Towards the implementation of a predictive maintenance strategy: Lessons learned from a case study within a waste processing plant

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ABSTRACT

Successful implementations of predictive approaches to maintenance are seeing an increasing level of reporting in literature. While much of this relates to high value manufacturing industries, such as Aerospace, the potential of these maintenance approaches within low-value processing industries, such as Waste Management, where system availability is also critical, is receiving increasing interest. However, these industries vary significantly in terms of the asset volumes handled, life costs, safety criticality and the sophistication of equipment/plant. Consequentially, the implementation of predictive maintenance in these contexts is likely to present different requirements. In order to understand the potential differences, this paper seeks to explore the potential issues/challenges for predictive maintenance in this context through a qualitative study of maintenance personnel within the Waste Management industry and reflections on the implementation o f a prototype condition monitoring system. The findings from these two aspects provide the basis for elicitation of a set of potentially generalizable issues for the processing industries, which it is proposed must be addressed before successful implementation of the technology can be realised. The main issues highlighted with predictive maintenance implementation within Waste Management plant concern industry characterisation, socio-technical and technical considerations, perceptions of value in predictive maintenance, measurement of maintenance performance and barriers to both implementing and realising beneficial and sustainable success of predictive maintenance.

1. INTRODUCTION

The maintenance of an asset, within the broadest engineering context, can be considered to constitute any action taken to preserve the function of the asset, as required by its stakeholders (Moubray, 1997). General approaches to maintenance employed across different industries can, as described by Starr et al. (2010), be divided into three major categories, ordered in increasing complexity of implementation: reactive (RM), planned preventative (PPM) and predictive (PM). The potential benefits to maintenance performance that can be realised through the adoption of PM are numerous and well documented in literature (see Heng, Zhang, Tan, & Mathew, 2009; Heng, Tan, et al., 2009; Jardine, Lin, & Banjevic, 2006; Jennions, 2011).

Such adoption has been pioneered primarily within the Aerospace sector, with operators within the general processing industries yet to exploit such technology. This initial application focus within Aerospace is suggested to have been primarily driven by an assumption that the high cost of failures associated with the low-volume-high-value assets operated within the industry could extract the most value from the technology, as noted by Jennions (2011). Given the constraints of the industry, predictive approaches to maintenance offer an opportunity for operators to demonstrate airworthiness with more cost effective maintenance.

However, operators in the general processing industries are increasingly seeking solutions to realise similar improvements in maintenance performance and therefore these industries may also benefit from exploiting such technology. The implementation of prognostics technology within these industries would represent a shift towards PM of high-volume-low-value assets, and as such, the technology would be expected to satisfy an industry specific set of requirements. For example, in contrast to the highly restrictive legislation relating to airworthiness found within the Aerospace sector process safety is typically a much less significant factor within the Waste Management (WM) industry, due to an inherent absence of persons within the process. However, in contrast to the high revenues realised by the Aerospace industry the WM industry is less lucrative and thus operators typically possess comparatively fewer resources in terms of maintenance activities.

To successfully implement PM supporting prognostics technologies within industries such as WM these differences must first be understood. Consequently, this paper seeks to explore the characteristics of maintenance practices within the WM industry, using a specific operator as a case study, with a view to developing the requirements for PM and the underlying failure prognostics technologies within the industry.

Initially, maintenance at the operator's Plant is characterised through the conduction of a series of semi-structured interviews with key personnel within the Plant maintenance team. From this qualitative data a number of specific technical issues are identified, the impact of which upon plant availability it is proposed could be reduced through a shift towards PM. As such, a bespoke condition monitoring system, developed by Stirling Dynamics and termed AWEAR, is trialled at the Plant to increase the observability of asset conditions, as a step towards predicative maintenance implementation. Within the design of this system, technical implementation issues such as sensor selection are considered to explore the cost/benefit trade-off between different condition proxies.

Based upon the characterisation of Plant maintenance and observations of the trialled AWEAR system a series of key findings are subsequently presented and discussed. These are then considered in the context of the wider WM industry to provide a number of key findings to support future implementation of PM within the industry.

2. BACKGROUND

2.1. The Waste Management Industry

WM is a global industry concerned with the collection, transport, recovery and disposal of produced waste (European Parliament and Council, 2008). In the UK alone the industry turns over £9 billion annually and employs 70,000 people within 3000 companies (UK Trade and Investment, 2014). Whilst levels of waste for disposal continue to rise year upon year local authorities within the UK have seen as much as 40% of funding cut since 2010, with similar cuts expected over the next 5 years (Ricardo-AEA & The Chartered Institute of Waste Management, 2014). In addition, legislation continues to place ever more stringent pressures on operators to improve operational efficiency despite reductions in personnel resources, rising energy costs and ageing plant. Thus, operators within the industry are seeking methods to increase the operational performance of plants without requiring significant investment.

The industry can be broadly characterised as technologically immature in comparison to industries such as Aerospace and Manufacturing as a result of minimal historical investment in innovation. As such the WM industry is yet to significantly exploit the recent advancements made within areas such as failure diagnostics and prognostics in the high-tech industries (examples of which are documented in Heng, Zhang, Tan, & Mathew, 2009; Jennions, 2012; Vichare & Pecht, 2006). Such technologies have the potential to support the improvements in performance sought by operators within the WM industry. However, due to differing operational characteristics between industries it cannot validly be assumed that the form in which these technologies have been implemented thus far will be appropriate for the WM industry.

2.2. Operator Case Study

The Operator's plant described within this case study is a mechanical and biological treatment (MBT) facility, handling all household refuse other than food waste. It has been operational since late 2011 and currently runs 24/7 aside from a single 12 hour planned shutdown period per week. The Plant was constructed with a design capacity of ~180k tonnes per year and currently operates at ~175-180k tonnes, however has operated at as high as 200k tonnes per year previously. The Plant comprises approximately 80 conveyors moving product linearly between a series of specialist process. The environment within the Plant is extremely aggressive in nature as a result of the diverse makeup of the waste processed.

The combination of a challenging operational environment and near constant target utilisation results in significant pressure being placed on the maintenance team to facilitate such operation. The maintenance team comprises 14 engineers supported by 16 plant technicians, with 2 from each group on shift at any time. The role of the plant technicians is to supervise and control the operation of the Plant as well as performing general cleaning.

As such, any unscheduled stoppages at the Plant incur significant financial penalty to the operator. According, seeking to maximise the effectiveness of maintenance activities on site, the operator engaged with Stirling Dynamics (SD), a specialist engineering consultancy, with the aim of identifying and implementing any solutions for realising such improvement.

