten types of particle counters were reviewed to determine the most suitable for the machine's working environment. The final choice was based on accuracy, flow rate and pressure differential requirements and size. There were two types of pumps on the machine; and, due to the dynamic pressure, flow condition and technological limitations, the particle counters were installed at the outlets of the primary pump and the secondary pump (referred to hereafter as the main pump and pilot pump). Figure 4 is a simplified hydraulic schematic diagram to show where the sensors and oil sampling points were installed.

To improve reliability, two additional sampling points were established at the outlet of the main pump and at the inlet main return filter in the hydraulic tank. An electronic oil sampling system was designed and installed to allow oil samples to be taken from areas that were not suitable for particle counters. These samples were taken to a laboratory for further analysis by ICP/OES.

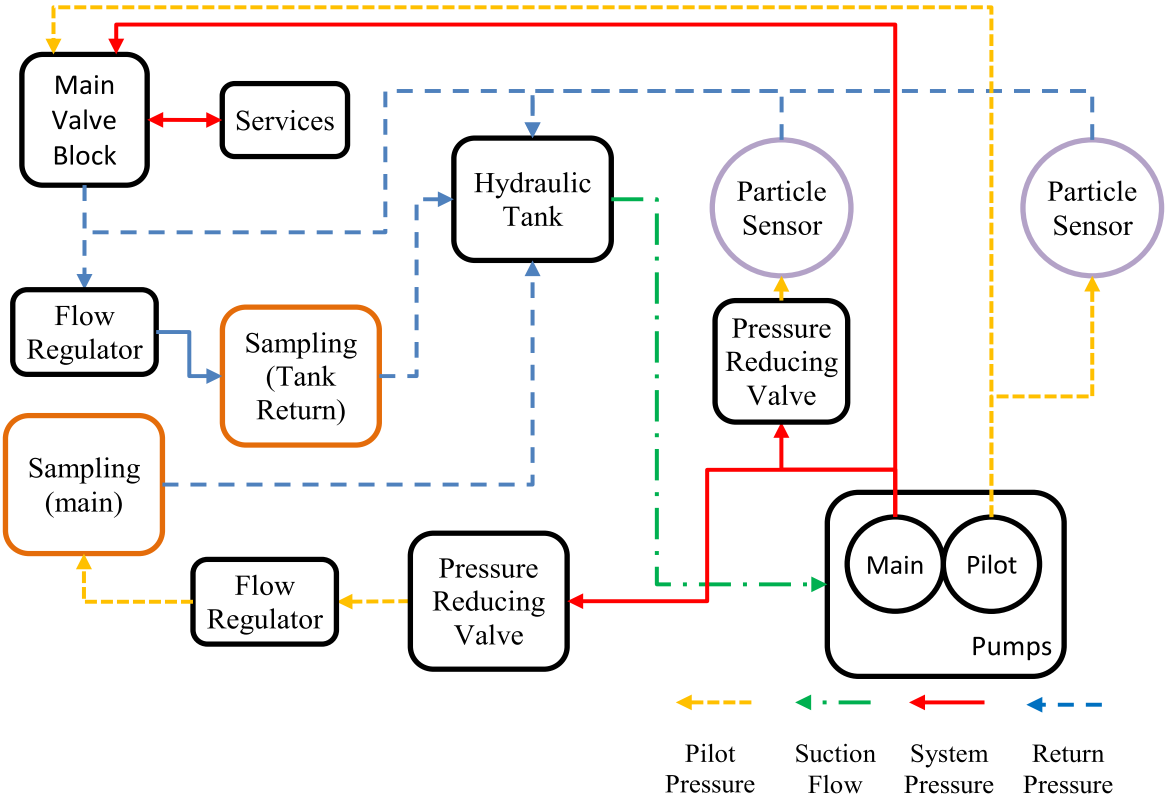

Figure 1 - Simplified diagram of the hydraulic system for a 22-tonne excavator

Pairs of oil samples were taken after the end of each shift. The sampling system was designed to be simple, minimising risks to the operators and potential cross-contamination of the sample.

Data Collection

Four primary sources were used to collect data. Each source provided data to test the hypothesis and also to validate the reliability of other data from each individual source.

Source A - Particle Counter - Sensors

The particle counters were set to take readings at one minute intervals. This was to ensure that no data was missed, although, when analysing the data, averages can be taken using various period lengths to expose hidden behaviours and reduce 'noise'. Pressure reducing and flow control modules were also used to ensure particle counters worked efficiently. An external data logger was installed onto the machine to record data generated by the particle counters. This data was extracted at the same time each week, to act as a useful checking point, to see if any repairs were necessary. Sensors were calibrated by the suppliers in accordance to ISO 11171:2010 Hydraulic fluid power: Calibration of automatic particle counters for liquids, before being installed onto the machines. Further verification was conducted in accordance to ISO 4407:2002 "Hydraulic fluid power: Fluid contamination- Determination of particulate contamination by the counting method using an optical microscope", to match with readings from the sensors when they were initially installed.

The data collected from this source were:

1.) Particle counts from both main and pilot pumps of ≤4 μm, ≤6 μm and ≤14 μm in ISO codes.
2.) The temperature and saturation levels of the hydraulic oil.

1.) Timestamp of each data point.

Source B– ICP/OES – Laboratory analysis

All oil samples were taken by operators who were briefed on the oil sampling standard operational procedure (SOP), which is based on BS 5540-3:1978,"Specification for evaluating particulate contamination of hydraulic fluids - Methods of bottling fluid samples" [59]. The results were split into three categories of "oil additives", "contamination" and "wear metals". A copy of the SOP was fixed behind the bay door where the sampling took place and a copy was kept in the office on site. A clear means of contact was established with the site manager, in case any queries were raised.

The data collected from this source were:

1.) Particle counts in the oil of 24 periodic elements from the main pump and tank return in values of particles per millilitre (ppm) also known as mg/kg.
2.) Particle counts of ≤4 µm, ≤6 µm and ≤14 µm in ISO codes.
3.) Exact counts of ≤4 µm, ≤5 µm, ≤6 µm, ≤7 µm, ≤10 µm, ≤14 µm, ≤20 µm and ≤30 µm particles.
4.) Timestamp of each data point and the machine hour at the time of the reading.

Source C – Filter Debris Analysis

Each main return filter was sent for filter debris analysis to allow the quantity of the trapped particulates to be measured and determine the cause based on their shapes. Reports were generated containing analysis and evaluation of the debris found in the filter. A standard elemental analysis was also included, providing the elements' counts in ppm.

The data collected from this source were:

1.) Particle counts of the 20 periodic elements in the filter debris and oil mix trapped inside the filter.
2.) Microscopic images of debris.
3.) Analysis report based on the data.

Source D - Telemetric System

The on-board telemetric system broadcast most data generated by local machine sensors. The data described the machine location, engine on/off status, machine error codes etc. Source D provided primary background information about the machine's activities, which was used to analyse the reasons behind the data identified by the other three sources.

The data collected of particular interest from this source were:

1.) Timestamp of machine activities such as on/off status of engine, duties etc.
2.) Fuel consumption at a given time.

Source E – Operators' Score Sheets

At the end of each shift, test operators were required to quantitatively evaluate the machine's performance in their shift. Information gathered included maintenance activities and observations such as refilling hydraulic oil, fuel, oil leaks and any other abnormal events. These records were treated as secondary background information, to provide validation of actual machine activities when combined with telemetry source data. Source E may not be wholly reliable as there could be differences in practices between individual operators.

The data collected from this source are:

1.) Unscheduled events such as oil leaks, refills, breakdowns etc.
2.) Machine hours in the shift period.

Method of analysing data

Data collected from particle sensors and physical oil samples were organised in Microsoft Excel to enable a quick initial assessment of sources A and B (See section 4.1.2). These assessments looked for trends in the data resulting from various operating behaviours and duties, thereby known as behavioural patterns, i.e. the rate of change between different particle sizes and relationships between different elements. Sources D and E provide coverage of other possible variables, i.e. leaks, oil changes, type of work etc., that may affect a particular pattern. Specialist programs (Matlab and Statistical Package for the Social Science, more commonly known as SPSS) were used to reorganise the data to filter out "noise" as well as filling in missing data by interpolation, and statistically analyse the data to identify correlations and differences in means and variances. In summary, these programs provided a good background platform to refine the data set for further visual and mathematical analysis. Figure 5 shows a simplified flow chart explaining the analysis method.

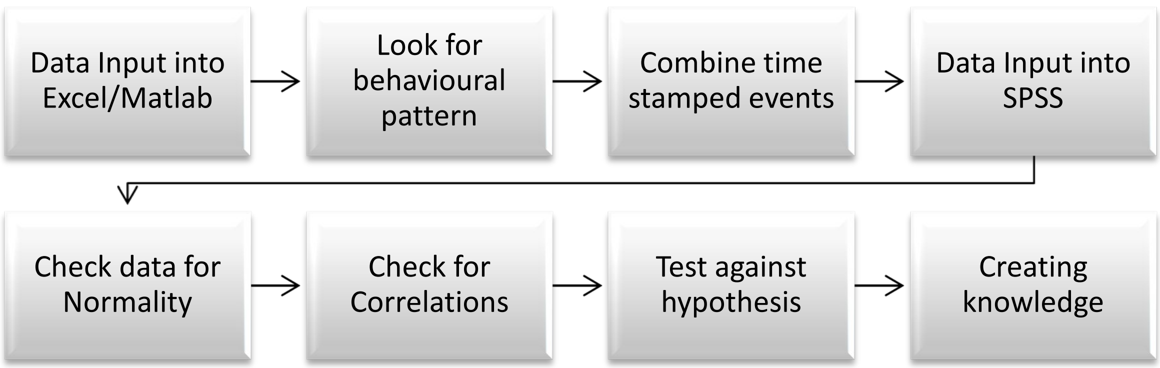

Figure 1 - Data Analysis Pathway

Data analysis

Duty breaks down

	Sensors - Main Pump			Sensors - Pilot Pump		
	ISO4	**ISO6**	**ISO14**	**ISO4**	**ISO6**	**ISO14**
Duty A	15.8	13.6	9.0	16.9	13.4	8.7
Duty B	16.2	13.9	9.0	16.8	13.5	8.7
Duty C	16.0	13.7	9.0	16.8	13.5	8.7
Duty D	16.1	13.8	9.1	16.8	13.5	8.8
Duty E	16.1	13.9	9.1	16.9	13.6	8.8
Total	**16.0**	**13.8**	**9.0**	**16.8**	**13.5**	**8.7**

Table 1 - Contamination by Duties (source A)

Although the experiment was conducted under 24/7 technical supervision, unexpected break downs and repair work were unavoidable during the experiment. Sources C and D were used to calculate the actual duty ratios compared to the specific ratios mentioned in section 3.1.

were performed in the exact ratios planned.

Contamination by duty

Table 1 shows the average contamination levels over the total hours for the five duties (A to E) from Source A. There is no significant difference in the contamination levels between the duties. All differences shown in the table are within the ±½ ISO code tolerance of the sensors' accuracy. Therefore, based on Source A, different duties do not have any effect on the contamination levels at the hydraulic pumps.

The differences in the contamination levels identified at the main and pivot pumps are not significant. However, the quantities of particulates that are equal to or larger than 4 µm per millilitre do have a large gap compared to the quantities of 6 µm and 14 µm.

