



ELSEVIER

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Improving hydraulic excavator performance through in line hydraulic oil contamination monitoring

Felix Ng^{a,b,*}, Jennifer A. Harding^a, Jacqueline Glass^b^a Wolfson School of Manufacturing and Mechanical Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom^b School of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom

ARTICLE INFO

Article history:

Received 29 March 2015

Received in revised form

8 June 2016

Accepted 10 June 2016

Keywords:

Hydraulic oil contamination

Particle sensors

Construction equipment

Diagnostic

Prognostic

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.

© 2016 Published by Elsevier Ltd.

1. Maintenance strategy for mobile products

1.1. 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.

* Correspondence to: Centre for Innovative and Collaborative Construction Engineering (CICE), Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom.

E-mail address: f.ng@lboro.ac.uk (F. Ng).

<http://dx.doi.org/10.1016/j.ymssp.2016.06.006>

0888-3270/© 2016 Published by Elsevier Ltd.

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 1900-h 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.

1.2. 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 optimisation of specified capabilities", [9]. In this definition, "the optimisation 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].

1.3. 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 1900 h oil contamination monitoring study.

2. 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 (Fig. 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.

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

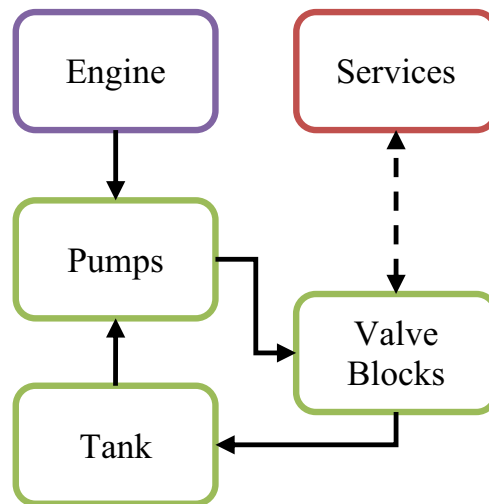


Fig. 1. Typical hydraulic system (simplistic).

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 5000–10,000 particles per millilitre. ISO 21 represents any counts from more than 10,000–20,000 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 pressurised 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

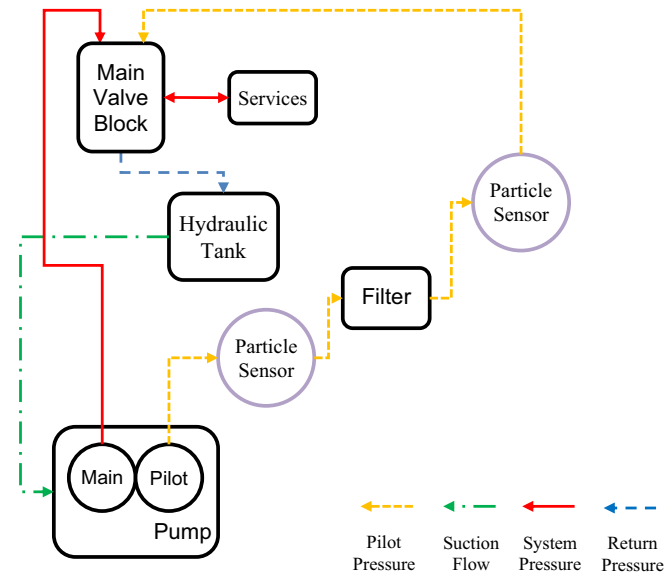


Fig. 2. A typical contamination sensors set up on a Hitachi machine.

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. Fig. 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 (Fig. 3).

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

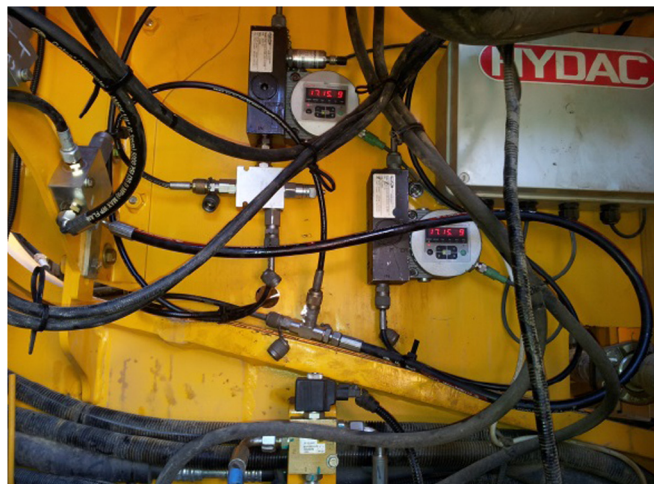


Fig. 3. Particle sensors and external data logger installations.

according to 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 1 ml [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:

$$Re = \rho \nu D / \mu \quad [60].$$

Where ρ is the density of the fluid, ν 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 min 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.

