Condition-based maintenance: a case study focusing on the managerial and operational factors

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Abstract

Reliability has been consistently an essential feature in the evaluation of industrial assets (products and/or equipment), as a result maintenance is a continuous process implemented by hard facilities management (FM) providers not only with the core goal of reducing downtime caused by unexpected failures, but also to reduce the associated energy usage whilst maximizing performance and asset life.

Maintenance policies are categorised into two main strategic streams: corrective and preventive. Condition Based Maintenance (CBM) is a subdivision of preventive methodology and is based on the belief that 99 per cent of equipment will evidence some sort of indicators prior a fault develops. Through utilisation of science and technology CBM exploits the operating condition of assets to diagnose faults at early stages of occurrence thus triggering proactive maintenance based on the need. Although the field of CBM is extensively researched, the studies appear to be technical, computer and information science or mathematical modelling orientated. Consequently, contradictions remain between literature and practice concerning the consequences of CBM implementation and the impact on the managerial and operational processes. Concentrating on managerial and operational barriers and success factors, this study investigates centrifugal pumps and associated motors to ascertain the extent to which vibration provoked faults can be identified and diagnosed through the use of Vibration Analysis (for misalignment, looseness and imbalance faults) and Shock Pulse Method (SPM) (for bearing faults), albeit routine Planned Preventative Maintenance (PPM) is applied.

The study establishes that a PPM schedule based on original equipment manufacturers recommendations and best practice standards, is not sufficient at completely eliminating the investigated mechanical faults, thus CBM techniques should be utilized in conjunction to compensate. Moreover, the study recognizes key managerial and operational barriers and success factors for implementation, while drawing attention to the significant role of FM Supply Chain Management.

Keywords: Facilities Management, Condition Based Maintenance, Supply Chain Management, Reliability.

1. Introduction

Although good asset design is significantly linked to high reliability, regardless of design, over time deterioration will occur consequent of real environment operation stress or load (Jardine et al., 2006). An effective way to assure a satisfactory level of consistency during the useful life of a physical asset and reduce random failures (which has a direct effect on efficiency) is to perform maintenance (Martin, 1994; Jadine et al., 2006). There are many definitions of maintenance, they all somewhat emphasize that it is 'a set of activities or tasks used to restore an item to a state in which it can perform its designated functions' (Dhillon, 2002; Tinga, 2010; Ahmad and Kamaruddin, 2012). Due to the significant operational importance, over the years there has been rigorous effort applied to maintenance planning and management (e.g. as highlighted by Dunn (1998)), not only with the core goal to reduce downtime caused by unexpected failures, but also to minimize the associated cost of maintenance which can be as much as 40% of the operational budget in many large-scale plant-based industries (Eti et al., 2006). This is further reinforced by Alsyouf (2007) and Veldman et al., (2011a), highlighting that facilities managers within industry are increasingly accepting that maintenance is not just a cost but can actually generate a profit.

Usually, maintenance policies are categorised into two main strategic streams: corrective and preventive (also referred to as scheduled) (Martin, 1994). In contrast to corrective, preventive tackles the problem of equipment failure prior to failure occurrence. Following proactive principles, this strategy aims to reduce the failure rate or its frequency, at the same time allowing for better product quality and reduction of failure costs (Ahmad and Kamaruddin, 2012). Literature indicates that Preventive Maintenance (PM) technique can be applied through either experience, which is a conventional practice, or recommendations made by the original equipment manufacturer (OEM), which in contrast is performed on a regular prescribed basis (Nakagawa, 1984; Sheu et al., 1995). The former practice strongly relies on the technicians' and engineers' knowledge and lessons learnt acquired in the past. Based on their experience they can evaluate and predict the condition of a machine. Consequently avoiding the machine failure through applying appropriate PM actions. The disadvantage of this PM technique is considerable dependency on the human factor, i.e. the engineers or technicians who are responsible for maintenance can at any point leave the company taking away their valuable expertise on the assets, consequently increasing the operational risk (Ahmad and Kamaruddin, 2012). The other PM practice is original equipment manufacturer (OEM) recommendation, which is carried out on a pre-agreed set times (for example month, 3 months and annual). Nevertheless this technique fails to minimize operation costs and maximize machine performance. According to Labib (2004) and later supported by Tam et al. (2006) the OEM is considered to be flawed in this sense due to the fact that firstly each machine operates in different environment hence requires different PM schedules; secondly the machines designers focus more on the product delivery rather than later machine failure consequently are not as knowledgeable as the engineers or technicians who on regular basis maintain these appliances; lastly the OEM companies at times can act upon hidden agendas recommending spare parts replacements through frequent PMs. An alternative to OEM reference is SFG20 (standard maintenance specification for building services), which is a monthly reviewed library consisting of over 400 maintenance specifications, thus considered the industry standard tool for PM (SFG20, 2013).