	Laboratory – Pilot Pump			Laboratory – Tank Return		
	ISO4	**ISO6**	**ISO14**	**ISO4**	**ISO6**	**ISO14**
Duty A	18.5	15.8	11.2	18.6	16.0	11.2
Duty B	18.2	15.6	11.0	18.8	16.0	11.3
Duty C	18.3	15.6	11.5	18.9	16.4	12.0
Duty D	17.9	15.3	10.9	19.0	16.6	12.1
Duty E	18.5	15.9	11.4	18.6	15.9	11.2
Total	**18.3**	**15.7**	**11.2**	**18.7**	**16.1**	**11.4**

Table 1 - Contamination by Duties Source B

The ISO values from Source B were determined in a laboratory environment with higher accuracy than the sensors used in source A. Table 2 shows the average contamination level by duty for the same period as in Table 1. Results again show insignificant differences in contamination levels for the different duties. Surprisingly, the positive difference in oil contamination levels between the return line and the pilot pump was not as significant as expected.

Contamination by filter periods

In previous sections, only the average contamination levels of various locations were shown, which may mask significant fluctuations in individual contamination levels. As mentioned in section **Error! Reference source not found.**, the main return filter was changed every 500 hours to ensure filtration efficiency was kept at the highest possible level. Therefore, this section focuses on the behavioural pattern of contamination levels between filter periods.

The locations in which the sensors monitor the contamination level can be used as an indicator of the minimum contamination level the hydraulic system was experiencing at a given time. Twenty graphs were plotted, with machine hours against ppm values from Source A. Five categories of graphs were created in accordance with the individual and combined periods of the four main returned filters used in the simulated field endurance test. Four individual graphs of 4 µm, 6 µm, 14 µm and other sources were found in each category. Temperature and saturation levels of the hydraulic oil were linked to chemical oil contamination, and this results in thermal and oxidative degradation of the oil [64]. As a result, these factors were included in all graphs.

ISO code/hr	**4 Micron**	**6 Micron**	**14 Micron**
Main Pump	-0.0059	-0.0077	-0.0105
Pilot Pump	-0.0004	-0.0028	-0.0058
Differences	*0.0055*	*0.0049*	*0.0046*

Table 2 - Rate of change in contamination level (1st filter period)

Within the first 500 hours, the average decreasing rates of 4 µm, 6 µm and 14 µm particulates are shown in Table 3. The main pump always achieved a higher rate in comparison to the pilot pump by an average of 0.005 ppm/hr. In between the second and third filter periods, the 14 µm particulates dropped down to the 11 ISO code level and remained so throughout the two filter periods. A small increase in ISO level can be seen from both pumps of both sizes, until the third period when the 4 µm pilot pump particulates gained a higher ISO code than the main pump, but matched the same increase rate of 0.0071 ISO code/hour, and remained so throughout the rest of the experiment.

By 180 hours of the machine running, 4 µm, 6 µm and 14 µm particulates from both pumps were decreasing at the same rate. On average, the main and pilot pumps have the same 4 µm contamination level. There is clear evidence to suggest the main pump suffers higher contamination levels than the pilot at 6 µm and 14 µm, by at least 1 ISO code. However, for the next 820 hours the 4 µm and 6 µm contamination levels from both pumps stabilised at about ISO levels of 18 and 15 respectively. The 14 µm contamination level dropped down to the 8 ISO level, but increased up to the 9 ISO level at 1000 hours.

ISO code/hr	**4 Micron**	**6 Micron**	**14 Micron**
Main Pump	0.009	0.0067	0.0008
Pilot Pump	0.0073	0.0065	0.0007
Differences	*0.0017*	*0.0002*	*0.0001*

Table 1 - Rate of change in contamination level (4th filter period)

A full hydraulic system oil change was conducted at 1000 hours and thus a drop of contamination can been seen in both pumps, however the magnitude varied depending on the size of the particulates. At the main pump, 24% and 28% drops in ISO code levels can be found at 4 µm and 6 µm respectively whilst 14 µm dropped back to ISO 8 level. At the pilot pump, 6 µm particulates dropped by 23% and 14 µm remained at the ISO 8 level. However 4 µm readings only dropped by 12%, which is half of the observed value of the main pump. Table 4 shows the average increasing rate of 4 µm, 6 µm and 14 µm contaminations in both the main and pilot pumps. The rate of difference between the pumps is much less than the data shown in Table 3. However at the 4 µm particulates level the pilot pump was on average 3 ISO codes higher than the main pump, whereas at 6 µm the main pump has a greater ISO code than the pilot pump, and the 14 µm contamination remained the same at both the two pumps. By the end of 1900 hours the 4 µm contamination of the pilot pump was over 2 ISO codes dirtier than the main pump, whereas 6 µm and 14 µm particulates were 2 ISO codes cleaner in both pumps.

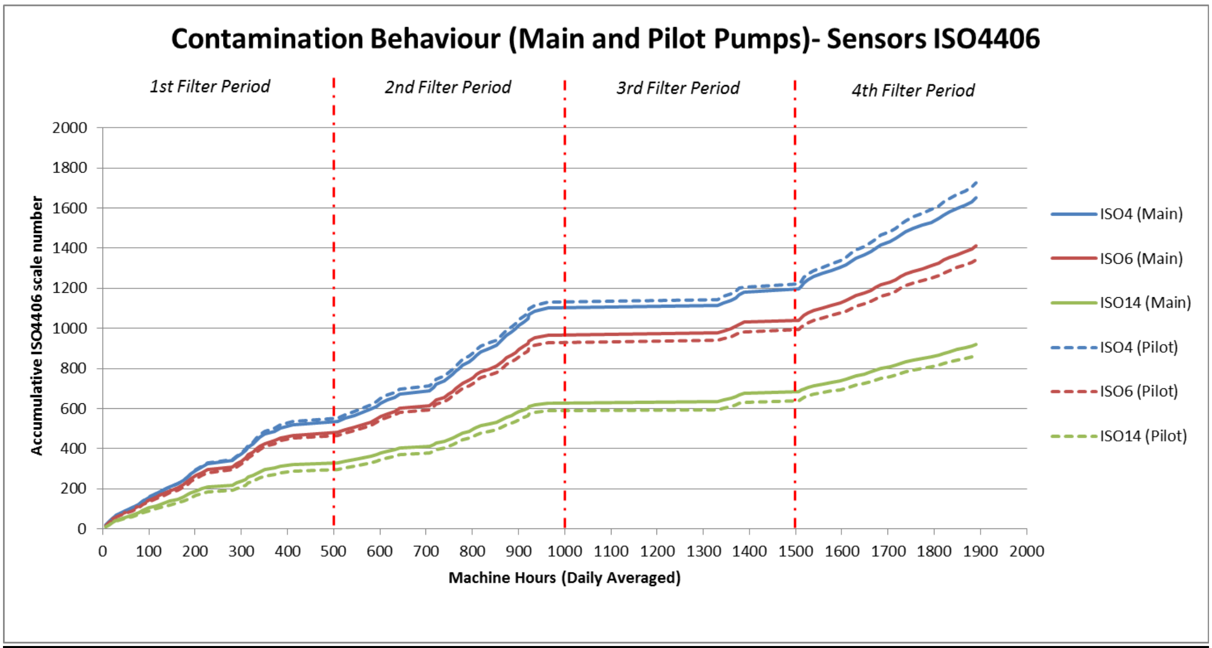

Figure 1 - The correlation of oil contamination (sensors – main and pilot pumps)

Figure 6 shows the correlation of three different levels of contamination at 4 µm, 6 µm and 14 µm captured by particle sensors situated at the outlets of the main and pilot pumps. In general, despite there being two types of pumps the contamination levels have a very strong correlation to each other at 4 µm, 6 µm and 14 µm. Contamination at the 14 µm level has a maximum of 2 ISO codes difference between the main and pilot pumps. The large sizes of these particles suggest that these are likely to be built-in contaminants, as the system is cleaning itself within its first 100hrs of oil circulation. Despite the differences in contamination levels in the last 500 hrs of the endurance program, strong correlations can still be seen clearly.

Additives

The ppm values of the 24 elements from Source B show more turbulent behaviour than the ISO codes. A two-tailed Spearman correlation test was conducted on the additives from two locations, due to the data's non parametric behaviour (Pearson product-moment correlation was not suitable for the data collection in this experiment, as the data does not behave in a linear manner). Most additives have a 99% confidence level of a strong correlation to each other, with less than 1% chance that these correlations only happened by chance. These additives were added into the oil to increase its anti-wear and frictionless properties. Events obtained from Source D, such as the main return filter change, and oil changes suggest minimal, but detectable, influence at the measured ppm levels. Despite a strong correlation, the sulphur level in the hydraulic oil is on average 50 ppm higher at the main pump than at the pilot pump, which suggests that the sulphur has been added to the oil internally between the main return filter and the main pump.

Contamination

There is a strong correlation (99% confidence level) between Sodium (Na), Potassium (K), Silicon (Si) and Lithium (Li) identified through the four periods. The existence of both Na and K potentially meant that the system had been suffering coolant leaks into the hydraulic system.

Li is often found in grease, which is used on the pivot points of the structure of the machine. Although it does not correspond with any known events specified in Source D, the correlation with K could suggest that grease breached the hydraulic system with the coolant. However, the recorded values of both K and Li are minimal suggesting that coolant or grease leaks are unlikely. The hydraulic system, coolant system and the grease lines are completely separate systems, and are located as separate components, therefore these particles are likely to have been introduced into the hydraulic system from the tank when the hydraulic system was refilled.

Dirt ingestion

The combination of Si and Aluminium (Al) suggests that dirt was present within the system. These particles are usually introduced when the hydraulic system is breached, such as refilling hydraulic oil, disconnection of hydraulic hoses, and connection of hydraulic attachments. After 1900 hrs, only low levels of Si and Al were found, therefore dirt contamination must have been controlled by the filtration unit. However between 1500 hrs and 1900 hrs, the ppm values of Si started to increase from 2 ppm to 3.5 ppm, unlike previous periods where Si values were consistent at 2 ppm.

Wear Metal

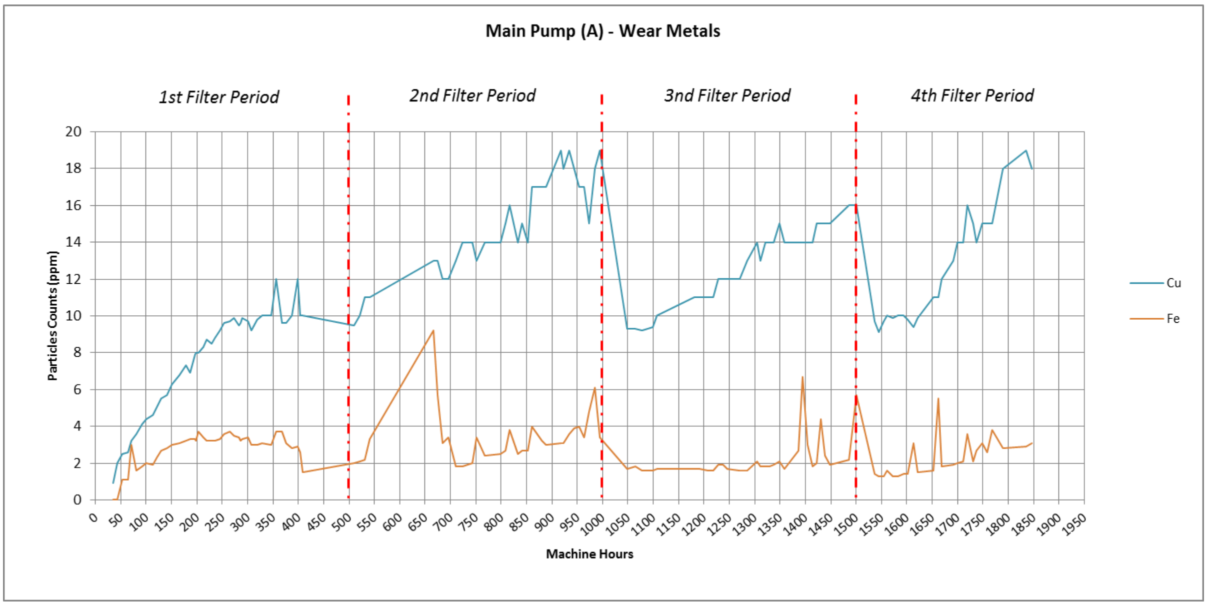

Figure 1 - The effects of filter change on contamination of wear metals

Strong correlations (99% confidence level) can be found between Copper (Cu), Iron (Fe) and Manganese (Mn). All wear metals except Cu and Fe were maintained below 3ppm level throughout the period. Fe was increasing at an average rate of 0.0185 ppm/hr, but remained below 3 ppm after the first filter change. Cu had a similar increase rate as Fe up to the first filter change, as the rate of increase dropped down to an average of 0.0132 ppm/h. A dramatic drop in ppm values can be observed after the third and fourth filter changes, but the ppm increase rate remained the same. However after the fourth filter change the rate increased to 0.0329 ppm/hr. The consistent increase rate in Cu ppm values between filter change periods suggests a constant wear of bushings in the pumps and other hydraulic components (such as the slew motor). As shown in Figure 7, the ppm values peaked at 20 ppm before the filter change period. The increase in the wear rate as well as ineffective filtration of Cu, can eventually lead to system failure.