3. 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.

3.1. Experimental design

A 22 t excavator was selected and scheduled to perform a 2000 h 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. Operators were instructed to record any abnormal events (e.g. needing to refill fluids or seeing leaks) in their end of shift reports.

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).

3.1.1. Oil sampling

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 Fig. 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). Fig. 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.

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.

3.1.2. 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.

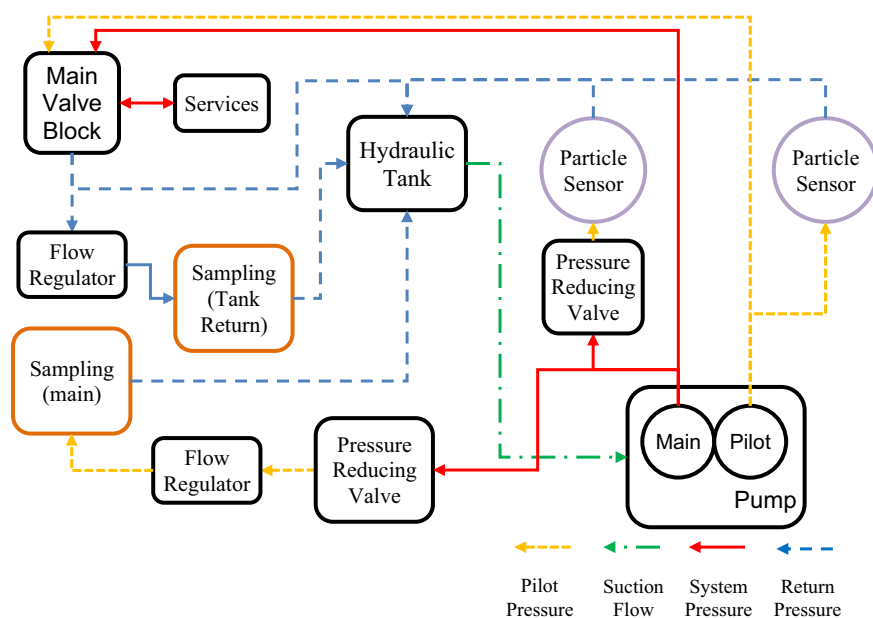


Fig. 4. Simplified diagram of the hydraulic system for a 22-tonne excavator.

3.1.2.1. 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 $\leq 4 \mu\text{m}$, $\leq 6 \mu\text{m}$ and $\leq 14 \mu\text{m}$ in ISO codes.
- 2) The temperature and saturation levels of the hydraulic oil.
- 3) Timestamp of each data point.

3.1.2.2. 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 $\leq 4 \mu\text{m}$, $\leq 6 \mu\text{m}$ and $\leq 14 \mu\text{m}$ in ISO codes.
- 3) Exact counts of $\leq 4 \mu\text{m}$, $\leq 5 \mu\text{m}$, $\leq 6 \mu\text{m}$, $\leq 7 \mu\text{m}$, $\leq 10 \mu\text{m}$, $\leq 14 \mu\text{m}$, $\leq 20 \mu\text{m}$ and $\leq 30 \mu\text{m}$ particles.
- 4) Timestamp of each data point and the machine hour at the time of the reading.

3.1.2.3. 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.

3.1.2.4. 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.

3.1.2.5. 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.

3.1.3. Method of analysing data

Data collected from particle sensors and physical oil samples were organised in Microsoft Excel to enable a quick initial

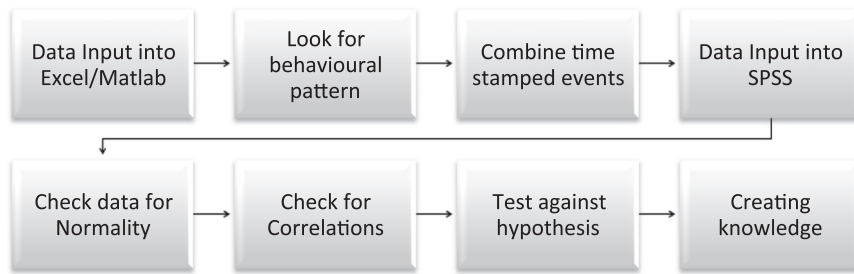


Fig. 5. Data analysis pathway.

assessment of sources A and B (See Section 3.1.2). 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 programmes (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. Fig. 5 shows a simplified flow chart explaining the analysis method.