2.3. Research Context

SD are an SME with headquarters in Bristol, UK, operating predominantly within the Aerospace sector where they provide expertise in modelling, simulation and control to a range of industry-leading companies. Seeking to utilise this niche capability in new areas SD agreed to support an investigation into the feasibility of improving maintenance performance at the Operator’s plant through the implementation of condition monitoring techniques. The reported work forms part of the overall scope of this feasibility study.

3. RESEARCH METHOD

To support the characterisation of maintenance operations at the Plant a series of discussions were held with key stakeholders within the operator’s maintenance team. In addition to characterisation, these discussions aimed to identify the limitations of current maintenance practices and highlight where perceived improvements could be made. Subsequently, a series of semi-structured interviews were conducted individually with key stakeholders from the maintenance team, to further explore and formalise the maintenance approach from each individual’s perspective. Finally, findings were validated by an external expert from within the waste processing industry to provide a measure of the extent to which conclusions could be extrapolated across the industry.

A series of high-level questions were designed to help frame the interviews, comprising 3 main sections. The first section sought to characterise the interviewee including their role, responsibilities and qualifications with the purpose of understanding the plant maintenance team. The second section aimed to characterise the Company’s attitude and approach to maintenance from the perspective of the interviewee, including attitudes to training and maintenance planning. The final section aimed to identify specific maintenance issues within the plant in the context of factors such as incurred downtime and frequency of occurrence, as well as identifying the most reliable aspects of the plant.

To enable obtained data to most completely reflect on-site maintenance practices participants were selected across the team’s hierarchy. It is also suggested by Glaser & Strauss (1967) that the generality of a substantive theory can be increased through comparison between different groups, therefore sampling all groups within the hierarchy may increase the degree to which conclusions from this plant can be validly extrapolated to similar plant. At the Plant the maintenance team comprises 14 maintenance engineers, with 2 on site per shift. It should be noted that the Maintenance Manager supports multiple plants in addition to the subject plant. From these fourteen, four interviews were conducted with personnel fulfilling roles within the hierarchy as shown in Figure 1. Plant Technicians were unable to participate in interviews due to availability issues.

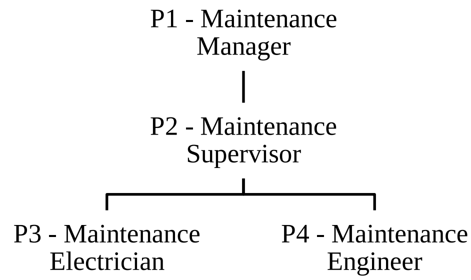

Figure 1 - Hierarchy of participants within the site maintenance team

Ideally a larger section of the team would have been sampled to maximise validity of data however personnel availability constraints prevented this. In addition, to achieve the aim of characterising the maintenance process on site, ensuring quality of data over quantity can be considered a priority, with the concept of saturation (Glaser & Strauss, 1967) relevant.

Interviews were conducted with selected maintenance personnel on site and audio recorded. Recordings were subsequently interrogated using Computer Assisted Qualitative Data AnalysiS (CAQDAS) software, enabling emergent themes in the data to be both highlighted and logged. As much as possible the analysis process was approached inductively to maximise the accuracy of the resulting characterisation. As suggested by Graham Gibbs (2007) recorded audio was coded directed rather than via transcriptions in an attempt to maximise validity of analysis. Initially, recordings were listened to multiple times from which general emergent themes within the data were elicited. These themes were then reinforced with direct excerpts taken from the data. This process was completed iteratively with themes refined until coherent and evidenced conclusions were obtained.

4. FINDINGS

Based upon evidence acquired during conducted interviews it was possible to characterise on-site maintenance practices at the Plant, as summarised in Table 1.

Table 1 - Summary of plant maintenance characterisation

	Factors	Description	Examples
Workforce Characterisation	Qualifications	The standard of formal qualifications typically held by employees	"I've got NVQ3 in Maintenance and Repair" "I was at agricultural college for 4 years [where I gained] a BTEC, National Diploma and City and Guilds"
	Training	Evidence of tangible training provided to on appointment and ongoing as well as employee's perception of company attitudes towards the provision of training	"Initially it's the usual Health and Safety things mainly" "A lot of H&S courses", "For the specialist machinery we've got they [the company] always try and get you on a course" "They're pretty open [to funding training]" "There have been a variety of key areas in which we've had to put a lot of training into when it comes to H&S… we're trying to make a standard for [the company]"
	Length of service	The time spent working in the plant's maintenance team	"I've been here since start-up… at least 5 years" "I'm coming up to 5 years here" "I've been with the Company for 7 years" A churn rate of ~20% within the maintenance team was reported
Maintenance Approach	Objectives	Employee perception of the principle objectives of the maintenance approach within the plant	"Keep the plant running really… until the scheduled shutdown period" "Keep the plant running and keep it in a condition where it's easily serviceable" "At this plant it's just fire-fighting basically" "A top-level objective from a management perspective is plant availability, how long can we have that plant running for… minimal downtime, reduced expenditure to keep costs down"
	Scheduling and Documentation	Overview of the degree to which maintenance is planned and documented within the plant	"I think some [PPM intervals] came from the manufacturers, others are basically experience… it's really trial-and-error" "Basically here it relies on experience... this, this and this have gone. Right, I'd better do this one first then" "Any jobs we do we have to do job sheets for, we put the asset numbers, time it took, date"
	Condition Identification	Primary methods used within the plant to identify the onset of undesirable equipment conditions	"Every week he [external belt technician] goes around and surveys all the belts using his knowledge and says 'right, this is what needs doing.' He gives me a list of faults he's found and the importance of them" "Mostly you will pick up [issues] visually with the checks that we do" "They're [plant techs] supposed to walk around, it [issue identification] all depends on how quickly they notice it" "The ones [conveyors] which are less likely to go are the ones they frequent. If they [plant techs] can see it, they notice it starting to go wrong… otherwise it'll purely rely on a PPM [to identify issues]" "It'll trip, sometimes they'll [plant techs] see it [the issue], stop the plant and clear it but 9 times out of 10 the plant will come to a halt because it's tripped"
Existing Issues	Importance of Cleaning	Evidence of impact of poor cleaning on plant performance	"The plant will get a blockage and they'll clear it off, hopefully they'll spot it before it gets too bad, and clean it" "Blockages, lack of cleaning basically, is your biggest cause [of downtime]" "Ingress of dirt and mess, that can cause a lot of damage"
	Impact of Belt Failures	Evidence of the impact of belt failures on plant availability	"We identified a [belt] split but we couldn't get around to changing it... it split on a night shift and they were down for 6-7 hours"
	Process Linearity	Indications of the limiting effect of process linearity on plant availability	"If we can divert the waste off of that belt we'll do that [repair will be scheduled]. If we can't, if it's one of the main feed belts it'd be a plant shutdown… it [the repair] would be done there and then" "Literally every belt gets used… you can't just bypass it [product]"
	Under Resourcing	Demonstrations of under resourcing of maintenance effort	"You have a massive list of PPMs… when the plant is running you can't get access… you get one day to try and get every job done... you can't win" "They vary the shutdowns so much… some weeks sections are shutdown so you can do 12 hours on each, other months you just get 12 hours a week on it [the plant], everything else suffers as a consequence" "Because we run so often we only get an hour of cleaning in the morning… a lot of them [conveyors] are hard to access... you're never going to get them all done"