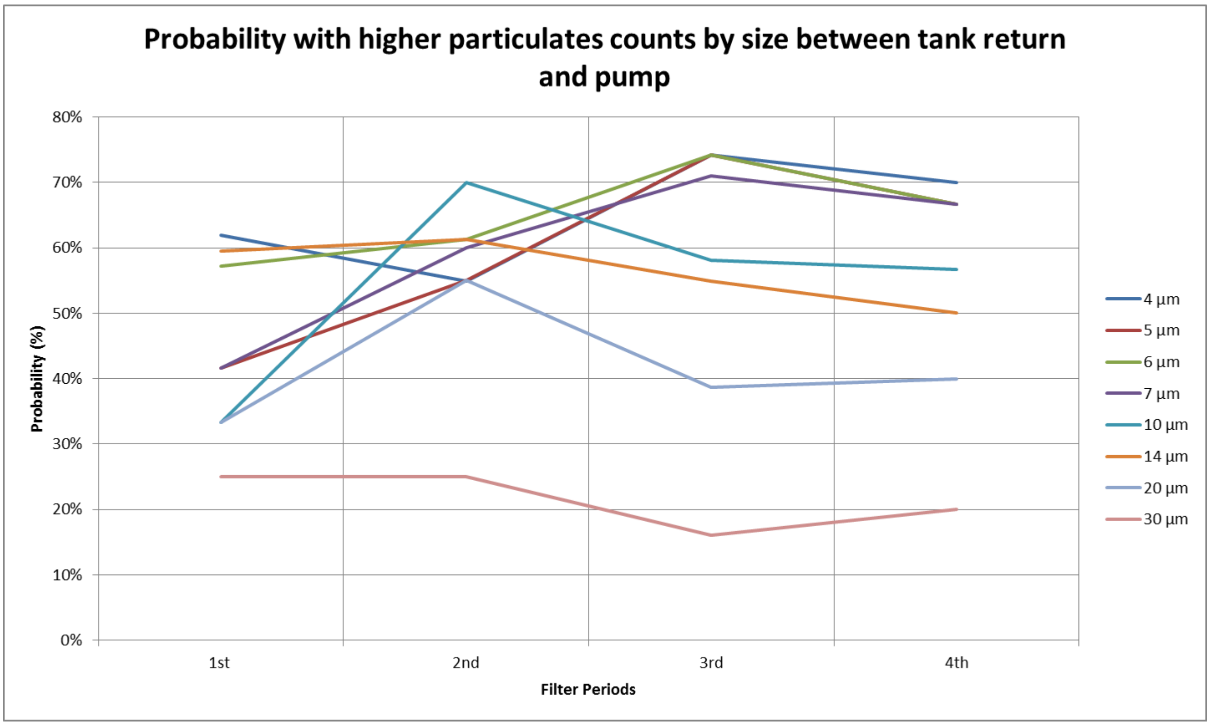

Figure 1 - Comparing tank return and pilot pump (ICP/OES)

Figure 8 shows the behaviour patterns between different particulate sizes throughout the 1900 hrs. At the end of the experiment, particulates that are less than 10 µm reached about a 70% chance of increasing at the tank return compared to a 30% chance of failing at the pump. Yet the probability for particulates that are equal and larger than 10 µm decreased after the first filter period. This suggests that the 10 µm rated main return filter is working effectively in filtering particulate that are larger than 10 µm, and any built-in contaminants larger than 10 µm are usually caught in the first 500 hours of machine usage in any case.

Difference between ISO 4406 and ICP/OES

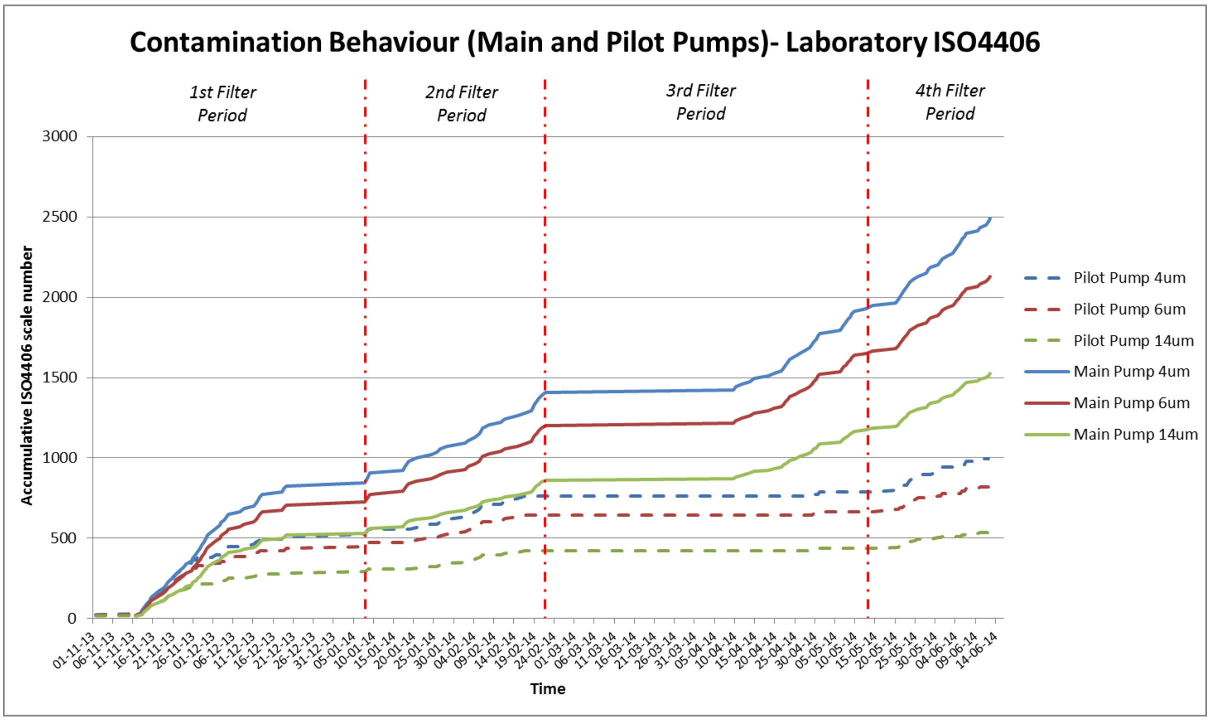

Figure 1 - Contamination Behaviour by ISO4406 (ICP/OES

Figures 6 and 9 show the results based on the ISO 4406 standard collected from Sources A and B of both pumps. Results from both sources exhibit a steady increase of 4 µm, 6 µm and 14 µm particulates at the beginning of the filter 1 period and at the end of the filter 4 period, and a decrease at the end of the filter 1 period. Source B consistently gives a cleaner reading than Source A throughout the study.

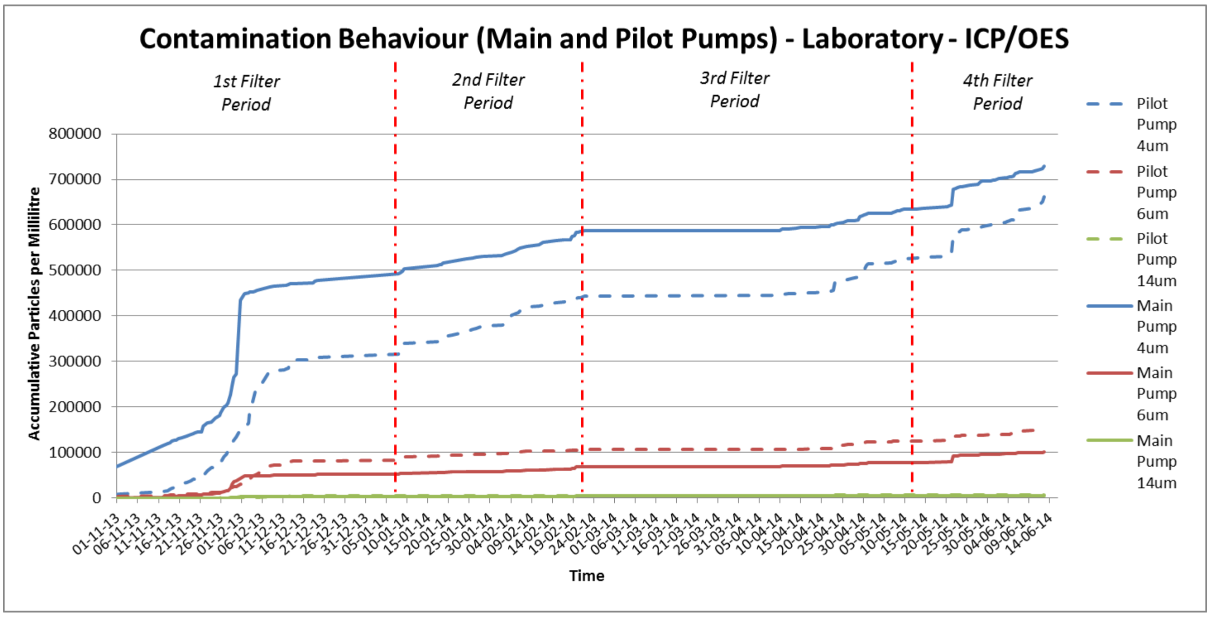

Figure 2 - Contamination Behaviour by ICP/OES (Laboratory)

As mentioned in section 2, ISO 4406 data limits at a certain quantity range of particulates. Hence comparing the actual values of ppm shown in Figure 10, within the filter 4 period, clearly shows that only the 4 µm particulates were increasing steadily.

Filter Analysis

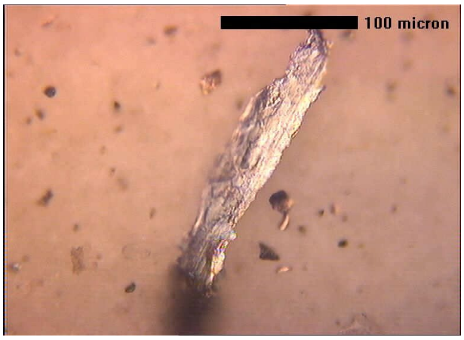

Figure 1 - 1st Filter Microscopic Image A

Large amounts of particulates with varied shapes were found in the first filter. In particular large quantities of 100 µm particulates shaped in thin straight stripes were found. Based on the size and shape of the particulates, the majority would have been generated through erosion, where material is removed due to particle impacts. Particulates would have been forced through tight clearances, causing high pressure and stress on the contact surfaces and creating severe sliding wear particles. The grain on the sliding wear particle shown in Figure 11 indicates the direction of the sliding motion. Large amounts of particulates over 100 µm were also found only in the filter used in the first 500 hours. These particulates, as shown in Figures 11 and 12, are built-in contaminants described in section 3. Moderately high levels of Fe and Cu are found in the sample mix extracted from the filter. Combining this information with data from Source A collected in the first 500 hours, leads to the conclusion that these Fe particulates were probably generated from the pump housing clearance and valve spool clearance.