3.2. Data analysis

3.2.1. Duty breaks down

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. The conclusion is that all duties were performed in the exact ratios planned.

3.2.2. Contamination by duty

Table 1 shows the average contamination levels over the total hours for the five duties (A–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 $\pm \frac{1}{2}$ 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 $4 \mu\text{m}$ per millilitre do have a large gap compared to the quantities of $6 \mu\text{m}$ and $14 \mu\text{m}$.

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.

3.2.3. 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 3.1, the main return filter was changed every 500 h 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

Table 1
Contamination by Duties (source A).

	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 2
Contamination by Duties Source B.

	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

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.

Within the first 500 h, 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/h. 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/h, and remained so throughout the rest of the experiment.

By 180 h 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 h 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 h.

A full hydraulic system oil change was conducted at 1000 h and thus a drop of contamination can be 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 h 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.

Fig. 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 100 h of oil circulation. Despite the differences in contamination levels in the last 500 h of the endurance programme, strong correlations can still be seen clearly.

3.2.3.1. 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

Table 3
Rate of change in contamination level (1st filter period).

ISO code/h	4 μm	6 μm	14 μm
Main Pump	–0.0059	–0.0077	–0.0105
Pilot Pump	–0.0004	–0.0028	–0.0058
Differences	0.0055	0.0049	0.0046

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

ISO code/h	4 μm	6 μm	14 μm
Main Pump	0.009	0.0067	0.0008
Pilot Pump	0.0073	0.0065	0.0007
Differences	0.0017	0.0002	0.0001

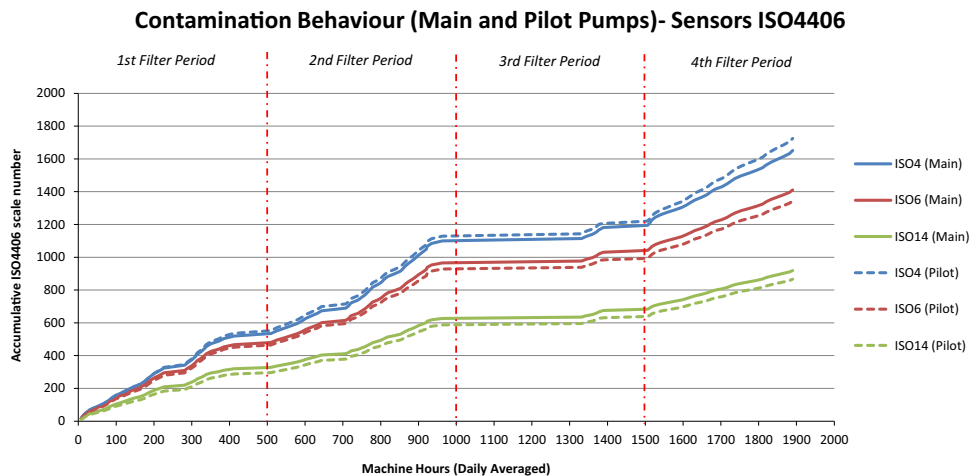


Fig. 6. The correlation of oil contamination (sensors – main and pilot pumps).

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.

3.2.3.2. 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.

3.2.3.3. 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 h, only low levels of Si and Al were found, therefore dirt contamination must have been controlled by the filtration unit. However between 1500 h and 1900 h, 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.

3.2.3.4. Wear Metal. 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 3 ppm level throughout the period. Fe was increasing at an average rate of 0.0185 ppm/h, 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/h. 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 Fig. 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.