4.1. Workforce Characterisation

4.1.1. Qualifications

Participants all reported to have spent most, if not all, of their working career within the area of maintenance, however, not necessarily exclusively within the WM industry. Typically formal qualifications around level 4-5 of the UK Regulated Qualifications Framework were held including BTEC, HND and NVQ level 4.

4.1.2. Length of Service

A range of service lengths were held amongst participants, from less than 2 years to over 5. A number of participants reported to have been working at the plant since its inception in 2011.

In General, length of service was observed to increase with seniority within the maintenance team as may be expected, with both senior employees within the hierarchy reporting to have achieved multiple internal promotions.

However, within the wider maintenance team populous a churn rate of ~20% per annum was reported by senior management, with turnover of personnel particularly within the lower levels of the team. Post completion of interviews, Maintenance Supervisor P2 was reported to have left the Company.

4.1.3. Training

As a result of the nature of the Plant environment significant mandatory health and safety related training is proved to all staff upon commencement of employment as well as periodic updates. It was reported by P1 that they Company were “trying to make a standard” with regards to health and safety, beyond the minimum stipulated by regulations, that all employees were being brought up to.

Additionally, significant investment in maintenance specific training was reported, particularly for specialist equipment e.g. shredders, sorters, which are provided by OEMs, generally off site. For example, it was reported that a number of members of the maintenance team had recently returned from a manufacturer training course held overseas, funded by the Company.

Company attitudes towards supporting the provision of training beyond the core requirements were generally reported as very positive by participants. P4 suggested that “they always try and get you on a course” and others suggested additional training, both technical and non-technical, is available to personnel.

4.2. Maintenance Approach

4.2.1. Maintenance Objectives

Primarily participants stated that maintenance activities at the Plant are for the purpose of maximising operational availability, with sentiments such as ‘fire-fighting’ and ‘keeping the Plant going at any cost’ echoed. However, the more senior personnel did include considerations for caveats to this, with considerations for minimising costs, increasing performance and satisfying safety legislations mentioned.

A perception that the effectiveness of maintenance within the Plant has improved significantly since start-up was reported by a number of participants, with many previously common issues now rarely occurring. It was suggested by the Maintenance Manager that the remaining issues are usage-based ‘wear and tear’ failures of consumables such as belts and bearings, with the aggressive operational environment and high utilisation being the root cause of these.

4.2.2. Scheduling and Documentation

The maintenance approach at the Plant was described by participants as a combination of reactive and planned preventative elements. Aspirations to increase the degree of PPM implemented on site were suggested during interviewing, however, it was indicated that completion even of current schedules was challenging. The maintenance team are provided nominally with 12hrs/week of scheduled downtime however the limitations of this were raised; “It’s a nightmare. You get one day a week in which to get it [PPM] all done, you can’t win.”

Additional frustrations around the certainty of this PPM window being available were apparent from participants. Numerous examples of the impact of reactive maintenance on scheduling were provided, wherein the occurrence of a failure within the Plant would result in the PPM window being moved and time lost to completing the reactive repair. “I’ve spent 7 hours fixing that, that’s 7 hours that comes off the next [scheduled] downtime. You won’t get a [scheduled] downtime window that week because of that 7 hours. Normally we get 12 so you’ve already been robbed 5 hours.”

Participants reported that the overall maintenance approach at the Plant is very much developed in house using heuristics, supported initially by operator guidelines. Essentially, intervals for services and inspections are set and then adjusted in response to the observed performance. P4 described the process as “I check them every 3 months and they keep failing, I’d better check them every month.” Generally schedules are temporal usage based e.g. a conveyor is serviced at every x operational hours. However, the presence of constraints set by manufacturers were indicated by the Maintenance Manager i.e. a specific machine may have to be serviced at certain intervals to retain its warranty.

Despite being a manual data capture process (i.e. paper based), maintenance planning and actions at the Plant appear to be generally well documented. PPM and reactive jobs scheduled are documented and circulated to the team weekly, and maintenance personnel are required to complete a record of all jobs completed. However, it was reported by some participants that fluctuations in the diligence of maintenance personnel in ensuring proper documentation is completed have been observed at the Plant. As such, the Maintenance Manager did indicate aspirations to adopt the utilisation of a computerised maintenance management system (CMMS).

No indication was given by participants of captured maintenance data being used for purposes other than record keeping, no analysis in the context of quantifying performance is obviously performed.

4.2.3. Condition Identification

All interviewees reported visual inspection to be the most effective mechanism utilised by maintenance personnel in identifying plant issues. Issues that are severe enough to stop the Plant (e.g. a motor overload) will be reported to personnel automatically via a control room human-machine interface (HMI) however this is a binary state (i.e. fault or no fault) and no additional diagnostic information to aid the rectification of the issue is provided.

As well as component failure some undesirable process conditions, such as the build-up of product at transfer points (termed 'clumping'), were reported as relying on visual inspection for identification. It was also indicated that such issues can be very difficult to detect due to their transient nature, relying on a person being in the right place at the right time to spot them.

Within the Plant, visual inspection of assets is performed both formally as part of the PPM schedule, as well as informally by plant technicians during their regular duties. However, these informal inspections are not enforced, nor is there a clear and effective mechanism for the reporting of identified issues, verbal communication appears to be the accepted method. Thus, the effectiveness of visual inspection in preventing failures appears limited - "The ones [conveyors] that are less likely to go [fail] are the ones they [plant technicians] frequent, the ones with good access. If they can see it they'll know it's starting to go wrong. A conveyor that's up in the air, you can guarantee the tail drum will go [fail] on that."