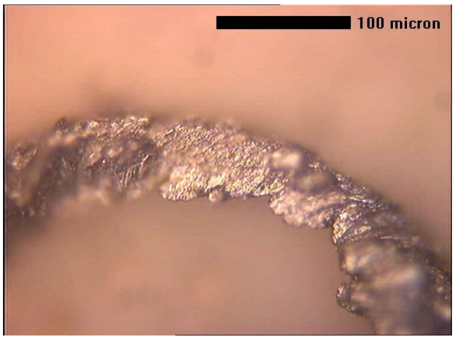

Figure 2 - 1st Filter Microscopic Image B

Figure 3 - 4th Filter Microscopic Image A

Particulates found in the second, third and fourth filters were different in shape and quantity to those found in the first filter. These particulates, as shown in Figures 13 and 14, tended to be flat with irregular shapes, which is an indication of fatigue wear, and most commonly occurs by normal and tangential force through contacting asperities [58]. As the machine worked towards the 1900 hrs, a larger quantity of small particles, can be observed in the filtered elements from Source C as well as from the particle sensors of Source A and ICP/OES of Source B. Elementary analysis from Source D further suggests that these particulates are largely Cu, Fe and Sn. Based on knowledge of the materials used to manufacture hydraulic components and understanding gained from the discussions above, a conclusion can be reached that the machine was suffering bushing wear at the main pump and/or the slew motor.

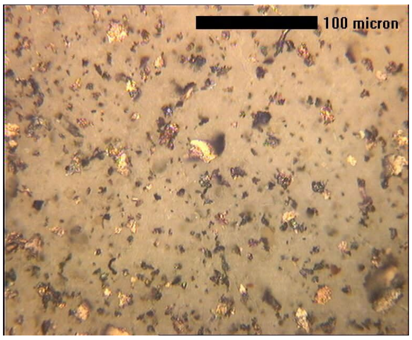

Figure 14 - 4th Filter Microscopic Image B

Overall contamination behaviour

Figures 6, 9 and 10 are accumulative graphs of ISO codes values and the amounts of particles per millilitre from the samples physically extracted from the pilot pump for ICP/OES analysis. These figures exhibit similar contamination behavioural patterns, which show the various increased rates of contamination level, however the amount of information available is insufficient to give warnings of premature faults or be able to suggest the source of the fault. Hence, if a sudden spike was observed, it will almost certainly be too late to prevent the machine breaking down. In particular with ISO 4406 reporting methods that decrease the resolution of the data, the chances of supporting CBM are low.

The sudden spike in ppm count of 4 µm particles at the beginning of the experiment was the result of a build-up of contamination through the system before being cleaned by the filter. Some of these particles will have been broken into smaller sizes when they were forced through narrow clearances such as valve blocks and pumps. This theory is supported by the increased rate of 4 µm particles identified between the first and second filter periods. After the first filter was changed, the increased rate of 4 µm particulates stabilized until reaching the fourth filter period.

Experimental Results

The experiment carried out in section **Error! Reference source not found.** aimed to identify the hydraulic oil contamination level behaviour on a mobile construction machine during the use phase of its lifecycle. The results discussed in section **Error! Reference source not found.** show that the increase and decrease of certain elements such as Cu and iron are affected by filter changes. The correlation between Tin (Sn) and Cu that was only discovered by the use of SPSS suggests that bronze (which is used as a bushing material in the hydraulic pump) was wearing out more quickly as the machine ran towards 1900 hours. An analysis was then undertaken to answer the hypotheses stated in section 3, as outlined below.

$H_{0:}$ there is a difference between the levels and types of contamination generated by the two types of pumps in the machine.

According to Source A, the overall average contamination levels between the main and pilot pumps can be deemed to be the same. However further analysis in section **Error! Reference source not found.** identified fluctuations in contamination levels between various filter periods. Events such as oil leaks or refill of oil do not produce a large effect compared to the full hydraulic system oil change, in which the cleanliness level changes sharply on both pumps.

Spearman's rank-order correlation was used to determine the relationship between the contamination levels of various micron sizes and pumps. Only the 4 µm main pump particulates do not have any correlation with temperature. However, there were strong, positive statistically significant correlations found between the 4 µm, 6 µm and 14 µm particulates in both pumps. Furthermore, the saturate level in the oil also shows a strong positive correlation between the 4 µm, 6 µm and 14 µm particulates of both pumps, in particular for the main pump. This is understandable because if saturation level increases the amount of water particles in the oil will also increase. A significant negative correlation can be found between temperature and the pumps. This can be exist in the oil because they evaporate. Hence there will be a lower contamination level in the oil and therefore a negative correlation.

As a result, H_0 was accepted.

H_1: the contamination level at the inlet to the main return filter is higher than at the outlet from the main pump.

According to Source B, there is no obvious variation in contamination level in the hydraulic oil between the pump and the tank return area. Levene's test for equality of variance was used to determine if the hydraulic oil contamination level between tank return and pump has the same or different amounts of variability in particulates, by size and type. Significant variance equality can be found in Pb, Molybdenum (Mo), Cadmium (Cd) and particulates that are larger or equal to 7 µm, 10 µm and 20 µm. Based on the two-tailed test, significant mean differences between particulates in samples from the tank return oil and the pump oil can be found between 4 µm, 6 µm, Pb, Mo and Cd.

Despite the low significant differences found by the statistical analysis, the results from section **Error! Reference source not found.** do show higher, more obvious differences as the machine worked towards 1900 hours. Therefore, H_1 was accepted.

H_2: online particle sensors and ICP/OES have matching ISO code readings on the oil samples taken at a given time.

The cleanliness level of hydraulic oil (ISO 4406) at the outlet of the pilot pump was sampled and tested by both the particle sensor and ICP/OES. The result shows an average of two ISO codes differences in 4 µm and 6 µm particles between the two testing methods, and the sensor's results are cleaner than the ICP/OES results. The ICP/OES results were very stable at 18/16/12 throughout the experimental period, with only on average 0.4 code of difference among the 3 µm sizes. By comparison, the sensors' results exhibit a 2-3 codes difference for 4 µm and 6 µm particulates and 1 code difference for 14 µm particulates. In particular during the period of hydraulic oil low saturation level, the average differences between the cleanest and dirtiest samples have increased to 3 ISO codes, making this the cleanest period according to the sensor. Yet the machine would have been working constantly, maximising the expected output of the machine as well as the hydraulic system. Subsequently oil would have been pumped and channelled much more vigorously, leading to the system temperature increasing and then stabilising at about 70 degree Celsius. At this temperature, moisture content will decrease due to evaporation and hence saturation level will be low during a machine's heavy duty period. During this heavy duty, the pump will be forced to suck hydraulic oil from the tank as quickly as possible to supply the required pressure and flow to the rams. Under such circumstances, aeration is a common problem, because a cavity can be created if the oil does not flow fast enough to replace the oil that has been sucked from the tank [65]. If aeration goes through the particle sensor, the measurements will not be accurate [50].

ICP/OES samples were taken offline, where a temporary breach into the system occurred. Hence cross contamination when obtaining the samples may be the reason for the difference. However, seasonal factors such as temperature (dust) and humidity (rain) will also have a direct effect on the cross contamination of the samples. Yet the consistency of the gap size does not support the possibility of occurrence of cross contamination, hence the difference in the sensors and ICP/OES results are more likely caused by the sampling methods. Particle sensors in Source A have straight hoses connected to the inlet and the outlet, creating a laminar flow at the area. The inlet of the sampling system in Source B is connected to a 90 degree elbow adaptor, creating a turbulent flow. Samples from turbulent flow may have a higher ppm value due to the fluid being stirred much more vigorously than in laminar flow samples.

Another possible reason is the technology and the design of the particle sensors (optical-based), emitting a single laser beam perpendicularly through a narrow passage where oil travels through. This sensor measures and counts the size of particulates by measuring the intensity of the laser that successfully reaches the other side of the passage. The passage has to be a certain size to ensure that it is free of blockage no matter how dirty the oil becomes, hence two or more particulates may have been seen as one. Furthermore, aeration and water in the oil can scatter and block the beam resulting in a false, cleaner reading.

After combining the evidence from these results, H_2 was rejected.

Conclusions and Further Work

Uncertainties about the condition of products operating in the field make it extremely difficult for OEMs to plan maintenance schedules efficiently and cost effectively. This results in a greater risk that products are under-maintained, which can lead to failure. Real-time oil contamination data provides vital information that can help service technicians to follow and conduct suitable service procedures to prolong a product's service life, and prevent downtime; this principle is at the heart of CBM. The majority of oil analysis facilities and contamination monitoring equipment available on the market measure and represent the contamination level in accordance with ISO standards such as ISO4406, and thus provide a lower resolution of the actual oil contamination pattern. Yet the experiment presented in this paper has shown that the ICP/OES method provides a higher resolution, and therefore offers a more accurate measurement of fluctuation and origin of particulates within the hydraulic system. More advanced oil analysis methods such as ICP/OES are available and offer the data that inline particle counters fail to provide. These methods are capable of measuring the size and quantity of specific metallic particulates. This study shows that metallic particulates such as Cu and Fe should be the main focus, as these wear metals represent the majority of the main materials used in current hydraulic components (such as pumps and valve blocks). Such an understanding will enable more targeted diagnostic work and service planning for a machine, especially if it is working in a remote area. Clearly, access to this type of information has the potential to save OEMs a substantial amount of time and money.

An important outcome from this research is that dynamic data gathered by inline particle sensors is not sufficiently detailed to underpin a successful CBM strategy for mobile applications in the construction industry. However, the major and original contributions arising from this research are, that;

The assessment of current methods in measuring hydraulic oil contamination expose both technological methods, and at the same time raises questions about the benefits of current maintenance routine, e.g. the effectiveness of oil change in removing contamination from the system.

The main focus in contamination detection should be metallic particulates such as Cu and Fe, as they are considered as wear metal and represent the majority of the main materials used in current hydraulic components such as pumps and valve blocks. However little research can be found in both academia and industry to allow metallic particulates to be detected at the required resolution level.

Although in-line particle counters do offer OEMs a real-time capability for monitoring hydraulic systems, the limitations in contamination measurement and their inability to measure metallic particulates, make the tangible implementation costs higher than the (currently) intangible gains. OEMs need a reliable, accurate oil contamination sensor that monitors (metallic) wear particulates. It is a key recommendation from this study that the research community undertakes further, collaborative research with the OEM industry to design and test in-line particle sensors that are truly suitable for mobile applications within the construction industry.

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APPENDIX Y ROAD MAP FOR DEVELOPING A BESPOKE PSS SYSTEM FOR CONSTRUCTION MACHINES OEMS (PAPER 4 – AWAITING REVIEWER APPROVAL OF REVISION)

Full Reference

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Abstract

In recent decades, a growing number of original equipment manufacturers (OEMs) have moved towards product service system (PSS), as a strategic means to increase market share and improve customer satisfaction. A PSS is a system that integrates product and service as one package at the point of sale. PSSs are increasingly popular because customers are demanding more supplier involvement to prolong and maintain the life of products and keep them functioning at maximum performance levels for longer. This provides incentives for OEMs to incorporate PSS into their business model to remain competitive. PSS is commonly used for high value products in which sensors provide critical real time data, allowing premature faults to be detected by the OEMs before major problems emerge. PSSs promote more transparent flows of information, however, the prerequisite knowledge and systems required to operate effective PSSs are often underestimated, as although the condition of the products are being monitored, insufficient knowledge and understanding or interpretation of that knowledge is available. Firms often struggle to interpret and fully utilise the monitored data, either due to lack of detailed understanding of normal operating parameters or critical usage data. Considerable research exists into the advancement of PSS infrastructures, knowledge management etc., yet little research can be found on the identification or creation of the necessary prerequisites, which are critical to the set up and operation of a successful use-oriented PSS. This paper presents a roadmap for the creation of use-oriented PSS, with a strong focus on OEMs in the off-highway equipment industry who wish to implement use-oriented PSS. The roadmap clarifies the required prerequisites such as product usage data, real time monitoring strategy, maintenance strategy etc. that OEMs need to determine and examine to validate their readiness level towards the adoption of a use-oriented PSS driven business model.