Fig. 8 shows the behaviour patterns between different particulate sizes throughout the 1900 h. 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

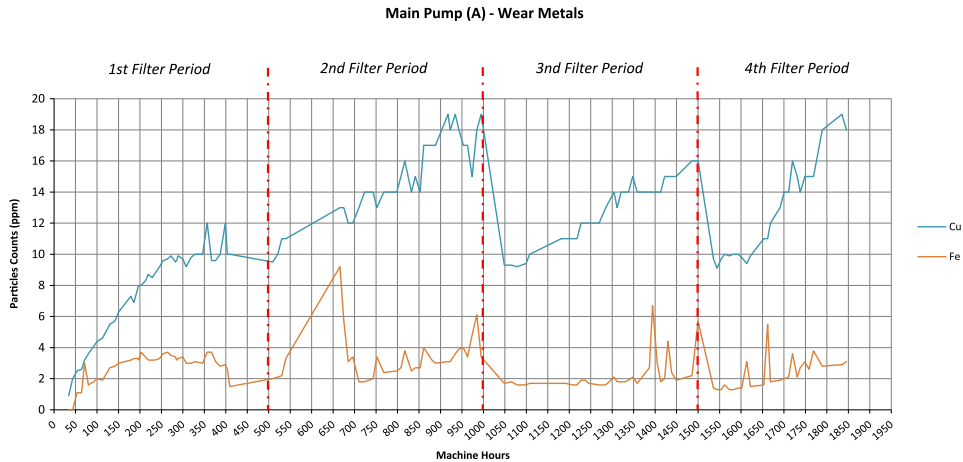


Fig. 7. The effects of filter change on contamination of wear metals.

are larger than $10\ \mu\text{m}$, and any built-in contaminants larger than $10\ \mu\text{m}$ are usually caught in the first 500 h of machine usage in any case.

3.2.4. Difference between ISO 4406 and ICP/OES

Figs. 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 $4\ \mu\text{m}$, $6\ \mu\text{m}$ and $14\ \mu\text{m}$ 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. 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 Fig. 10, within the filter 4 period, clearly shows that only the $4\ \mu\text{m}$ particulates were increasing steadily.

3.2.5. Filter analysis

Large amounts of particulates with varied shapes were found in the first filter. In particular large quantities of $100\ \mu\text{m}$ 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 Fig. 11 indicates the direction of the sliding motion. Large amounts of particulates over $100\ \mu\text{m}$ were also found only in the filter used in the first 500 h. These particulates, as shown in Figs. 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 h, leads to the conclusion that these Fe particulates were probably generated from the pump housing clearance and valve spool clearance.

Particulates found in the second, third and fourth filters were different in shape and quantity to those found in the first

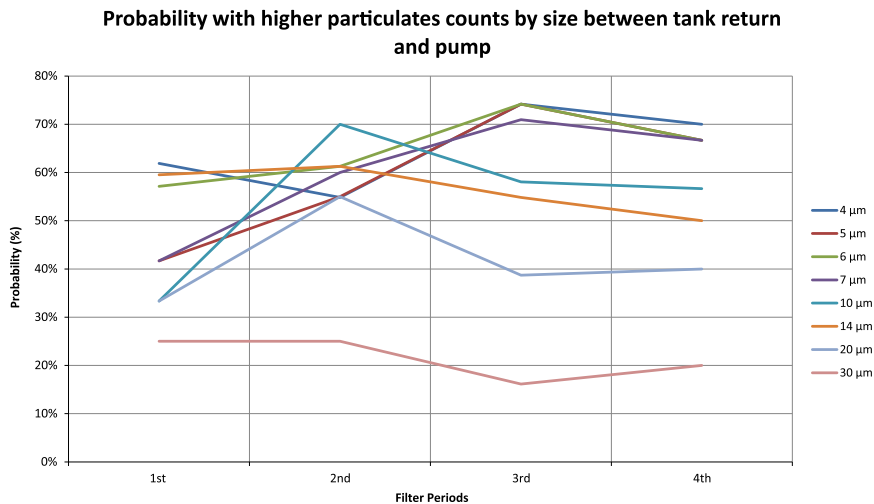


Fig. 8. Comparing tank return and pilot pump (ICP/OES).