Condition Based Maintenance (CBM) is a subdivision of PM and similarly is widely talked about, although in contrast it is not a fully explored field in practice. This paper presents a natural study of centrifugal pumps and associated motors to ascertain the extent to which vibration provoked faults can be identified and diagnosed through the use of Vibration Analysis (for misalignment, looseness and imbalance faults) and Shock Pulse Method (SPM) (for bearing faults), albeit routine (planned) Preventative Maintenance (PPM) is applied. Additionally, it explores the managerial and operational aspect of CBM implementation.

2. Condition based maintenance

Through utilisation of science and technology CBM exploits the operating condition of equipment to predict a failure occurrence thus preventing any unexpected downtime and reducing maintenance cost by avoiding unnecessary preventive actions (Tinga, 2010; Veldman et al., 2011a; Veldman et al., 2011b; Ahmad and Kamaruddin, 2012). The underlining theory of CBM is based on the belief that 99 per cent of equipment will evidence some sort of indicators prior a fault develops. Therefore according to the thorough examination of these signs an engineer can determine how severe the problem is and how long the machine can perform as normal without any actions being taken to repair the fault (Ahamed and Kamaruddin, 2012). Consequently, according to the CBM theories, it is possible to identify the fault (detection), determine the root cause (diagnosis) and establish the severity and longevity of the equipment's optimum life (prognosis) through monitoring and evaluating of data collected through various techniques such as vibration, temperature, oil and acoustic analysis (Veldman et al., 2011a; Ahamed and Kamaruddin, 2012). Moreover, CBM is also able to verify where exactly the fault is, how quickly and to what extent the component is degrading (Veldman et al., 2011a; Veldman et al., 2011b). The focus of research in the last decades within the maintenance field appears to be CBM orientated with the general conclusion that it *"is to be preferred above PM and other policies"* (Koochaki et al, 2011, p.400) thus the literature relating to CBM is extremely widespread, (as highlighted by Jardine et al., 2006 and Ahamed and Kamaruddin, 2012), and too numerous to extensively list within this review. However, generally the studies can be categorised into three areas namely technical (engineering related without any thought of the business aspects), computer and information science (focus on protocols of data/information exchange and different design in order to establish that investment is required for subsequently improving asset management) and finally, mathematical models and decision-making (i.e. the use of algorithms and stochastic models (e.g. Markov chain concept) to explain mechanical degradation) (Koochaki et al, 2011). Seemingly, companies can invest a lot of money in CBM and although implementation is successful from a technical perspective, evidence suggests that in practice CBM is not always successful economically in practice (Koochaki et al, 2011; Veldman, 2011a; Lianghua et al, 2009). This may be due to the lack of managerial and operational impact consideration, as highlighted by Koochaki et al, (2011, p.399), the justification used to invest in CBM implementation *"do not often include the operational consequences"* and incline to "*mainly focus on a single piece of equipment*" thus lacking the overall vision required for successful delivery and benefit realisation. Furthermore, Muchiria et al., (2009) provide empirical evidence of alignment deficiency between managerial and operational KPIs and maintenance objectives from CBM implementation.