Keywords

Product Service System, Product Monitoring, Data Mining, Knowledge, Servitization

Road map for developing a bespoke PSS system for construction machines OEMs

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The shift towards service

In recent decades, there has been a significant shift in business strategy from manufacturing towards service industries. Herrendorf suggests that the underlying increase in salaries during this period encourages consumers to be willing to pay for additional services[1]. Industries that manufacture high-value products, such as construction and aerospace, thus find the demand for services with their products is much greater than in other industries. This shift in business strategy often involves companies either adding service elements into their pre-existing core competence, or completely transforming themselves into a service provider. There is a growing trend in the demand for support from customers, which is extending further within the product's lifecycle. While customers clearly expect functional requirements to be fulfilled, the expectation of a substantial after-sales service from the Original Equipment Manufacturer (OEM)/ service provider exists at the same time. Customers want to ensure that the reliability level of their purchases will continue at the highest possible level until or beyond their return on investment (ROI) period. As the number of OEM products being sold into the market has accumulated over the years, the size of the aftermarket will increase exponentially. For the past 8 years, between 76% and 79% of the nation's Gross Domestic Product (GDP) comes from the service sector [2], compared to the 10% contribution in GDP by the manufacturing sector [3]. In the US, American business and consumers contribute approximately $1 trillion every year into the after-sales market [4]. The service division of Cisco systems, a system data storage manufacturer, saw an increase of revenue of 13% between 2004 and 2006 [5]. Companies have recognised the importance of gaining a significant after-sales market share in order to maintain their competitiveness within the industry [6]. In 2014, IBM derived over $13 billion of its revenue from its service segment, which is over 55% of its total revenue in the same year [7]. This shift began in the 1990s, when companies started to diversify investment from manufacturing to service capabilities, to offer product service system (PSS) to customers. There are three basic orientations of PSS; product-oriented, use-oriented and result-oriented as shown in figure 1.

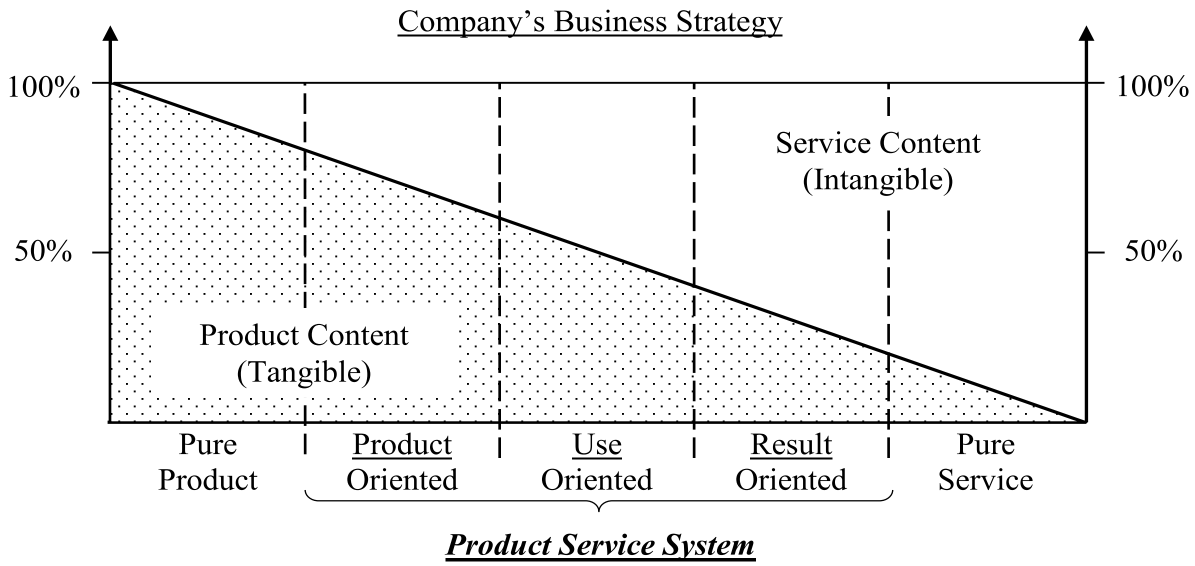

Figure 1 - Product Service System Types (Adapted from Tukker) [8]

These orientations are classified by the split between product ownership and service support that customers receive. Product-oriented is the most common and demands the least

involvement and monitoring abilities from the OEM and service providers. Product ownership transfers completely from the OEM to its customers, when the terms and conditions of the service agreement and product specification are satisfied. In contrast, in service-oriented PSS, the OEMs and service providers have a responsibility to meet the customers' desired outcome(s). No ownership of the product, except the outcome, will be transferred to customers, and the customers tend to pay fees for the achievement of the outcome. This orientation relies hugely on proactive real-time product monitoring and analysis abilities from the OEMs and service providers. The best example of such a PSS offering is Total Care from Rolls Royce, whereby about 80% of Rolls Royce engines are not being sold but rented to airlines, and the outcome is the "thrust" provided by the engines that keep the aeroplane air bound [9].
This paper will focus on use-oriented PSS adopted within the off highway construction industry, which is a 50/50 balance between product and result-oriented PSS. A use-oriented PSS dictates that the product stays in the ownership of the provider, and is made available in a different form to the customer (user), and is sometimes shared by a number of users [8].
Despite extensive research which has been carried out into PSS design and strategy, there is a research gap relating to the generation, analysis and management of use-oriented PSS data. This gap is a substantial barrier to the implementation of the use-oriented PSS research in the commercial world.

The requirements for the move to servitization

The problems faced by OEM operations can be framed in terms of operations and information management. PSS is a marketable set of products and services capable of jointly fulfilling a user's need [10]. It can also be defined as an integrated product and service offering that delivers value in use[11].To implement PSS effectively, OEMs must provide an integrated product-service, which requires inter-organizational integration through the coordination of manufacturing systems, maintenance systems, spare parts supply systems, and logistics systems[12], in order to support both their product and service delivery to customers. Manufacturing capacity may therefore need to be increased to support the service requirements for products under service agreements. The capabilities and knowledge required to plan and manage delivery of service are very different from manufacturing planning and management as typically applied [13]. Some OEMs outsource a service business to a third party logistics/service provider, to gain access to the required additional new technologies and resources to extend the organisation's service capability, without the need of capital investment or time commitment to restructure the organisation [14]. Erkoyuncu categorised the different types of uncertainties that exist when delivering an Industrial Product Service System (IPS2), a business to business (B2B) form of PSS, concluding that these uncertainties need to be examined to allow industries to focus on providing the right level of service support to customers[15]. Indeed, the off-highway equipment industry faces challenges to achieve a profitable balance between supply and demand, as a result of dynamic service requirements demanded by products in the field. Some uncertainties are related to operations, which are linked to reliability and repairability of products, mean time failure rate etc. Even OEMs with telemetry systems may still lack the ability to fully exploit them in the context of PSS as they do not necessarily have an in-depth understanding to interpret the telemetry data to clarify of the state of products in the use-phase, and consequently reduce PSS uncertainties. In-depth real-time remote product monitoring such as telemetry can be expensive and requires skilled employees to determine the health of the products. As a result, the most common form of PSS (product-oriented) in most industries is preventive maintenance, in which services are scheduled periodically based on either the time period of usage, or days between services. In each service interval, service technicians will follow a standard list of checks and replace worn parts to ensure that the product is running at peak efficiency, unless a specific investigation or repairs are necessary. It is the nature of construction machines to have irregular usage patterns known as duties, and thus create deviations between the actual usage profile and the predefined profile that the preventive maintenance program for the product is based on. Therefore, it is more common for such products to require repair or servicing before the pre-scheduled maintenance is due.

To meet the growing demand in after-sales support and to address the dynamic usage profiles commonly exhibited in the construction industry, practical implementation guidance is needed for OEMs to clarify any data and structure prerequisites to operate a use-oriented PSS in their business model. However, such practical implementation guidance for industry has attracted little interest from the research community compared to academic projects on the continuous development of PSS. Furthermore, use-oriented PPS requires good understanding of the condition of the product in real-time, to allow OEMs/service providers to determine the right time and level for service provision. In truth, little real-time usage data are being collected from the products by construction OEMs and service providers, and consequently OEMs do not necessarily have sufficient information to clearly determine the type of duty that the products were carrying out. Although some OEMs have marketed their maintenance programs as condition based maintenance (CBM), as yet most of these programs do not possess or fully utilise the real-time data needed in CBM for use-oriented PSS. OEMs and service providers are simply not equipped or ready to run a CBM program, and instead end up providing preventive maintenance program support based on very limited real-time data. Furthermore, Redding suggests that the key to a successful PSS is to increase the understanding of product performance, component, system and subsystem degradation, diagnostics, prognostics and assessment of the product's availability and remaining useful life (RUL)[16].

Therefore, it is important to emphasise that this paper analyses the requirements for use-oriented PSS, and presents a bespoke road map for construction OEMs. The purpose of the roadmap is to clarify prerequisites (such as product usage data, real-time monitoring and maintenance strategy) that are critical for OEMs to determine and examine their readiness for a CBM-powered, use-oriented PSS.

The remainder of this paper proceeds as follows: a literature review is provided focusing on the nature of PSS and explaining the critical role that real-time maintenance plays based on views from both industry and academia. The literature review concludes with a summary of the essential requirements for implementation of a use-oriented PSS in off road vehicle industrial contexts. The literature review is followed by the proposed roadmap. The paper ends with a conclusion that covers the contribution of this research to both industry and academia.

Combining product and service

This review introduces PSS as a paradigm that can fit into various business models within industry, and in particular discusses use-oriented PSS and its close relationship to real-time maintenance.

Product service system (PSS)

In recent decades, there has been a dramatic increase in demand for goods in emerging markets such as India and China. As a result, OEMs who are mostly based in developed countries face two main challenges. 1.) To increase manufacturing capabilities to supply the growing global demand. 2.) To increase service capacity, including logistics infrastructure, to support increasing global product populations. Fundamentally, nearly all products designed and manufactured by OEMs are sold to generate revenue and gain market share. In order to capture revenue from the expanding service sector, most OEMs offer service agreements to customers, hence customers are likely to be offered a combination of the tangible product as well as an intangible service element. This combination is known as a PSS.

PSS can be defined as a marketable set of products and services capable of jointly fulfilling a user's needs [10]. PSS is a system that includes and integrates products, services, support networks and the necessary infrastructure to offer services such as maintenance, recycling, recovery and software/hardware update etc. [13]. PSS can also be considered as a combination of tangible products and intangible service, targeting the specific needs of customers [17]. The balance between product and service can vary based on the function fulfilment or economic value in respect of manufacturers, service providers and customers [8]. PSS was developed as a sustainable approach towards the conventional concepts of production and consumption for both manufacturers and consumers [18]. There are two forms of PSS, with use depending on the type of business relationships between the two or more parties [19], and these are either B2B or business to consumers (B2C). PSS is typically found in B2C markets, where customers are most likely to be the end-user retaining the full ownership of the products. In addition, use of these products will also be facilitated or supported by various service agreements such as maintenance or upgrade plans either directly from OEMs, or indirectly from dedicated service providers [20]. IPS2 is essentially a B2B version of PSS, where the business demands a shift towards selling functionality instead of products [21] , e.g. van and photocopier rentals.