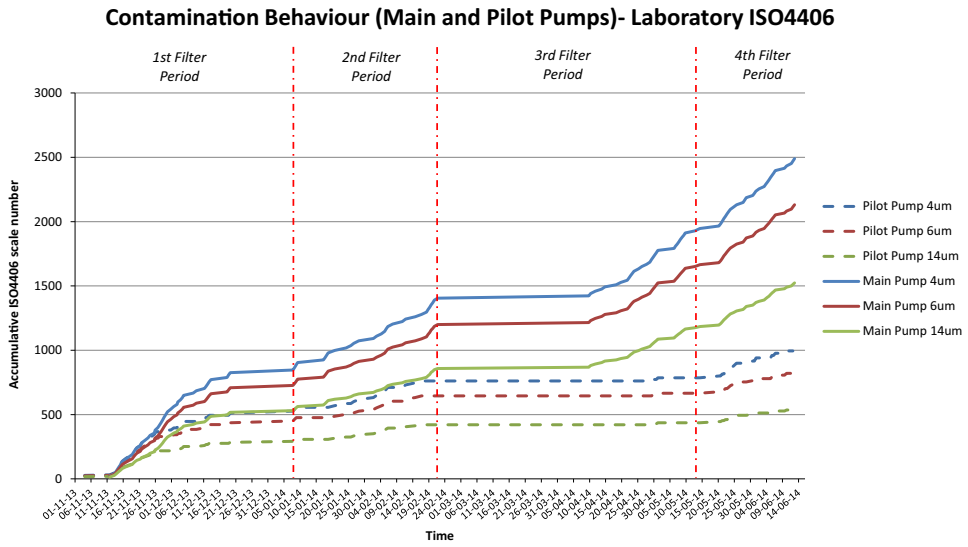


Fig. 9. Contamination behaviour by ISO4406 (ICP/OES).

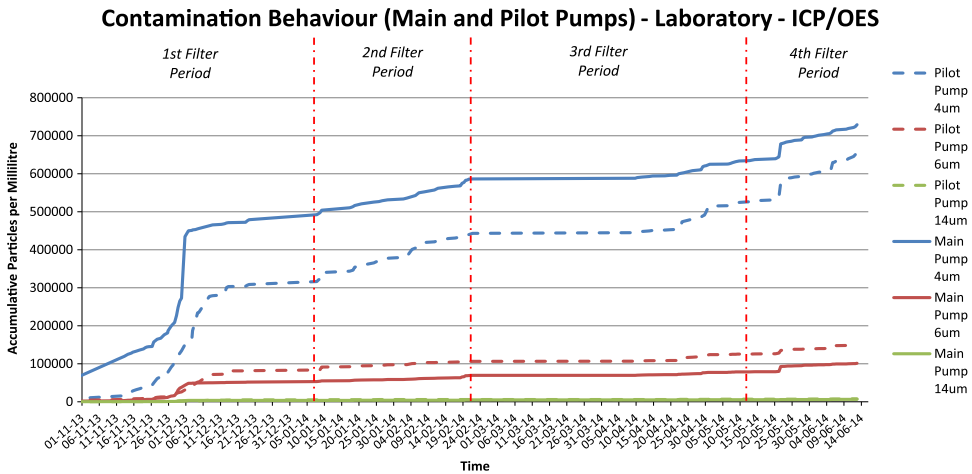


Fig. 10. Contamination behaviour by ICP/OES (Laboratory).

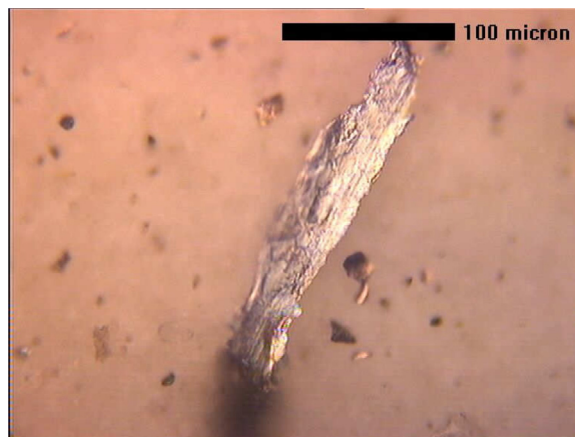


Fig. 11. 1st Filter microscopic image A.

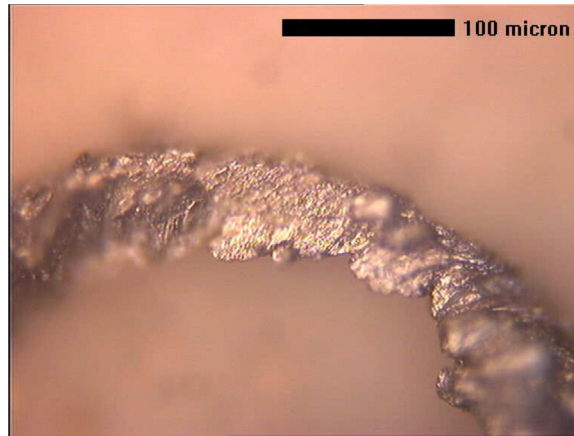


Fig. 12. 1st Filter microscopic image B.

filter. These particulates, as shown in Figs. 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 h, 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.