This statement also indicates an inherent issue with reliance upon visual inspection for condition identification at the Plant. Within the Plant, access to many areas is severely restricted for safety reasons, with certain areas only accessible during shutdowns. Additionally, physical constraints around assets can restrict access further, resulting in specialist equipment being required such as cherry pickers or scaffolding to gain access. This compromises the ability of personnel to complete visual inspections and thus identify adverse conditions further, with P4 noting that "when the Plant's running you can't do a lot, you can't get in there and have a good look."

4.3. Maintenance Issues

4.3.1. Importance of Cleaning

All participants highlighted general blockages of product within conveyors as being amongst the most significant causes of downtime at the Plant. Inadequate cleaning leads to build-up of product on conveyors, often around bearings and motors, which can lead to a multitude of issues such as overheating, ingress of contaminants and mechanical damage.

Not only is adequate cleaning important in preventing direct stoppages, participants indicated that it also has an influence on the occurrence of more severe issues. The secondary effects of blockages can be much more significant if not rectified, for example build-up of product can lead to bearing failure which in turn can damage the shaft, requiring significant effort to repair. It was also suggested that minor component failure can be acceptable if it enables the indication of a potential more severe issue and thus prevention of occurrence.

The identification and clearing of blockages within assets is primarily the responsibility of plant technicians, who are given a cleaning schedule to follow, however, there was suggestion from some participants that these are not always completed and, as such, assets often operate in non-optimal conditions. P3 commented that "because we run so often we only get an hour of cleaning in the morning… a lot of them [conveyors] are hard to access... you're never going to get them all done."

4.3.2. Belt Failures

Issues related to conveyor belts were noted by all participants as being significant causes of unplanned downtime at the Plant. These issues were suggested as being unavoidable with cumulative wear a consequence of the Plant environment – "Because they're rubber they're going to wear out. We predict them [belt failures] much better now, we try to repair them before they break."

The corrective action required in response to belt issues, and thus their impact on availability, is dependent on the severity of the damage incurred. If damage to the belt is small e.g. a hole or gash, then the belt can be patched during scheduled maintenance. However, the completion of such a repair is dependent on both the damage being identified and a judgement call by the maintenance personnel as to the severity. P2 commented that "if it [a belt] has been noticed that it's worn, we'll monitor it and it'll be done [repaired] in a maintenance window. If it's worn to an extent that it snaps, where no-one has noticed it [the damage], obviously it would have to be done there and then."

If a belt is to completely fail (i.e. is completely severed) it will always incur downtime, and generally will be tackled immediately to ensure the Plant can return to operation as soon as possible. As such it was reported that the Company have requested an employee of the belt manufacturer be on site at all times to ensure issues can be tackled immediately. The financial implications of this to the Company were not reported.

To mitigate against belt failures a weekly check of belts is performed by the belt manufacturer's on site employee. He assesses the condition of the belts visually and, using his experience, provides the Company with a list of recommended actions. No objective measure of belt condition was reported to be used by participants.

Some participants reported improvements in the frequency of belt repairs, with it suggested that much less variance in failure periods between belts is now observed as a result of increased experience with operating the Plant. However, others suggested that belt failures were 'random,' with it possible to go extended periods without observing any or equally observing multiple failures in a short time period. It was also noted that all participants provided a different answer when asked to provide the frequency of belt failures occurring.

In terms of the distribution of belt failures throughout the Plant, it was suggested by the Maintenance Manager that "most of our conveyors are the same and they wear pretty evenly." In contrast, it was suggested by participants P3 and P4 (who are "at the coal face") that specific conveyors can be more problematic. Experience tells them that for example more issues can be expected at specific conveyor due to their form (e.g. a right-angle as oppose to a straight conveyor) or their location (e.g. located below other conveyors).

4.3.3. Process Linearity

The issue of linearity within the processes at the Plant was indicated by some participants as being problematic. Due to the configuration of the process, failures in any one section will generally result in the entire process having to stop, and thus unscheduled downtime being incurred. As noted by P4, "Literally every belt gets used… you can't just bypass it [product]."

As such, significant maintenance effort is given to the prevention of failures to specific process critical assets. For example, P3 commented on the importance of the shredders and the impact of this on their maintenance - "That [shredder] is the biggest priority. If your shredder goes down, that's it, game over… our welder spends 12 hours a week on [the shredders]… without that they would be breaking down all the time." As a result of this effort the shredders are considered to be one of the most reliable areas of the Plant as reported by a number of participants.

4.3.4. Under Resourcing

Inherent issues around the inability of the maintenance team to implement planned actions, and the impact on Plant availability, were noted throughout the interviewing process. "You have a massive list of PPMs… when the plant is running you can't get access… you get one day to try and get every job done... you can't win" commented P4.

The approach from the Company with regards to operational capacity appears to be to keep increasing it until it breaks down. Little consideration seems to be given to the impact of this mindset on the ability of the maintenance team to keep the Plant operational. Running at such high levels (24/6.5hrs/week) not only overworks the equipment thus increasing the likelihood of failure, but also reduces the time available to the maintenance team to complete PPM actions. As noted by the Maintenance Manager "ideally we could service everything every week, but that's unrealistic."

5. IMPLEMENTATION

Based upon the nature of the maintenance issues identified within the Plant it was concluded that maintenance effectiveness is inherently limited by a reliance upon reactive and preventative approaches. As described in Section 4, a number of technical issues are present which could be potentially more effectively managed through a predictive approach. However, the ability to implement such an approach is restricted by a lack of objective asset condition data. Therefore, it was proposed to implement a trial system within the Plant capable of facilitating increased observability of the asset conditions, as a step towards the implementation of elements of PM on site.

This section describes the system implemented, including rationale for sensor selection and findings related to the success of the trial implantation. In addition, the task of acquiring the data required to facilitate condition monitoring of assets is considered. In current literature this task is often assumed trivial (Nembhard & Sinha, 2015; Teja, Kjell, Hamid, & Karimi, 2016) with a lack of consideration given to potential issues associated with data acquisition. However, in practice, outside of a laboratory environment, this task can prove challenging and as such issues encountered in relation to data acquisition will also be discussed.