A successful PSS or IPS2 depends on the quality of the service as well as on the reliability of the product. Typically the strategy for the improvement of product reliability is dictated by data and information gathered from feedback from product end-users through various channels. Service quality is usually measured by the period in which the product is unable to perform its desired functionalities; this is typically known as down-time. Similar to the assessment of the acceptable defect rate within manufacturing using six sigma, in which there is tacit acceptance that zero defects is a target that will never be reached, there should also be an understanding that zero down time is not possible. However, in PSS it is important for both suppliers and customers to minimise downtime as far as possible. Extensive and frequent down time periods within the service sector can be the result of unrealistic maintenance programs, inadequate understanding of product behaviours during the use phase, lack of real-time product monitoring programs etc. Therefore without a real-time maintenance program that provides vital diagnostic and prognostic analysis, measuring the deterioration of products due to age and actual usage, OEMs and service providers will not be able to maximise PSS potential to gain additional market share, and may even suffer financial loss. Furthermore, construction equipment is often subjected to very harsh and unknown operating environments and styles. To maintain competitiveness, implementing use-oriented PSS that is supported by real-time maintenance programs in their business model, is a solution to ensure product reliability and prolong operational life[22, 23].

Real-time maintenance programs in PSS

Maintenance has a key role in delivering performance driven solutions in PSS[24], as it offers opportunities for OEMs and service providers to provide high value added services based on the condition of the product. It is also in the OEMs' and service providers' interest to ensure high product performance levels through maintenance at a reasonable cost. Hence the development of maintenance and product support should be considered at the product design phase [25]. The goal of maintenance is to reduce down time by improving product reliability by capturing and analysing any relevant product data [26]. The Oxford English Dictionary [27] defines maintenance as, "The process of preserving a condition of a situation or the state of being preserved", which implies that a certain level of understanding of the products' actual condition and state is essential in order to determine what maintenance is required. Therefore, it is essential for OEMs and service providers to have at least a basic understanding of the products' condition at any given time. In fact, most OEMs lose track of product lifecycles after the warranty period has expired [28]. As a result, most off highway construction equipment is maintained through a fixed scheduled maintenance plan, commonly known as preventive maintenance. The maintenance is typically based on the use of the equipment, e.g. number of engine hours used, thus removing the need for real-time data. Maintenance provision is commonly set up as a form of service agreement between customers and OEMs/service providers in a product-oriented PSS environment. Scheduled maintenance is one of the most popular types of maintenance within the industry, where specific types of service are carried out to minimise down time by controlling the rate of deterioration of the product. However, Diego Navarro, the global fleet management solutions manager for John Deere Construction and Forestry Division suggested that the rigidity of such maintenance contracts causes fleet managers to tend to wait for components to fail, before doing something about it [29]. He further suggests that the industry should focus on maximising uptime instead, by adopting condition based maintenance (CBM), and continuous checks for failure symptoms to identify the health status of equipment at a given time, hence allowing impending faults to be prevented. For example, most automotive products now contain an electronic system that is capable of detecting the presence of a fault condition and displaying a Diagnostic Trouble Code (DTC) [30] to the operator, which can be captured and transmitted via a telemetric system. CBM is a type of predictive maintenance based on frequency of product wear deemed to be responsible for the eventual cause of mechanical breakdown [31]. Such real-time data or information can be generated or captured by methods such as an oil analysis program [32] or on-board sensor units, and as a result, large amounts of wear data or information would need to be stored and processed to achieve CBM.

But what is real-time data, and where do they come from? The basic infrastructure of a real-time monitoring system is comprised of a data collection system, a data transmission system and an information processing and distribution system [33]. Scheidt categorizes product data into two types: static and dynamic life cycle data [34]. Static data refers to the product specification, bill of materials (BOM) and service parts that can be found in the owner's manuals, service manuals or performance handbooks etc. As suggested by its name, most of the data of this type will remain static throughout the lifecycle of the product, unless a major update is due. In general, most dynamic data are extracted by a telemetry system and transmitted via a Global System for Mobile Communications (GSM) or Global Positioning System (GPS) back to the OEMs or service providers, where the data are analysed to determine whether any actions need to be taken. Dynamic data is only generated during the use phase of the product and hence is the key focus of real-time monitoring. It is one of the six principal applications for condition monitoring [35]. OEMs and service providers can schedule in a service if an occurrence of a fault is deemed to be imminent, without the threat of causing any down time. Although the primary function of the dynamic data is to support the condition monitoring of products, the same data can play a significant supportive role within product improvements or new product development. In the context of a use-oriented PSS, OEMs and service providers need to expand monitoring criteria to other key systems on the product to support the service intention of PSS. Dynamic data from construction equipment can provide information such as: idle time and working periods, fuel usage, oil contamination etc. Such data should also be treated as the life history of the individual product regarding its usage behaviour from the particular point of view of the data set, e.g. oil contamination. It is now an industry standard to have such real-time information output from any piece of construction equipment on the market. Jeff Davis president of Edge Contracting was able to cut his fuel costs resulting in a saving of $50,000 to $100,000 per year, only by knowing the amount of idle time his machines were generating [36].

Use-oriented PSS in the construction equipment industry requires telemetry systems to monitor the product and pre-alert customers of any premature faults (i.e. by achieving CBM). That said, most maintenance programs offered within the market still provide preventive maintenance support in a product-oriented PSS, rather than CBM support in a use-oriented PSS. The lack of dynamic data could be one of the reasons for unsuccessful CBM implementations. Furthermore, Doug Oberhelman, Caterpillar's Chairman and CEO claims that all Caterpillar dealers struggle to provide an adequate level of data management to support CBM, due to lack of resource to enable the interpretation of both static and dynamic data for CBM, as well as an inability to create and maintain infrastructure to handle the data [37]. CBM which is a type of predictive maintenance takes time to implement; Schlouch's chief operating officer, Don Swasing claims to have taken 48 to 60 months to establish the baselines and benchmarking of conditions for various components, before being confident enough to successfully apply CBM on their own fleet [29].

In summary, this review has identified some important problems relating to PSS and the necessary infrastructure to channel their delivery of service, such as:

- Insufficient quantity and reliability of dynamic data that could provide a service-critical product usage profile.
- Lack of understanding in, and infrastructure for, analysing dynamic data to support a PSS.
- Recognition of the extended level of cross-functional participation from engineering to service departments.

The roadmap presented in this paper will address each of these problem areas. In particular, industry will struggle to implement a use-oriented PSS without detailed understanding of the related knowledge requirements. In truth, a use-oriented PSS demands OEMs to have adequate, ongoing awareness through real-time monitoring of the condition of their products. These real-time product data or information should be consistently analysed and data mined to detect any patterns of behaviour or performance, and hence any recurring or historical conditions, that are beyond the normal acceptable parameters. The materialisation of any such conditions should influence the product's dynamic maintenance (service) schedule, needs and requirements, as significant savings and efficiencies may be gained in this way. It should therefore be worthwhile for OEMs to dedicate substantial resource to the management of this important static and dynamic data and a knowledge hub could be designed to systematize the discovered data and knowledge. The active participation, co-operation and interaction of all stakeholders are also important and a knowledge hub could also provide a strong visibility and links to all the stakeholders internal or external to the OEM. Finally, OEMs need to accept and manage the dynamic nature of PSSs which is due to continuous product and service improvements throughout their product range, as well as the complexity and uncertainty which are inherent due to the importance of product real-time data. A tool is therefore needed to aid the off highway OEMs to comprehend the complex dynamic network and infrastructure of a use-oriented PSS, the development of which is presented in the next section.

The need for a PSS roadmap for the construction industry

Use-oriented PSS relies heavily on dynamic data captured from products on a real-time basis. With emerging telemetry technologies, more real-time data could be extracted to support the transition from product-oriented PSS (scheduled maintenance) to use-oriented PSS (CBM) in the construction industry. However, there is a lack of understanding or poor analysis of available dynamic data, rather than insufficient dynamic data. Some current CBM programs, although limited in their monitoring capabilities, are deemed to be successful as they still follow the basis of a scheduled maintenance program whilst being supported by limited real-time data. The key criterion for a successful use-oriented PSS is the ability to access and take advantage of the most beneficial dynamic data as it becomes available, in a timely manner. It is common practice within the construction equipment environment, for a substantial amount of manual work to be involved in collecting the generated dynamic data and interpreting data to facilitate asset management decisions [37]. All stakeholders within the PSS's service centric environment, such as OEMs, service providers, fleet managers, owner etc., need to focus on the benefits available from dynamic data and integrating them with other information to direct decision making processes. Therefore there is a need to create a roadmap that clarifies the required data and structure prerequisites, for OEMs to determine and validate their readiness level towards the adoption of a use-oriented PSS driven business model.
In summary, the roadmap should answer the following questions in response to the research gap identified earlier:

1. What are the critical elements for a use-oriented PSS?
2. How are these elements to be linked together?
3. How should dynamic data be determined and collected?
4. Who within the organisation should be involved?
5. How should the data be processed, and how might its intangible value be captured?

Development of the roadmap

A roadmap has been designed to address the knowledge requirements for use-oriented PSS identified above. The roadmap applies to any construction machines that are equipped with telematics, and hence to OEMs who have the ability to extract real-time data. However, any service or warranty data records where real-time extraction is not possible may still be applied in DM and KH. The Roadmap was constructed using an adaptation of the IDEF0 (Integrated Computer Aided Manufacturing Definition for Function Modelling), functional modelling (FM) methodology, based on Structured Analysis and Design Technique (SADT). FM is designed to present complex product development processes, especially involving complex interdisciplinary elements in the process[38]. Furthermore, IDEF0 plays an unquestionable role in making the acquisition of knowledge related to the as-is state easier[39], and hence the assessment of current practice for today's need. It breaks down each function from the highest hierarchical level into more detailed diagrams until the necessary level of detail is achieved for the specified purpose[40]. Therefore IDEF0 fits the purpose of this research which aims to clarify the prerequisites for the adoption and implementation of a use-oriented PSS.
Figure 2 shows the basic context diagram of IDEF0, from which the road map has been developed. The rectangular box presents a function, which is carried out by a mechanism, by following certain controls, such as specified standard operation procedures (SOPs) or data mining within databases, to process inputs that result in a single or multiple outputs.

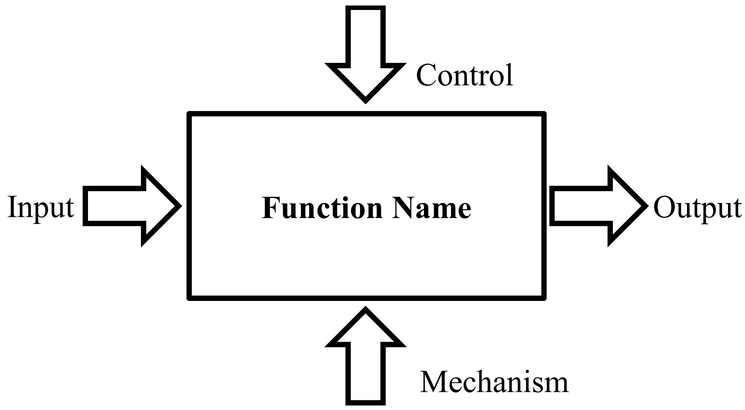

Figure 1 - IDEF0 Example

In the use-oriented PSS implementation roadmap, inputs can be data sets, company information, knowledge or official documents. The product is the most important input as it is the driver of the core idea of PSS as well as use-oriented PSS implementation. The mechanisms are facilitators in the form of OEM departments, OEM dealers, or software that processes inputs in accordance with controls that the mechanism has to abide by. The OEM's internal SOPs, which include its standards and protocols, as well as international standards (e.g. ISO 4406) or regulations, are the main controls. They set the boundaries such as product monitoring criteria for emission regulation, electrical and electronic infrastructure used for communication and diagnostics among vehicle components (J1939 / J2012 protocols) etc. to which the OEMs have to comply.