3.2.6. Overall contamination behaviour

Figs. 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 $4\ \mu\text{m}$ 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 $4\ \mu\text{m}$ particles identified between the first and second filter periods. After the first filter was changed, the increased rate of $4\ \mu\text{m}$ particulates stabilized until reaching the fourth filter period.

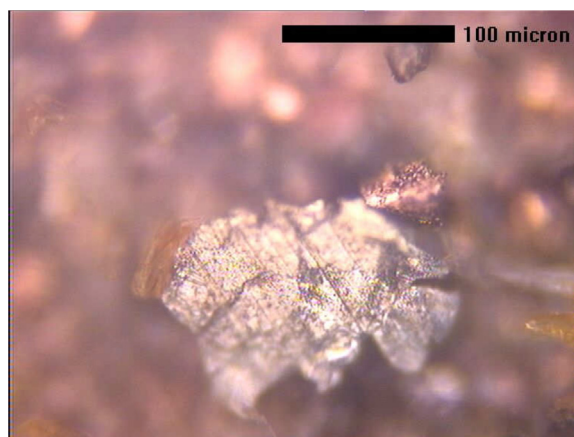


Fig. 13. 4th Filter microscopic image A.

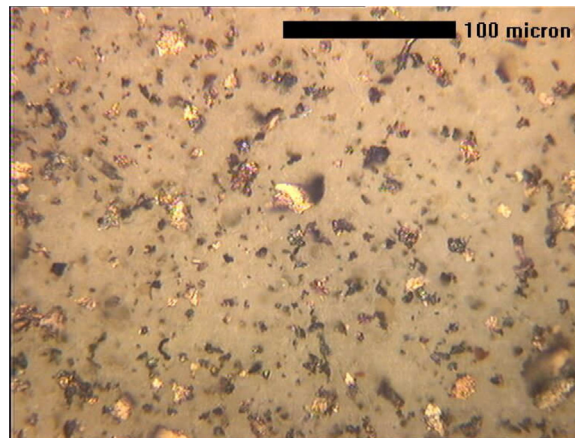


Fig. 14. 4th Filter microscopic image B.

4. Experimental results

The experiment carried out in Section 4.1 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 4.2 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 h. An analysis was then undertaken to answer the hypotheses stated in Section 3, as outlined below.

4.1. 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 3.2.3 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 explained by the relationship between saturation level and oil temperature. The strong negative correlation between these variables means, as temperature increases, fewer water particles will 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.

4.2. 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 3.2.3.4 do show higher, more obvious differences as the machine worked towards 1900 h. Therefore, H_1 was accepted.

4.3. 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 °C. 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° 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.

5. 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;

1. 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.
2. 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.

Acknowledgement

This research was undertaken as part of an EngD project funded by Centre for Innovative and Collaborative Construction Engineering at Loughborough University and a leading company in the off highway industry. The support of the Engineering and Physical Sciences Research Council is gratefully acknowledged (ESPRC Grant EP/G037272/1).