5.1. Hardware

To support the monitoring of an asset's condition in the context of PM a range of proxies can typically be employed. As noted by Heng, Zhang, et al. (2009) most commonly within extant literature this selection is given little consideration or justification, with sensors selected based solely upon the form of data they provide (e.g. Yang et al., 2014). Some examples give an indication of additional factors such as the financial implications of transducer types, however this is mostly constrained to the initial purchasing cost of the hardware only, with very few examples giving consideration of the feasibility of installing and maintaining operation 'in the field' (e.g. Cheng & Azarian, 2008).

In the context of the WM industry the characteristics of the industry constrain sensor selection in terms of what can feasibly and economically be implemented. Therefore sensor selection must be carefully considered. As described by Jennions (2013) the three primary requirements for a sensor within the context of condition monitoring are: accuracy, stability and lack of interference with the physical quantity being measured. For WM applications (and processing industries generally) the nature of the assets (high-volume-low-value) has implications on sensor selection also.

Here, the scale of plants combined with the aggressive nature of the environment in which they operate impacts upon the viability of utilising high cost sensors, such as those providing acoustic emission and vibration information, within the context of overall PM cost-effectiveness. For example, if a sensor costs ten times as much as the asset it's monitoring and only enables an average 20% life extension, the financial value of the increased observability it provides will be minimal.

With this in mind, the main criteria for condition monitoring sensor selection within the AWEAR trial implementation were cost (both initial and maintenance) versus the observability of assets condition facilitated. The trial was decided to focus on the monitoring of a single conveyor within the Plant, which was broken down into 6 main components: drive motor, reduction gearbox, two head drum bearings and two tail drum bearings.

To increase observability of the motor condition a transducer was retrofitted onto a single phase of the motor power lines to provide a continuous measurement of current draw. This data could be used to identify any abnormal increases in current draw above normal operation, thus highlighting increases in load and potentially wear.

To increase observability of wear within conveyor components a Resistance Temperature Detector (RTD) temperature transducer was retrofitted to all major components along with a local ambient transducer. RTDs were selected due to their stability over wide temperature ranges, and were bonded to components using a metalised epoxy to improve thermal conductivity. The raw temperatures from each component were normalised against ambient and inputted to a dynamic thermal model of a generic component, to provide an estimate of the thermal energy emitted by each component. This model enables a significant degree of lead over differential temperature monitoring only when monitoring fluctuations in operating condition. This estimate could be used as a proxy for monitoring the frictional loading of each component, with increases over time indicative of increasing wear.

5.2. Software

Commonly with the WM industry SCADA systems are employed within plants to control processes. However, in the context of CM the data that such systems provide can often offer limited benefit, primarily due to: low sample rate, the presence of noise and fluctuations in operating condition (Igba, Alemzadeh, Durugbo, Eiriksson, & Thor, 2016; Yang et al., 2014).

Whilst many COTS SCADA-type systems are available to support CM implementation (see Yang, Tavner, Crabtree, Feng, & Qiu, 2014 for a summary of packages), as noted by Waeyenbergh & Pintelon (2009) the wide range of factors influencing the characteristics of a specific plant can limit the suitability of such generic solutions. Therefore, based upon the understanding of Plant operation and maintenance issues as described in Section 4, a bespoke, prototype condition monitoring package was developed in house by Stirling Dynamics, termed AWEAR. The AWEAR system enables visualisation and interrogation of the acquired data described in Section 5.1 and follows the general IVHM architecture specified in ISO13374 (ISO, 2003).

Utilising the expertise of an external UI design consultancy, the system GUI was designed with both simplicity and intuition as key requirements, such that little training is require to operate it, thus minimising potential barriers to utilisation.

In addition to data visualisation secondary features were incorporated into the system in response to the findings described in Section 4. The system allows users to input asset observations to improve the capture and recording of issues as well as SMS functionality to enable immediate announcement of observed issues thus improving communication between plant technicians and the maintenance team. An autoreport function was also provided to enable the large volumes of acquired data to be condensed and thus more easily interrogated by management.

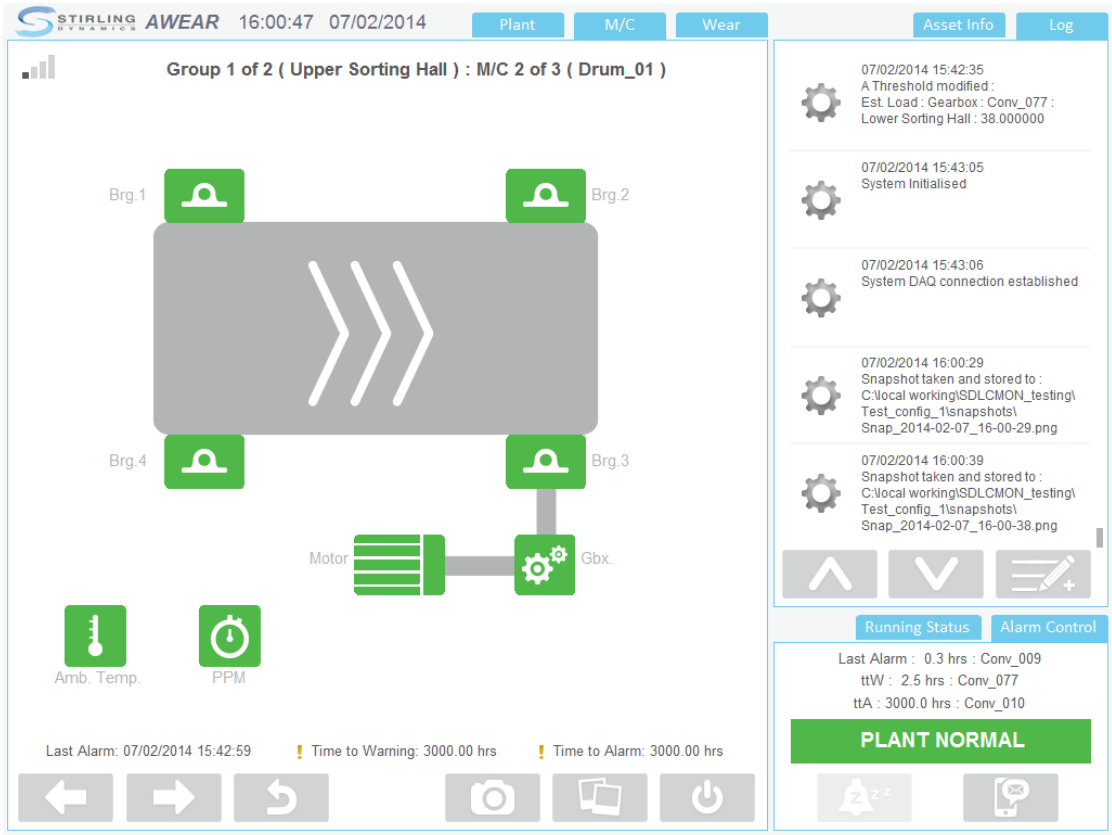

Figure 2 - Graphical user interface of AWEAR system

5.2.1. Observations

The trial system was commissioned on site at the Plant and operated for a period of around 1 year. Throughout the trial period a number of issues were encountered relating to the system, both technical and cultural. These issues impacted upon the validity of collected data, restricted the ability of a long term, reliable data historian to be compiled.