The use-oriented PSS implementation roadmap is divided into three clusters; Product Monitoring (PM), Data Mining (DM) and Knowledge Hub (KH). PM is carried out by using the knowledge created and organised in the KH to investigate the plausibility and feasibility of the decisions when applying a real-time monitoring strategy on products or components. DM may be used to find patterns and relationships within the data (that PM has clarified and combined with the knowledge from KH), to determine the type and timing of service action that the OEM should conduct. KH governs and organises the multiple databases of historical warranty data, service and telemetry records, which may be processed by cognitive and analytical methods. This analysis may produce two streams of knowledge, i.e. one that can be used in problem solving for current products and another which can facilitate innovation for new products; both streams are essential elements for OEMs to remain competitive in their respective markets.

The use-oriented PSS implementation roadmap also contains a mixture of sequential and loop functions between the three clusters, which reflect the nature of analytical root cause analysis such as Fault Tree Analysis (FTA), and continuous improvements of service protocols, SOPs etc. that OEMs implement to derive service requirements. In this way, a PSS can be treated as a partially "live" system which is comprised of both static and dynamic data as classified by Scheidt. The static elements represent the company's organizational structure, core products' model and functionality etc. These are the elements that are likely to remain unchanged until a major reorganization, such as a reacquisition or change of market occurs. The dynamic elements refer to new technological improvements on products, change of legislation etc. which will have a direct impact on service protocols, and even on the design of the product. For example, Tier 4 emission regulations have forced OEMs to install after treatment systems into their products in order to meet the regulations. As a result, service protocols and, product monitoring strategies were changed in order to compensate for the implementation of new technologies, with the exception of basic systems of the products. The databases in KH that are used as controls for functions within PM and DM shall be subjected to constant updates, that are driven by the changes triggered by specific outputs within PM and DM.

Managing the database – knowledge hub (KH)

This cluster as shown in Figure 3 manages all the information and knowledge needed to support the functions within PM and DM, as well as setting an internal standard regarding the renewal of the information and auditing of the entire PSS infrastructure.
A loop function is used, which is adapted from the concept of 5S methodology, which is the creation and maintenance of an orderly system, through reduction of waste and standardization of upkeep, to achieve high productivity and consistent results. The loop function is needed to allow new records, protocols and company policies to be captured to maintain the high responsiveness of PSS. Due to dynamic market demands, master protocols and records have to be updated with new inputs at a certain frequency, to ensure an accurate and effective service is provided by the service department. This is a cautionary point: should any protocols be changed, say due to different component design, then it is important that the service instructions reflect this change, and are fully up to date. Should this not happens, then there is a risk that the service instruction could be unhelpful or even damaging. The roadmap also recognises the differences in business models within OEMs and therefore the company's own service and growth strategies are considered as a control for the function responsible for creating the master DTCs service action protocol. The service department ought to be the lead department among the four functions within this cluster. This department is responsible for validating the information given by other departments and integrating it into existing protocols or databases.

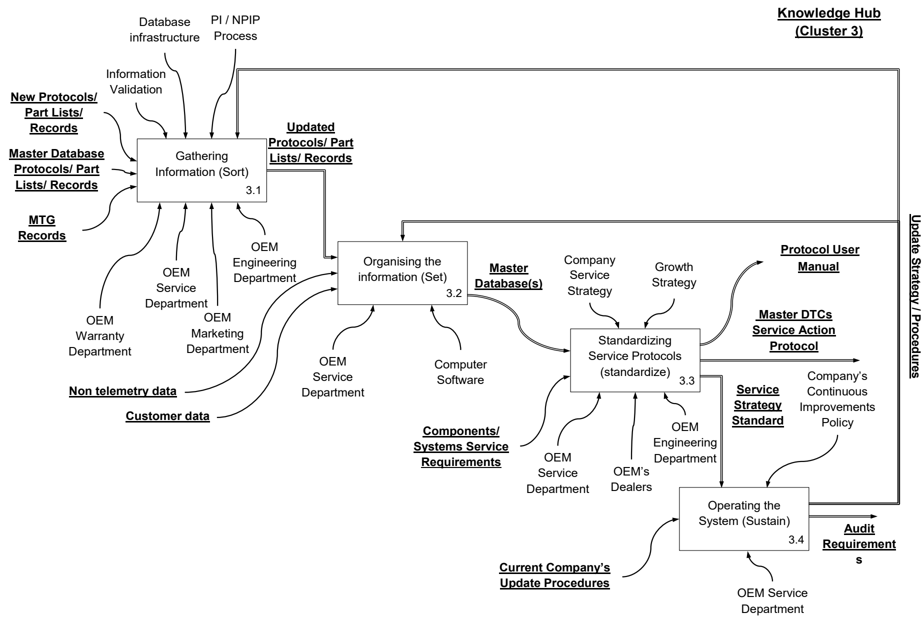

Figure 1 - Knowledge Hub (KH)

Furthermore, the service department will be one of the first departments to trigger requests for improvement or updates of the service action protocols for the purpose of maximisation of product uptime and ensuring that an effective master DTCs service action protocol is being maintained for a consistent PSS.

Setting the foundation - product monitoring (PM)

The focus of this cluster, Figure 4, is the creation of dynamic data from the products during their use phase. There are six sequential based functions within this cluster, with the first three functions focusing on the selection of sensor and monitoring instruments, and the last three functions focus on the successful extraction of raw data from the installed instruments on the products in the field. The main controls of this cluster are DTC warranty, service, telemetry historical records and diagnostic communication protocols, managed from the master database in KH.

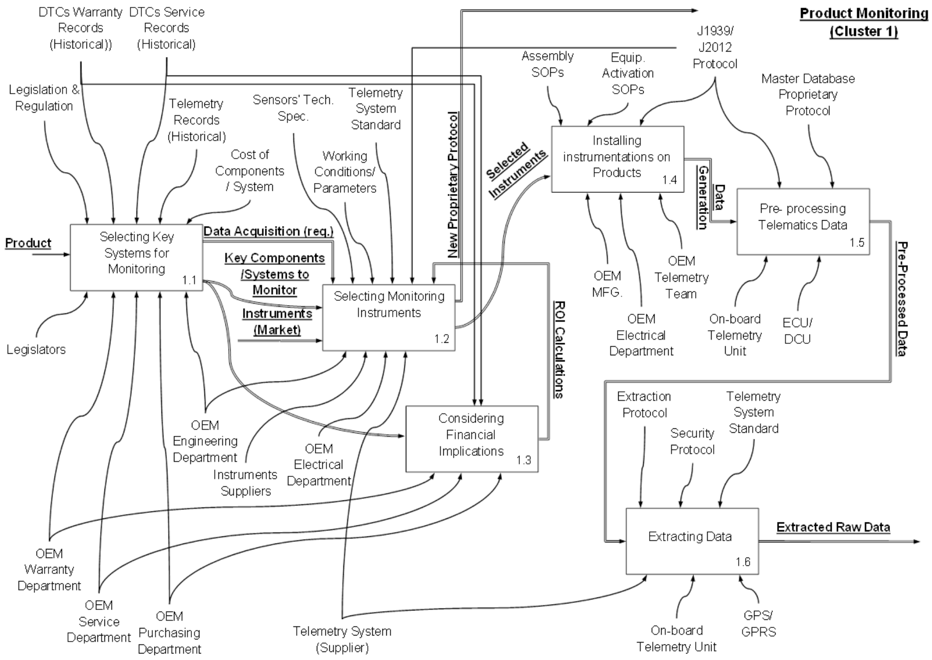

Figure 1 - Product Monitoring (PM)

The main element of PSS is the product, and this is also the case in the PM cluster. With maximising product up time as a goal, OEMs will use DTC historical records from the master database in the KH before selecting and installing instruments onto their products. These records offer knowledge to OEMs regarding the challenges they are facing in achieving 100% product uptime in the field. There are three main aspects for OEMs to consider when selecting the instrument. OEMs need to measure the Return on Investment (ROI) between the financial impacts on the business due to warranty and service costs, and the cost of instrument installation, maintenance, data extraction and analysis etc. which also includes the reprogramming costs of the telemetry devices. Failure of critical high cost components which provide the primary functionalities of the product, for example the engine and hydraulic system of modern excavators will almost certainly ensure the total unavailability of the product if their condition goes critical.

Finally, the selected instruments need to match the data acquisition requirements addressed by the engineering department, such as data compatibility with the electronic systems and the telemetry unit, and ability to function accurately within tolerances under the typical working conditions of the product. The data extraction strategy should not compromise the integrity of the generated data due to data size. OEMs should consult the data acquisition requirement when deciding on the extraction frequency, as well as adopting an appropriate data management system to reduce the data size via pre-processing the data within the telemetry unit before extraction.

Proactive responsiveness – data mining (DM)

The focus of this cluster, figure 5, is to convert the extracted raw data from the product into actionable items for OEMs. In order for the OEMs to decide what action can be taken as a result of the extracted raw data, the data has to be pre-processed, enriched and interpreted. The extracted raw data could be in a form of J1939 / J2012 protocols language or even software language, therefore it needs to be pre-processed into a recognizable language for further analysis i.e. DTCs. Enrichment is the most important function within DM, as it links the pre-processed data with the master database from KH which provides the essential background and historical information and knowledge to each individual activated DTC. As mentioned earlier, the database enriches and deciphers the occurred DTC, and identifies the checks or service that the OEM is required to perform. These challenges should be prioritised against a DTC based on financial impact, frequency, the effect of product uptime etc., as such prioritization allows the OEMs to attend to the most urgent, business threatening challenges first before addressing the minor issues.

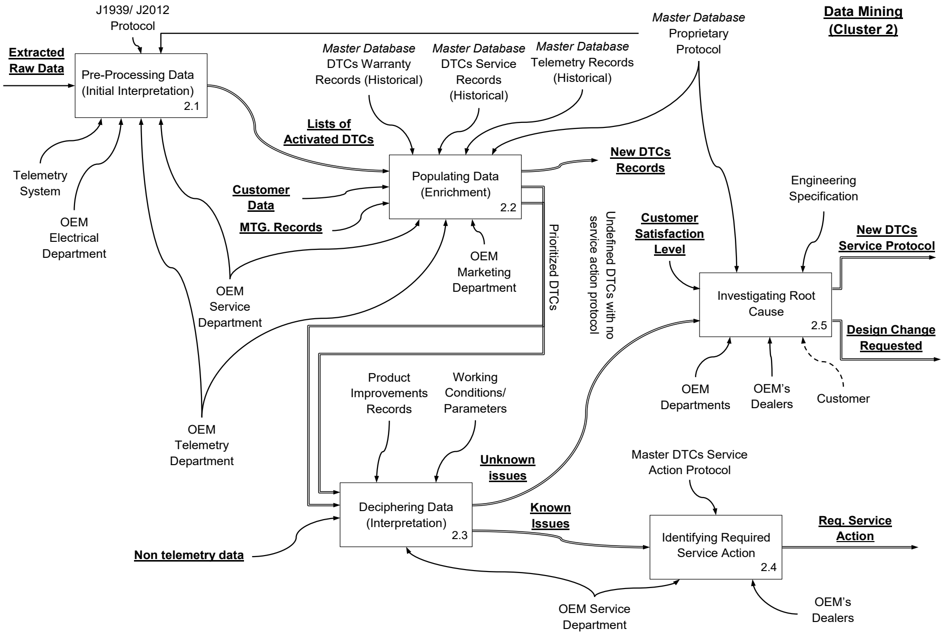

Figure 1 - Data Mining (DM)

Therefore, the output after enrichment is a new set of DTC records for KH to manage and update, and two sets of DTCs for interpretation, consisting of a set of high priority DTCs and a set of undefined DTCs. Depending on the business strategy adopted by the OEMs, customer feedback and usage behaviours could be available as a valid input for enrichment.