References

- [1] A.K.S. Jardine, D. Lin, D. Banjevic, A review on machinery diagnostics and prognostics implementing condition-based maintenance, *Mech. Syst. Signal Process.* 20 (2006) 1483–1510.
- [2] O.K. Mont, Clarifying the concept of product–service system, *J. Clean. Prod.* 10 (2002) 237–245.
- [3] A. Tukker, U. Tischner, Product-services as a research field: past, present and future. Reflections from a decade of research, *J. Clean. Prod.* 14 (2006) 1552–1556.
- [4] S. Rahimifard, G. Coates, T. Staikos, C. Edwards, M. Abu-Bakar, Barriers, drivers and challenges for sustainable product recovery and recycling, *Int. J. Sustain. Eng.* 2 (2009) 80–90.
- [5] H. Meier, R. Roy, G. Seliger, Industrial product-service systems—IPS 2, *CIRP Ann.-Manuf. Technol.* 59 (2010) 607–627.
- [6] B. Al-Najjar, I. Alsyouf, Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making, *Int. J. Prod. Econ.* 84 (2003) 85–100.
- [7] N. Madenas, A. Tiwari, C.J. Turner, J. Woodward, Information flow in supply chain management: a review across the product lifecycle, *CIRP J. Manuf. Sci. Technol.* 7 (2014) 335–346.
- [8] BSI, BS EN 13306:2010 – Maintenance. Maintenance terminology, 1993.
- [9] A.H.C. Tsang, A strategic approach to managing maintenance performance, *J. Qual. Maint. Eng.* 4 (1998) 87–94.
- [10] A.H. Tsang, C. Condition-based, maintenance: tools and decision making, *J. Qual. Maint. Eng.* 1 (1995) 3–17.
- [11] A.K.S. Jardine, A.H.C. Tsang, *Maintenance, Replacement, and Reliability: Theory and Applications*, 1st ed. Taylor & Francis, US, 2006.
- [12] A. Kelly, *Maintenance and its Management*, Conference Communication, 1989.
- [13] U. Kumar, D. Galar, A. Parida, C. Stenström, L. Berges, Maintenance performance metrics: a state-of-the-art review, *J. Qual. Maint. Eng.* 19 (2013) 233–277.
- [14] G. Abdulnour, R.A. Dudek, M.L. Smith, Effect of maintenance policies on the just-in-time production system, *Int. J. Prod. Res.* 33 (1995) 565–583.
- [15] J.M. Wetzer, G.J. Cliteur, W.R. Rutgers, H.F.A. Verhaart, Diagnostic- and condition assessment-techniques for condition based maintenance, *Electrical Insulation and Dielectric Phenomena, 2000 Annual Report Conference on.* 1, 2000, pp. 47–51.
- [16] US Air Force, *Condition Based Maintenance Plus*, 2014, 2010.
- [17] Y. Peng, S. Zhang, M.J. Zuo, Current status of machine prognostics in condition-based maintenance: a review, *Int. J. Adv. Manuf. Technol.* 50 (2010) 297–313.
- [18] S. Katipamula, M.R. Brambley, Review article: methods for fault detection, diagnostics, and prognostics for building systems—a review, Part I, *HVAC&R Res.* 11 (2005) 3–25.
- [19] Rolls Royce, *Monitoring Systems*, 2014, 2014.
- [20] C.S. Byington, M.J. Roemer, T. Galie, Prognostic enhancements to diagnostic systems for improved condition-based maintenance [military aircraft], in: *Proceedings of Aerospace Conference*, IEEE, vol. 6, 2002, pp. 6-2815–6-2824.
- [21] L.G. Scheidt, S.Q. Zong, An Approach to Achieve Reusability of Electronic Modules, 1994, pp. 331–336.
- [22] M. Simon, G. Bee, P. Moore, J. Pu, C. Xie, Modelling of the life cycle of products with data acquisition features, *Comput. Ind.* 45 (2001) 111–122.
- [23] S. Heng, S. Zhang, A. Tan, J. Mathew, Rotating machinery prognostics. State of the art, challenges and opportunities, *Mech. Syst. Signal Process.* 23 (2009) 724–739.
- [24] W. Moore, *Practical Telematics*, Construction Equipment, 2012.
- [25] M. Gardiner, *The Big Data Security Analytics Era Is Here*, 2013.
- [26] Off-Highway Research, *The Global Volume and Value Service*, 2013.
- [27] D.J. Edwards, H. Malekzadeh, S.B. Yisa, A linear programming decision tool for selecting the optimum excavator, *Struct. Surv.* 19 (2001) 113–120.
- [28] H. Park, Conceptual framework of construction productivity estimation, *KSCE J. Civil Eng.* 10 (2006) 311–317.
- [29] L. An, N. Sepehri, Hydraulic actuator circuit fault detection using extended Kalman filter, in: *Proceedings of the 2003 American Control Conference*, vol. 5, 2003, pp. 4261–4266.
- [30] M. Jovanović, D. Šević, V. Karanović, I. Beker, S. Dudić, Increased efficiency of hydraulic systems through reliability theory and monitoring of system operating parameters, *Stroj. Vestnik-J. Mech. Eng.* 58 (2012) 281–288.
- [31] NFPC, *Stage 2 Contamination Management*, 2014, 2014.
- [32] D. Douglass, *Understanding Truck Mounted Hydraulic System*, 2006.
- [33] R. Garvey, *Is Your Particle Counter Giving You PPM and Size Distribution? Machine Lubrication – Practicing Oil Analysis*, 2003.
- [34] NFPC, *Stage 2 Contamination Management*, 2014, 2014.
- [35] V. Macián, B. Tormos, P. Olmeda, L. Montoro, Analytical approach to wear rate determination for internal combustion engine condition monitoring based on oil analysis, *Tribol. Int.* 36 (2003) 771–776.
- [36] P. Ignall, M. Barnes, *Cut Operation Costs by Keeping Lubricating Oils and Hydraulic Fluids Free of Contaminants*, 2014.
- [37] W. Babcock, B. Battat, *Reducing the Effects of Contamination on Hydraulic Fluids and Systems*, *Machine Lubrication – Practicing Oil Analysis*, 2006.
- [38] Eaton Ltd., *The Systemic Approach to Contamination Control*, A., 2002.
- [39] J.S. Cundiff, *Temperature and Contamination Control*, 2014, 2006.
- [40] S. Mraz, *Contamination: Hydraulic System Enemy no. 1*, 2014, 2001.
- [41] Donaldson Filtration Solution, *Hydraulic Filtration Technical Reference*, 2012.
- [42] G.K. Nikas, *Theoretical Modelling of the Entrainment and Thermomechanical Effects of Contamination Particles in Elastohydrodynamic Contacts*, 1999.
- [43] M. Spurlock, S. Heston, *Practicing Oil Analysis- Evaluating the Source of Silicon in Oil*, 2014, 2008.
- [44] Parker Hannifin Hydraulic Filter Division Europe, *Guide to Contamination Control – Understanding and Answering the Threat of Contamination*, FDHB500UK, 2011.
- [45] ISO, ISO 4406:1999 Hydraulic fluid power – Fluids – Method for Coding the Level of Contamination by Solid Particles, 1999.
- [46] R. Bosch, *Automotive hydraulics*, in: K.H. Bauer, J. Dietsche, F. Dinkler (Eds.), *Automotive Handbook*, 5th ed. Robert Bosch GmbH, Germany, 2000,