Table 2 - Summary of data acquisition issues encountered during AWEAR trial

Issue		Description
Sensor detached		Bonded RTD sensors becoming detached from their mounting locations due to poor adhesion or mechanical action
Sensor failure		Damage to RTD sensor internals rendering output inaccurate
Cabling damaged	Poor installation	Cabling damaged by escaped product as a result of poor securing during installation
	Nefarious action	Cabling severed or removed by personnel, most likely to gain access
	Accidental damage	Cabling unintentionally damaged, most likely by power-hose during cleaning
Power loss	Connection removed	Main power feed to DAQ equipment removed by personnel during work completed to other power elements and not promptly reinstalled
	Entire system failure	Entire plant power supply lost due to external factors

As summarised in Table 2 a range of issues associated with the ability to reliably acquire data were experienced. Primarily these related to the reliability of RTD sensors and their ability to withstand the aggressive nature of the Plant environment. Frequent damage to the cabling of the sensors was observed resulting in regular data outages, with rectification of issues increasing the workload on the maintenance team. Typically the motor and gearbox RTD sensors proved most reliable, being in close proximity to the box housing acquisition kit reduced their cabling requirement.

Users reported the most valuable aspect of the trial system to be the continuous current draw data for the conveyor drive motor. Previously, if frequent motor overload trips were occurring personnel would increase the trip level to enable the Plant to continue operating. This can result in the motor operating overloaded and thus issues being masked, resulting in minor issues progressing into catastrophic issues for the motor. Therefore, by having access to continuous motor load information personnel can identify increases in loading beyond nominal and thus investigate issues, preventing potentially more serious issues.

In addition to technical issues associated with the trial implementation cultural issues were also observed. Due to the technical issues encountered users were unable to develop confidence in the system thus limiting its utilisation within the Plant. Additionally, whilst trying to enact the significant operational change associated with the introduction of the system, regular operation was both continued and prioritised, for obvious reasons. Therefore, it proved difficult to obtain the personnel resources required to both maintain and support the introduction of the system on a continual basis. As identified in Section 4.3.4, personnel at the Plant are already fully utilised and thus no on site resource could be dedicated by the operator to ensure success of the system.

Figure 3 - Examples of RTD sensor issues encountered (l-r) sensor detachment, cable severing and sensor head damage

6. DISCUSSION

Supported by the characterisation of plant maintenance activities as described in Section 4, 7 key findings relating to the application of predictive approaches to maintenance within the context of the WM industry were drawn (Table 3).

Table 3 - Summary of waste industry findings in context of predictive maintenance

Thematic issue	Description	Implications
Industry characterisation	Maintenance driven by availability and financial cost must be minimised. Equipment low tech but workforce skilled.	- PM must support increased availability. - PM must represent minimal financial investment and/or short and measureable payback.
Socio-technical considerations	Maintenance approach and implementation dictated by experience of key individuals as well as communication between teams.	- PM must support reduction in tacit knowledge through Explitization. - PM must support improved documentation and communication of manually identified issues.
Technical considerations	Maintenance effectiveness limited by inherent issues centred around access to and visibility of plant. Current approaches are not able to be implemented.	- PM must increase observability of asset condition. - PM must aid scheduling of actions through provision of priority metrics.
Perceived value of PM	Form of PM must address specific technical and financial requirements of industry.	- PM must cover maximum assets at minimal cost. - PM must not add to workload of personnel.
Measurement of Performance	Not straightforward to measure maintenance effectiveness as failures are varied and no performance benchmark exists.	- PM must be able to demonstrate clear, tangible improvement in effectiveness to provide business case and ensure on-going support.
Barriers to implementation	Solution must address significant cultural and technical issues present to realise successful implementation.	- Buy in to a PM approach from key personnel must be obtained. - PM system itself must be feasibly maintainable. - Consideration of the influence of manufacturers must be made.
Barriers to realising sustainable benefit	Realisation of successful solution implementation is an on-going rather than a one off task.	- Implementation should be recognised as a gradual process and designed accordingly, with tangible outcomes at each stage. - Buy in must be continual and resource allocated to project throughout duration.

6.1. Industry Characterisation

Maintenance within the WM industry based upon the observations made at the subject plant can be seen to be driven by availability. In contrast to the Aerospace industry for example, where additional factors such as satisfying performance and safety requirements or innovating within a competitive market are relevant, the WM industry view of maintenance appears to as a 'cost centre' or a 'necessary evil' (Jennions, 2011). As such, the industry is typically slow to take up new technology, with little evidence of innovation in the context of maintenance through the implementation of advanced approaches such as Reliability-centred Maintenance (RCM). This is despite the relative maturity of such approaches and the presence of a range of maintenance issues within the industry.

This lack of innovation is likely to be driven by financial implications; plants are operating to increasingly demanding legislation and with little financial compensation in return. Thus, the possibility of innovation can be expected to perceive a high degree of risk to operators. Additionally, due to a lack of technology development within the industry, a culture of innovation has not been harboured.

6.2. Socio-technical Considerations

From the characterisation of Plant maintenance described in Section 4 a number of socio-technical issues can be observed.

Much expertise within the maintenance approach is held by key personnel in tacit form. As such it can be deduced that the effectiveness of the maintenance approach implemented is dependent upon retaining these key personnel. The impact of a reported 20% churn rate within the maintenance team can therefore be considered a significant limitation on the ability of the maintenance team to both implement existing strategies as well as enact improvement. Improving the resilience of the Company to departures of key personnel through the undertaking of a series of Externalization activities as described by Nonaka (1994) may aid continued effectiveness of maintenance.