2.1 Managerial and operational aspect of CBM

Despite the fact that the literature around CBM illustrates the topic mainly in the light of technology (Koochaki et al, 2011), the barriers, drivers and success factors for the CBM implementation seem to originate from the operational and management side such as risk reduction, optimized use of resources, efficiency gains, and improved maintenance processes. It can be therefore deducted that CBM adoption cannot be employed in isolation from plant organisation but must be integrated within the entire facility operation (Koochaki et al, 2011). Maintenance accounts for one of the biggest proportion of the facility operation spending. It used to be considered as a 'necessary evil' where the costs could not be avoided or reduced. However the technological development along with the managerial and operational drive towards maximisation use of assets became biggest motivation for the organisation to implement CBM (IAEA, 2007). However such a major change from the traditional preventive maintenance to more proactive CBM significantly impacts managerial and operational processes, which are subjected to both change management as well as culture change. These require endeavour of both staff and management directly affected by the change but also the entire supply chain (IAEA, 2007). Such joint effort translates to the list of the success factors for CBM implementation. The first aspect suggested by the explored literature is full commitment of staff to the process and the use of new technology as well as management and the supply chain in procuring for the appropriate technology and training provision. Second critical success factor evidenced by the literature is participation of all the parties involved and confidence in positive outcome of the transition which must be reiterated by the lead management. Further, holistic approach must be applied throughout the entire facility. Finally, in order to ensure maximised long-term benefits of CBM, sustainable programme implementation must be put in place. This means the staff must be regularly trained, resources dedicated to the task must be made available at all times and the process must be granted with the management continuous support (IAEA, 2007). Overall in practice, since the process is not mandated, the management role, and leadership of the CBM implementation as well as involvement of the entire supply chain are vital to drive the process forward (Veldman et al., 2011a).

The literature suggests supply chain is also responsible for creating a value, which in maintenance and new process implementation is essential. Supply chain management (SCM) has multiple definitions; Lambert (2004) however identifies it as *an integration of key business processes across the supply chain for the purpose of creating value for the customers and stakeholders*. The critical components of SCM are strategic purchasing, supply management, supplier base reduction, and communication where two-way information sharing is fundamental to support Facilities Management (FM) processes (Noor and Pitt, 2009). When considering introduction of a new product or an innovation process, the supplier involvement becomes an instrumental factor in its successful implementation, which can proof to be beneficial to all partners involved from the perspective of cost efficiencies, rapid production cycle, better product quality and access to technological advancements (Noor and Pitt, 2009). Such collaborative innovation can encompass elements of process innovation management and product management within a network structure where neither partners could deliver on their own meeting same expectations for product quality delivery and overall cost. Researchers suggest that collaborative innovation brings integration of all relevant aspects of knowledge, technology, process and relationship management as a result creating value (Noor and Pitt, 2009). The conclusive driver in literature for CBM implementation is a drive toward quality and innovation which have been incorporated within strategies of all the ambitious organizations wishing to cut competitive edge not only with the cost but service delivery (IAEA, 2007). Such approach focuses not only on quality but also availability, reliability, post-delivery service as well as delivery performance (Noor and Pitt, 2009). Innovation on the other hand takes shape of more exploratory investment, where the organization learns from its past mistakes and examines the outcome of the project that can prove to be somewhat beneficial (Noor and Pitt, 2009). Finally, similarly to drivers and success factors, barriers for CBM for implementation relate not only to technological challenges but also operational and managerial ones and include economic justification, training, change management plan, use of resources as well as closely correlated culture change (IAEA, 2007).

3. Methodology

Pumps are one of the most important appliances in majority of industries, monitoring and maintenance is essential to prevent drastic failures, lengthy and costly work stoppages. Although there are several types of pumps (including turbo, propeller and positive displacement), the centrifugal pump is considered as one of the simplest and most important pieces of machinery, frequently referred to as the *'workhorse of the industry'* (Pump-zone, 2012). Therefore, this research focuses on thirty-one centrifugal pumps and corresponding motors (referred to as 'assets'). Furthermore, to allow for an unbiased results analysis, the selected assets were of the same make, belt driven, installed in 2004, subjected to the same maintenance schedules and spread out across the whole facility.

The research site was set within one of the UK major government based buildings with total area of 86000sqm. Since it is highly secure building, some site-specific information including its name and location had to be omitted in order to follow the research ethics. The existing asset maintenance protocol is part of the regular time based servicing and monitoring processes which include monthly checks (including visual inspections, operations and leaks), more robust three-monthly service and finally a detailed annual service. Additionally in case of breakdown, the engineer is called to repair the problem exercising reactive unplanned maintenance, also called Corrective Maintenance (CM). All activities performed on the appliances are recorded on the Computer Aided Facilities Management (CAFM) system, stipulating the time, date, detail of the asset, location, generic technical information, detail of the faults as well as resolutions. Nevertheless, neither of the process tasks documents details such as usage period, photographic evidence, as well as comprehensive technical information relating to on-going condition of the pumps to enable possible fault or part replacement patterns.