- pp. 816–831.
- [47] Parker Hannifin Corporation, Guide to Contamination Standards, 2014, 2011.
 - [48] Bosch Rexroth, Rexroth Oil Cleanliness Booklet, 2011.
 - [49] A. Mayer, Particle Counting – Peril or Prize? Machine Lubrication – Practicing Oil Analysis, 2006.
 - [50] Noria Corporation, The Low-Down on Particle Counters, Machinery Lubrication, 2002.
 - [51] Particle Measuring Systems Inc., Basic Guide to Particle Counters and Particle Counting, Particle Measuring Systems Inc., 2011.
 - [52] Hitachi Construction, EX5500-6 Excavator Specification, 2014, 2009.
 - [53] H. Satake, Device for Detecting Contamination Level of Operating Oil, US 13/001,573, 2014.
 - [54] X. Hou, B.T. Jones, Inductively Coupled Plasma-Optical Emission Spectrometry, Encyclopedia of Analytical Chemistry, 2000.
 - [55] T.T. Nham, M.R. Bombelka, Determination of Metals in Lubricating Oils by Inductively Coupled Plasma, ICPE-2, 2010.
 - [56] E.M.G. Navarro, M.E.V. Tagle, M.T.L. Marin, M.S.P. Alfonso, Comparison of USEPA 3050B and ISO 14869-1: 2001 digestion methods for sediment analysis by using FAAS and ICP-OES quantification techniques, Quim. Nova 34 (2011) 1443–1449.
 - [57] A. Ryan, Multi-Element Analysis of Fuel and Lubricating Oils by Simultaneous ICP-OES, ICPE-27, 2010.
 - [58] B. Fitch, Anatomy of Wear Debris, Machinery Lubrication, 2013.
 - [59] BSI, BS 5540-3:1978: Specification for Evaluating Particulate Contamination of Hydraulic Fluids, Methods of Bottling Fluid Samples, 1978.
 - [60] G.K. Batchelor, *An Introduction to Fluid Dynamics*, Cambridge University Press, United States of America, 2000.
 - [61] ISO, ISO 4021:1992: Hydraulic Fluid Power – Particulate Contamination Analysis – Extraction of Fluid Samples From Lines of an Operating System, 1992.
 - [62] Finning Canada, Oil Sampling Procedure, 2014, 2014.
 - [63] S. Lunt, Recent developments in online oil condition monitoring sensors and alignment with ASTM methods and practices, J. ASTM (2011) 86–106.
 - [64] M. Day, C. Bauer, Water Contamination in Hydraulic and Lube Systems, Machinery Lubrication, 2007.
 - [65] B. Casey, Symptoms of Common Hydraulic Problems and Their Root Causes, Machinery Lubrication, 2003.