In addition, to mitigate against this limitation, investigating the feasibility of reducing the churn rate may be a valuable exercise. Much investment in personnel in the form of training has been made by the Company, if personnel are not retained value in this training is not likely to be fully realised. It can be expected that the churn rate observed is a result of the undesirable physical conditions found in the Plant; to offset this inherent factor offering an improved remuneration package may realise savings when a longer term systems approach is considered.

An alternative, more disruptive approach could be to outsource the maintenance of systems to a third party or OEM, thus reducing risk, uncertainty and overheads in exchange for fixed outlay. This could also have secondary benefits such as providing access to state-of-the-art technology and predictability in outlay as suggested by Waeyenbergh, Pintelon, & Gelders (2001).

The secondary effect of a high churn rate within the Plant may be to reduce diligence and initiative from personnel in terms of identifying and reporting issues. The plant technician roles within the Plant were reported by management to be commonly filled by low-skilled transient workers, often of foreign origin. This is likely to further contribute to communication issues between the plant technicians and the maintenance team, again limiting the effectiveness of maintenance.

The introduction of a CMMS on site as suggested by the Maintenance Manager could help to improve communication, reporting and traceability. However, such a system would require significant initial and on-going investment, financially and in terms of effort, to ensure adoption realises success.

6.3. Technical Considerations

In addition to the presence of socio-technical issues, a number of technical issues within the Plant were highlighted as impacting upon maintenance performance.

A strong reliance is placed upon visual inspection to identify the condition of plant assets. Given the limited access provided to plant assets it is obvious that this approach inherently limits the possible effectiveness of plant maintenance. Additionally, inspections, whether this be as part of cleaning or PPM activities, appear to be based upon the experience of personnel to determine asset condition. Little to no evidence of objective measures being employed to assess condition was found. A comprehensive list of instructions for checks is provided to personnel to follow during each task, however, the resulting estimation of condition is still subjective and generally a binary state e.g. belt OK or belt needs repair/replacement. Therefore, inefficiencies are induced: assets can either fail due to lack of failure onset identification or assets may be too proactively maintained, introducing added cost and unnecessary effort.

Belt failures within the Plant are also a significant cause of downtime, both scheduled and unscheduled. The root cause of these failures appears to be either: one off events in which a belt is sliced (e.g. metal or glass) or as a secondary effect of primary issues occurring such as bearing failures or shaft damage. The complete failure of a belt due to slicing can be considered infeasible to predict prior to occurrence, due to the speed of development, therefore they may most suitably be tackled by design: either belts could be toughened to prevent slicing or the material causing slicing could be prevented from entering conveyors. However, belt failures as secondary effects could be reduced through better maintenance of primary issues. It was suggested that such failures are very difficult for personnel to predict due to the limited observability of condition afforded. Therefore, by increasing this observability, failure onset could potentially be identified and tackled prior to failure occurrence.

PPM approaches were found to be implemented significantly at the Plant. However, little formal review of the schedules implemented was observed. Revision of intervals was suggested as being a very much reactive approach, with no formal process for feeding back performance to inform future scheduling. Thus, with over 80 conveyors, plus specialist equipment, there is the potential for substantial inefficacy.

The Company attitude to maximising availability above all else also impacts upon the ability of the Plant to be effectively maintained. By operating equipment at maximum (or even above) design capacity increases the progression of issues, resulting in increased maintenance actions being required to support continued operation. However, maintenance resources do not appear to have been increased to reflect this. Personnel did report significant improvements in the effectiveness of maintenance at the Plant since start-up although this may only be a perception, with no real quantification of improvement provided in support.

6.4. Perceived Value of Predictive Maintenance

At the Plant, process downtime incurs significant financial penalty to the Operator, with specific equipment repairs adding further significant costs. These, in conjunction with the issues discussed in Sections 6.2 and 6.3, suggest significant potential for value to be realised through improvements in maintenance performance.

Based upon the nature of the issues encountered, a shift towards PM approaches at the Plant could realise such improvements through:

- Reducing reliance upon visual inspection for identification of asset condition
- Improving observability of inaccessible areas of the Plant
- Minimising the progression of failures from primary to secondary consequences
- Informing the scheduling of preventative actions

However, in order to provide a viable proposition the configuration of PM elements within the overall maintenance approach must be considered. Within the Plant, specific assets are responsible for large proportions of unscheduled downtime. Additionally, some assets are more process critical in terms of the ability of the Plant to operate without them. Hence, it may be most appropriate, given the financial constraints of the industry, to focus monitoring around these key assets as suggested by Waeyenbergh et al. (2001) who propose a framework for the development of a Knowledge-based Maintenance approach centred on the identification of the Most Important Systems within the process.

Overall, the implementation of PM must represent a proposition providing a balance between the cost of improving asset condition observability against the value of this information. Additionally, this cost must be considered as a combination of both the initial purchasing and installation costs to generate this information as well as the on-going costs to maintain the implementation.

6.5. Measurement of Performance

Whilst an evidenced rationale for the implementation of PM at the Plant can be made based upon technical suitability, as in Section 6.4, in order to obtain the required investment from management, tangible improvement realised by an implementation must be demonstrated. Thus, in order to demonstrate improvement the baseline performance of maintenance at the Plant must first be measured.

Maintenance performance is typically examined through two concepts: Maintenance Effectiveness and Maintenance Efficiency. Maintenance Effectiveness describes the degree to which a maintenance scheme is ensuring that the assets within its scope are continuing to fulfil the functions they are intended to. Maintenance Efficiency measures how well the resources available to the maintenance scheme are being utilised (Moubray, 1997).

Given this, it could be proposed that Maintenance Effectiveness improvement can be inferred from a reduction in the number of failures observed. Maintenance at the Plant was found to be relatively well documented, with significant effort apportioned during commissioning to assigning metadata to all assets, and ongoing through logging of completed actions, all of which could be utilised to support the quantification of observed failures.

However, many factors (e.g. demand, environment, personnel changes etc.) influence the effectiveness of the maintenance team in addition to asset condition. Additionally, failures at the Plant are nuanced and thus the impact of two ostensibly identical failures cannot necessarily be validly compared, further increasing the complexity of quantifying improvement.

Also, as observed as part of the AWEAR trial, PM can realise a number of secondary benefits which, whilst valued by the maintenance team, do not necessarily translate into tangible improvements. Therefore, it should be recognised that proving a business case for PM based solely upon technical or financial metrics may be challenging.

6.6. Barriers to Implementation

The success of a disruptive technology such as PM when implemented cannot be assumed, both technical and socio-technical issues exist which may influence success.