For the purpose of this study, an industry renowned CBM solution was procured from a third-party supplier and installed on the site equipment. Due to building security restrictions this solution was remote thus requiring manual data collection using a handheld device from the equipment. The solution utilised vibration analysis and was inclusive of the most recent version of SPM technique (SPM HD), which was preferred over vibration analysis for bearing fault detection and diagnosis since its not susceptible to external factors (Sundström, 2010). The supplier undertook the installation process, which involved initial site surveys of equipment, followed by the fitting of vibration accelerometer and SPM transducers and subsequently the setup of the analysis software on a designated standalone computer.

4. Findings and discussions

Literature clearly highlights arguably the most attractive for the industry preventative maintenance as planned (time-based), undertaken through OEM recommendations or SFG20 industry standard tool with the goal of fault detection and resolution prior to failure occurrence thus reducing the risk of machine failure and saving money (as highlighted by Veldman et al., 2011a and Ahmad and Kamaruddin, 2012). Alongside the PPM, it is common practice to implement CM in the event of unexpected fault occurrence or equipment breakdown (Ahmad and Kamaruddin, 2012). This is applicable for the assets selected in study, since they were all subject to monthly, three monthly and annual PPM schedules.

The first stage of the research design reviewed the historic maintenance carried out on the assets. The CAFM system held in-depth historic records of maintenance, which included both preventive and corrective ones (in the event of unexpected failures). The records show that 65% of the assets did not have any CM undertaken suggesting that the PPM schedule was sufficient, as it prevented any unexpected breakdowns. Furthermore, 13% of the assets required corrective intervention as a result of inverter (Variable Speed Drive (VSD)) faults and/or replacements, however since the VSD are additional equipment used to control the speed of the motors and are governed by other manufactures maintenance recommendations, these unexpected breakdowns cannot be attributed to the PPM of the assets themselves. However, this clearly highlights the risks of using VSDs to control centrifugal pumps, particularly since CM on VSDs will result in loss of pump operations (Spear, 2005; Ien.com, N.D). The records that can be considered as CM in addition to the PPM schedule appear to relate to a small 21% of the investigated asset, further analysis shows 19% required unexpected strainer cleaning intervention and 3% needed CM due to a leak from mechanical seal. This analysis firstly highlights that there is a wealth of historic maintenance records available for managerial and operational reporting and secondly, the current PPM schedule is only inadequate at completely eradicating unexpected faults for a small quantity of assets thus for large majority of the assets the PPM schedules currently used are sufficient and effective at minimising downtime. This provides strong support for implementing PPM as the main maintenance policy as emphasised by literature. Further in-depth analysis suggest that the assets which had unexpected failures and required CM were more susceptible to the investigated faults. The one asset that had '*leak from mechanical seal'* also displayed *bad operating condition* on the bearings both at the pump drive end and non-drive end data collections. This clearly suggests a correlation between bearing condition and leak from mechanical seal, as suggested by numerous literature i.e. machineryLubrication.com (2013), Thomas (n.d) and Mobil (N.D).

The second stage of the study investigated the most common detectable vibration induced mechanical faults as suggested in literature namely, bearings faults, misalignment, looseness and imbalance. This quantitative research was undertaken via acquiring the vibration and SPM readings and applying analysis in comparison to ISO Standard (ISO 10816-7) and bearing manufacturer's tolerances. It must be noted only the first set of readings collected were analysed as this would provide the truest reflection of the equipment condition, particularly as the Engineers were required to immediately resolve any issues before taking second reading. The analysis of results indicates that 48% of the investigated assets exhibited one or more of the investigated faults even though PPM had been undertaken accordingly, which evidently suggests that these assets are operating in a faulty condition thus not to the maximum capability nor efficiency. More specifically, the motor appeared to show more of the investigated faults than the pump. Labib (2004) and Tam et al., (2006) suggest that PPM practices fail to not only minimise operating costs but also disappoint at maximising the machine performance, clearly this can be related to this study, particularly in reference to their justification that machines operate in different environments thus require different PPM schedules specific to that machine and that environment. Therefore, this study indicates that PPM undertaken based on OEM recommendations and SFG20 standards (SFG20, 2013) may not be the most appropriate maintenance programme in eradicating these faults, which (as discussed in literature) can have severe consequences on the efficiency and life of the assets. Perhaps PPM schedules should be applied on assets in conjunction with CBM techniques to achieve optimum maintenance of in practice.