Once the data is enriched, the OEM can analyse them to determine the course of action to be taken according to the database, master DTCs service action protocol, from KH. OEMs should look for certain behavioural patterns within the data to match with records within the database. This could be anything from a DTC's activation duration to duties performed on the product which produce the DTC, e.g. a cold morning start on an engine may lead to harder cranking of the engine. OEMs have to match the cause of the extracted DTCs with the profiled root causes identified within the database, otherwise OEMs may pay warranty claims or send in service technicians needlessly.

Two outputs may be generated by the interpretation function; (1) unknown issues and (2) known issues. Known issues are DTCs with validated root causes, as a result the service department will be able to match the identified issue and then follow the master DTCs service action protocol from the database in KH. The protocol includes the requirement of resources, procedures and working duration for the service action needed to deactivate a validated DTC occurrence on the product. Adopting standardised protocols will ultimately reduce the down time of the product, and ensure the highest possible quality of the work conducted by the dealerships on the product. Unknown issues are DTCs that do not have matched profiles or do not exist in the master database, this could be the result of undesirable signals within the

Engine Control Units (ECUs) or a still open issue for the OEM to action. OEMs should form a cross functional team to identify the root cause of such DTCs, by examining the DTCs algorithms, measure parameters, customer satisfaction level etc. The customer satisfaction level should be based on fulfilment of customers' expectation and perception of the products; this quantitative input allows the OEM to prioritise its resource deployment, based on the degree of urgency with which a machine needs to be restored to fully operational. If such DTCs are not affecting the performance of uptime or even only affecting a very small number of products, with reference to six sigma methodology, there is an acceptable level of defects within the system.

The validation of the roadmap

The roadmap was used to underpin the real-time product monitoring strategy of a high profile project within one of the leading OEMs from the off-highway industry. Tools were created to allow the analysis of data and provide support for decision-making within the project. Upon project completion, six individual interviews were conducted with key personnel including: project general manager, project engineering manager, quality engineer, component OEM manager, marketing engineer and service manager.
Interviewees were asked to review the roadmap based on their own experience within the industry, and offer comments on its structure, and usability (i.e. suitability and relevance to the industry). Interviewees were also asked to provide detailed feedback on the roadmap, including any positive or negative impacts on the project. Their feedback confirmed that the roadmap allowed the OEM to realise the value of using telemetry data, allowing project completion to be achieved sooner and more economically. Issues were detected, investigated and responded to at a much swifter rate compared to previous projects. However, a number of refinements were also suggested to further improve the roadmap's suitability for the industry, in particular:

1. Early participation from end-users and customers in functions 1.1, 2.2, 2.3 and 2.5.
2. New output, "No Change", for function 2.5 to include acceptable fault that do not have significant effect to the performance of the product.
3. New mechanism, "OEM Sales Department", for function 3.1 include end-users' and customers' feedbacks.

Hence, the final version is presented in Figure 6, 7 and 8.

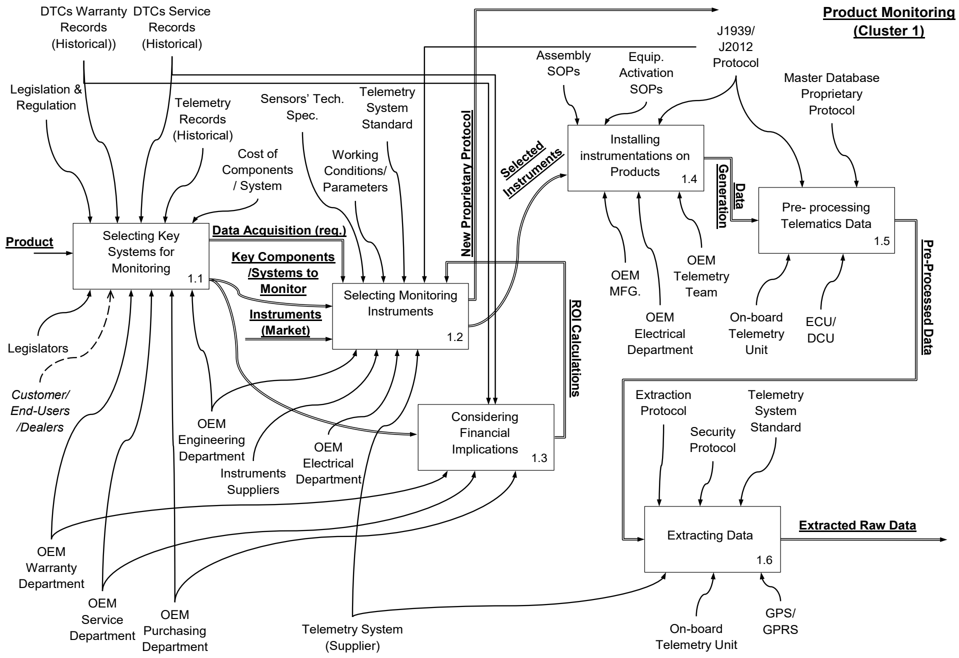

Figure 1 - Product Monitoring (PM) Revised Version

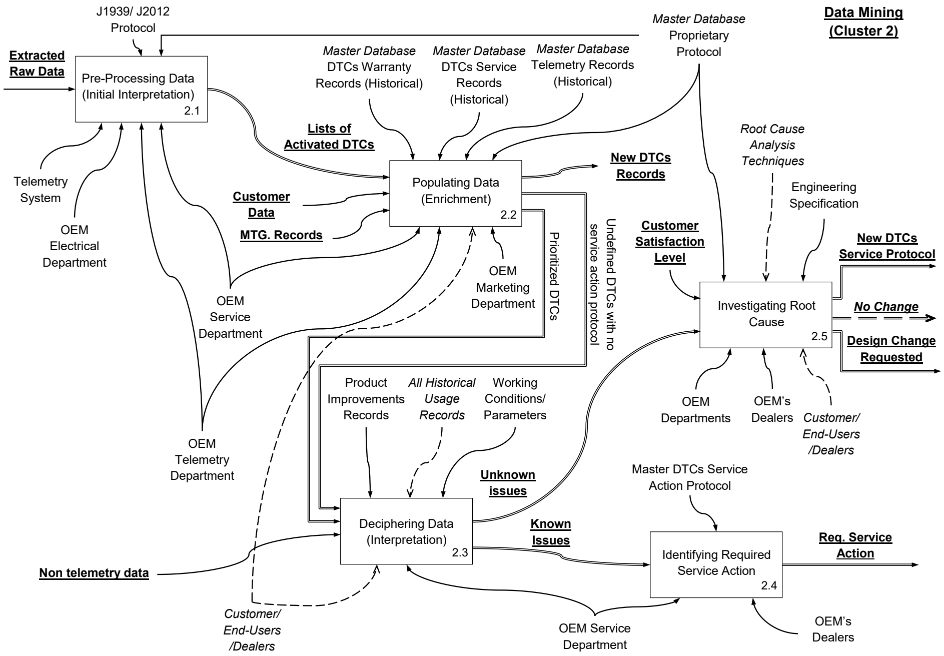

Figure 2 - Data Mining (DM) Revised Version

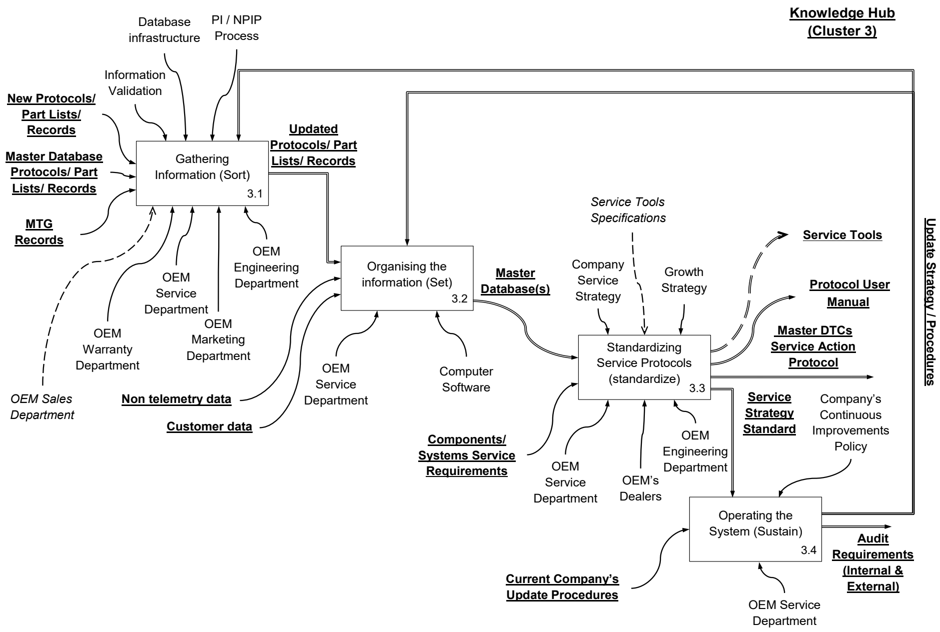

Figure 1 - Knowledge Hub (KH) Revised Version

Conclusion

The common first approach to PSS by OEMs is to simply adapt their existing preventative maintenance processes, but unless they also put substantial efforts and resources into understanding the knowledge requirements of PSS, they will subsequently fail to progress from a preventive maintenance model to a predictive business model. Traditionally preventative maintenance is the approach where service is applied at a fixed interval on the product to prolong its life. These fixed intervals are likely to be derived from outdated dynamic data, which may not represent the present usage patterns. Furthermore, products that are capable of performing more than two types of duties, such as construction machines, will have complex data that requires up-to-date background information to allow OEMs to act upon with an appropriate service protocol.

A use-oriented PSS implementation roadmap was constructed based on established organizational methods used in manufacturing, such as IDEF0 models, 5S and Six Sigma. The roadmap views PSS as a system which consists of the flow and transformation of data, and provides various functions and support in a form of information and knowledge within each individual function within the roadmap. It also includes the element which Redding[16] suggested to be important for a successful PSS to be achieved, i.e. gaining a better product understanding. The IDEF0's hierarchical structure places PM at the start of the chain of reaction with DM and KH following, however, at the same time PM is governed by some of the outputs from the other two clusters. OEMs need to transform the presented roadmap into their own language and adapt it to fit into their own infrastructure between the elements of product and service. As a result, OEMs may find that not only dynamic data are missing, but involvement of key departments or even the complete records of key service protocols may also be missing.

A novel roadmap has been developed and validated within the industry to help OEMs in the implementation of use-oriented PSS into their business model. The roadmap is designed to expose the critical prerequisites for implementing a use-oriented PSS, by simplifying the complex dynamic network and infrastructure requirements that are often underestimated or misunderstood by OEMs when they adopt the PSS paradigm.

The use-oriented PSS implementation proposed in this paper is original because:

1. It covers the fundamental prerequisites of PSS to allow OEMs to verify their abilities in achieving a successful PSS.
2. It explains the three fundamental functions required for the application of PSS; Product Monitoring (PM), Data Mining (DM) and Knowledge Hub (KH). These functions contain multiple sub functions interlinked with each other in both sequential and loop orders, representing the dynamic existence in the data, information and knowledge needed within PSS.
3. It addresses a gap in PSS research, regarding data creation in product monitoring and data mining, as these are often simply assumed to be available to OEMs.

This research therefore provides a new approach for OEMs to embed the benefits of PSS into their operations by addressing the essential prerequisites that OEMs ought to have, to ensure the successful implementation of use-oriented PSS.

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