As described in Section 5.3, robustness in the performance of data acquisition equipment must be demonstrated in order to enable confidence in the system. From the sensor issues encountered during the AWEAR trial it can be deduced that the sensing equipment must inherently be designed for the operational environment in which it will be deployed. For example, a number of sensor issues were theorised to have resulted from plant technicians power hosing equipment during regular cleaning activities. Therefore, the equipment must be capable of withstanding such treatment by design, something not significantly considered during the design phase. In this vein, increasing visibility and awareness of the presence of kit, particularly when equipment is retrofitted, may be beneficial.

Additionally, it can be concluded that the impact of plant design upon a data acquisition system must be considered. It can be assumed, based on observations of plant equipment, that it is designed solely to satisfy its primary requirement. For example, conveyors are designed to convey product, little consideration for accessibility or maintainability is made. The implications of this within the trial installation were that poor access made both installation and maintenance of bearing RTD transducers challenging resulting in significant outages of these data sources after issues. In contrast, the easier to access motor and gearbox transducers proved to be much more reliable data sources.

A PM approach enables potentially more efficient scheduling of service intervals to be implemented, with assets only maintained when required. However, often operators are implementing maintenance schedules dictated by the equipment manufacturer and the satisfaction of these can frequently be a stipulation of warranties. Whilst a PM approach could theoretically enable optimisation of these schedules beyond nominal guidelines, manufacturers may block such actions. This will result in the operator having to make a decision as to whether voiding warranties in return for increased efficiency is beneficial. This decision is likely to be influenced by a number of factors beyond purely technical. Potentially, such technology may be more suitably implemented as part of a manufacturer push, in doing so transitioning towards a servitisation-type model in which the responsibility for maintenance of equipment is transferred to the manufacturer.

6.7. Barriers to Realising Sustainable Benefit

As well as considering the impact of cultural issues upon the implementation of PM, consideration should be given to ensuring long term, sustained change is obtained.

A technology driven solution requiring an interface with personnel can be seen to be effective only if cultural 'buy in' is achieved. Enacting change to the way in which personnel work is challenging and, if not achieved, can result in technology becoming a 'white elephant.' This socio-technical issue is acknowledged in much literature (e.g. Cooper, 1994; Nah, Lee-Shang, & Kuang, 2001; Wong, 2005), and specifically within the context of PM, it is suggested by (Grubic, Redding, Baines, & Julien, 2011) that the key challenges in realising all the benefits of diagnostic and prognostic technology within the UK manufacturing sector relate to business and cultural issues rather than technology advances.

In the context of the AWEAR trial, cultural buy in from the Maintenance Manager was obtained at the outset of the project, with his input helping to drive the project to realisation. However, in terms of the actual users of the system (i.e. the plant technicians) the technology was very much 'pushed.' Little engagement beyond basic system training was provided, the purpose and developmental nature of the system was not necessarily obvious and strict enforcement of its utilisation was not made. As such, the system failed to establish itself as a regularly used tool within the teams.

To mitigate such scenarios when implementing disruptive technology a commonly employed mechanism is to assign a 'champion' to the project whose responsibility is advocacy and support for the introduction of the technology. However, within the AWEAR trial no such dedicated resource was able to be allocated to the project by the operator due to resource constraints. Instead, support of the system was allocated to a maintenance team member on top of existing duties, with no consideration for how the additional support required by the system would be delivered. As such, numerous examples of the system being neglected were encountered with data outages incurred as a result. Therefore, it can be concluded that enacting sustainable change will require recognition that the implementation of novel technology is a continuous process in which success cannot be achieved overnight. To reflect this, allocated project personnel should be provided the opportunity to support the project throughout its span, and this cost should be factored into the overall project cost from the outset.

Based upon operational observations it was concluded that the location of the trial AWEAR system also had an influence on its success. The subject plant was reported to be of the most aggressive form encountered within the industry, and as such, most challenging to maintain. This could suggest it as being the most obvious location for a trial PM system due to the potential for improvement possible. However, as highlighted by the consulted industry expert, often selecting the most challenging environment can be counter-productive. Conditions are much more challenging and thus success is much more difficult to achieve. Instead, selecting a well maintained plant may be more suitable. A well performing team is likely to be more motivated and the physical conditions are likely to be much more conducive to success. Subsequently, once a successful implementation has been achieved the system can be 'rolled out' to other plants where the initial team can act as champions, demonstrating the path to success.

7. CONCLUSIONS AND FUTURE WORK

Increasingly, operators within the Waste Management (WM) industry are looking to improve maintenance performance within processing facilities, with predictive approaches to maintenance suggested as a potential solution. With this in mind, a study was conducted within a household waste mechanical and biological treatment facility with the aim of characterising current maintenance practices in the WM industry.

Four interviews were conducted with key personnel on site to support characterisation, from which seven key findings were elecited. These findings suggest that inherent issues are present within current maintenance practices which have potential to be reduced through the introduction of predictive approaches. Inspection of these issues demonstrates that whilst nuanced to the WM industry, in terms of the high level drivers for the technology, many parallels to conclusions drawn from alternative industries can be observed such as those described by (Jennions, 2012; Moubray, 1997; and Sun, Zeng, Kang, & Pecht, 2012). However, to maximise realised improvement through the adoption of the technology within the WM industry, a tailored approach is required in comparison to implementations reported in alternative industries. As such, these findings can be considered a basis upon which the requirements of the technology, when applied within the WM industry, can be developed.

To address the maintenance issues identified within the existing approach at the Plant a prototype CM system was developed by Stirling Dynamics and a trial system implemented at the Plant, as a stepping stone towards PM. Driven by observations of the trial system's operation a number of both technical and socio-technical issues impacting upon the success of the trial were identified.

It was suggested that these should be addressed in any future implementations to maximise success of the technology. A system cannot be installed and assumed to realise success; it should be recognised from the start that the path to success will require the investment of significant time and effort.

Additionally, many of the issues encountered with the trial implementation are described by Hicks & Matthews (2010) suggesting that such issues are non-WM industry specific. To investigate the validity of this suggestion the characterisation undertaken at the subject plant could be repeated at alternative facilities.

To tackle the issues observed within the trial installation a number of challenging tasks must be addressed. Firstly, the business case associated with the implementation of the technology within the industry should be considered and a viable proposition developed, with particular consideration given to the cultural issues identified. Secondly, to improve the technical offering provided by the AWEAR system, the suitability and value of existing prognostics algorithms should be explored and any limitations addressed through the development of novel algorithms.

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