Finally, the third stage of the study, addressed the literature gap relating to the FM Supply Chains perspective of CBM and operational and managerial aspects through unstructured interviews and observations. The literature supplements give indication that both barriers and drivers for the CBM implementation stem from the managerial and operational aspects of the business therefore it is only natural that it should be considered in the wider context of FM and include similar challenges including supply chain and managerial and operational issues. It is also imperative to point out that the FM contributes to achieving strategic objectives of the company and maintenance plays such a profound role, managing it in strategic way is critical (Noor and Pitt, 2009). Always most controversial aspect, cost in CBM implementation can be considered as both a driver as well as barrier and relates to the operational part encompassing staff training as well as possible additional resource appointment (Koochaki et al, 2011). Justification for initial investment on the technology and resources contests with the risk minimization, improved asset quality, and savings made on corrective maintenance. Moreover, operationally, multiple barriers transpired on this project including *'the time required for data collection using the handheld'*, *'practicality of duty and standby*', and *'impact of VSD'*. Furthermore, as pilot project the CBM technology did not replace the existing PPM thus engineers were still required to undertake planned maintenance with expectation of committing additional time for CBM data collection. As a result, the operational success factors identified are limited to the fact that the detectable faults can be identified through CBM thus preventing asset failure. In contrast, an online (automatic data collection) CBM solution that replaces the existing PPM schedules could demonstrate numerous operational drivers and benefits (as highlighted in literature e.g. IPE, 2009).

On the managerial front, it is evident that the overall perception on the success and validity of the project varied across the board with management and staff as well as supply chain partners. The maintenance engineers were subjected to the introduction of new processes and additional duties, which resulted in expected reservation to changes. The project sponsor on the other hand focused on the project delivery and maximizing CBM effectiveness in order to improve asset performance and life. In-depth on demand asset diagnostic reporting for management can be considered as a driver for implementation, however this can only be achieved if internal team members are provided advanced continuous training to undertake reporting, which was not the case in this project. Furthermore, as demonstrated by this study, CBM mandates collaboration of multiple supply chain partners as such effective supply chain management ensuring all partners have clear goals throughout the project with visible benefits, can influence the success or failure of CBM implementation and practical endorsement. Therefore, based on the literature reviewed and findings of this study, it is non disputable that CBM implementation and industry acceptance should not merely be analyzed in technological perspective. As CBM is part of a complex FM maintenance, it is subjected to supply chain, managerial and operational challenges which must be identified and appropriately addressed.

5. Conclusion and recommendations

Literature demonstrates the technically feasible capabilities and benefits of CBM application, calling for a transition from PPM to performing proactive maintenance upon evidence of need. However, where research has been undertaken in these areas the application and acceptance in the practical field of maintenance appears to be limited for the following reasons, firstly, nearly all CBM research is usually undertaken in controlled environments with a single quantity of asset, consequently there is a discrepancy between the effects of CMB implementation reported in literature and the actual effects experienced in practice. Secondly, majority of literature investigating bearing faults has been undertaken through the use of Vibration Analysis. However, the significant disadvantage of using this technique to identify bearing damage in industry plant room environments is the limitation of external factor influence, by the time damage is detected it is too late to rectify. Moreover, there is limited literature focus around Shock Pulse Method (SPM) as a superior alternative in bearing condition monitoring (perhaps due to its patented exclusivity and cost of implementation). Lastly, the widely researched domain of CBM can be broadly categorised into three areas namely technical, computer and information science, and finally mathematical models and decision-making. Consequently there is a significant lack of understanding in practice relating to the managerial and operational impact of CMB implementation.

The research analysis points out the importance of managerial processes when implementing the CBM within the organization. The proved effectiveness and efficiency potential in data gathering as well as improvement in asset quality and risk reduction of CBM suggests that the technology is here to stay and be utilized on a greater scale however it requires an incremental culture change of the entire supply chain as well as the staff and management involved. It is envisaged that the future research focuses on maximization of CBM effectiveness while optimizing costs and benefits of the process. Likewise, managerial and operational processes during the transition from PPM to CMB should be a key research focus towards the endorsement of CBM in practice.

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