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Mr Jonathan Watkinson BEng (Hons) IEng CMgr

"Investigation into the influence of Condition Based Maintenance on employee safety and site profitability relating to Safety Critical Sites".

Supervisor: Dr Muhammad Khan

This thesis is submitted in partial fulfilment of the requirements for
the degree of Maintenance Engineering and Asset Management
MSc

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Abstract

Safety Critical Manufacturing Sites within the United Kingdom are governed by the Control of Major Accidents and Hazards (COMAH). These sites have a specific challenge through needing to keep their ageing sites safe and compliant, whilst also needing to keep manufacturing costs low, in order to stay competitive in an ever-changing market.

In order to meet the challenge of staying safe, and profitable, a Proactive Predictive Maintenance (PdM) Strategy is needed.

This paper will investigate the potential Condition Based Maintenance (CBM) has in enhancing sites safety, and profitability, by reviewing academic papers and industrial practices through multiple case studies; highlighting the gaps and providing recommendations.

The paper will include information from primary research, reviewing academic papers to ascertain from a white paper perspective what information is available. Similarly, it will then conduct secondary research via a technical questionnaire targeting industry to gather insights on practices and the challenges of using CBM.

Additionally, it will use multiple case studies to underpin the primary and secondary research, finally summarising all through a conclusion section.

Note. The work within this paper is drawn from academic research, industrial practices and from a specific case study. Any critical analysis and the thoughts relating to it are solely that of the author.

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List of Abbreviations

AAV	Air Actuated Valves
AB	Airbourne
AB	Air Borne
AODD	Air Operated Double Diaphragm Pumps
API	American Petroleum Institute
Ba	Bar
CapEx	Capital Expenditure
CBM	Condition Based Maintenance
CMMS	Computerised Maintenance Management System
COMAH	Control of Major Accidents and Hazards
FMECA	Failure Mode Effects Critical Analysis
HSE	Health and Safety Executive
ISO	International Standards Organisation
IT	Information Technology
MA	Motion Amplification
MEP	Mechanical Electrical Plumbing
MOD	Ministry of Defence
OCOGS	Operating Cost of Goods Sold
OpEx	Operating Expenditure
PdM	Predictive Maintenance
PF	Potential Failure
PM	Planned Maintenance
ROI	Return on Investment
SB	Structure-Borne
SB	Structure Borne
TI	Thermal Imagery
TotEx	Total Operating Expenditure
TQM	Total Quality Maintenance
UK	United Kingdom
VA	Vibrational Analysis

1 Significance and identification of research problem.

The purpose of this thesis is to investigate the influence that Condition Based Maintenance (CBM) practices have on safety critical sites within the United Kingdom (UK). The drive of this is to understand how data driven maintenance decisions can mitigate risks, which in turn can drive positive fiscal results and improve safety performance.

1.1 Background

Within the UK there are over 950 Manufacturing facilities (Department for Business Innovation and Skills (2013) (Figure 1), which pose a major hazard to the public should an abnormal situation occur.

These Safety Critical sites are governed under the Control of Major Accidents and Hazard Regulations (COMAH) (HSE (2005).

COMAH Sites are pivotal in supporting the accelerating growth in the UKs Manufacturing Sector, which has seen increased demand since the early nineties (Manufacturing Technologies Association (2024), (Williams (2025).



Figure 1 Map to show Safety Critical Sites Across the UK (As depicted by Author from FOI Information (HSE 2025)

However, Safety Critical Sites (COMAH Sites) have a specific challenge through needing to keep their ageing sites safe and compliant, alongside needing to sustain lower manufacturing costs, in order to stay competitive.

1.1.1 Control of Major Accidents and Hazards (2015) and Safety Critical Sites

Manufacturing sites are designated COMAH status depending on the volume of hazardous materials they handle. There are two predefined levels (Upper & Lower) (HSE(2005)). Both levels have differences, but both compel the site owners to strict regulatory oversight, which requires owners to *“take all measures necessary to prevent major accidents and limit their consequences to people and the environment”* (HSE (2015)). Maintenance activities are included within this.

COMAH Regulations are to be adhered to and failure to comply can lead to; Improvement Notices (BBC (2002), BBC (2018), Prosecution (HSE (2003) HSE(2022), (BBC (2024) and in worse cases prison time (Daily Mail (2023)).

1.1.2 Condition Based Maintenance

Conventional Preventative Maintenance (PM) shuts down assets at predetermined intervals to prevent a reactive breakdown. The challenge with PM is the equipment is only as good as its last PM check, alongside costly downtime and overly prescribed PMs to an asset, causing asset damage. CBM is used as a Predictive Maintenance (PdM) (Mobley (2002) tool to identify potential fault prior to functional failure occurring.

1.2 The Problem

Whilst the HSE provides guidance (HSE (2025)), it is kept at a high level. There are however standards which enable implementation of Condition Based Maintenance (British Standards (2025)). There is little information shared from Academia, and few Industrial cases which positively link Safety and Profitability within the PdM Spectrum.

1.3 Aims and Objectives

This paper aims to investigate the influence of Condition Based Maintenance, on employee safety and site profitability, specifically on Safety Critical Sites.

This will be achieved through the following objectives:

1. Conduct Primary research through literature review.
2. Conduct Secondary research through an Industrial Questionnaire.
3. Evaluate Gaps and Present findings.
4. Show Case Study Examples from ABC Chemical Manufacturing.
5. Create a Framework to enable CBM to be utilised to improve safety and cost.

1.4 Thesis Scope

The scope for this thesis is Maintenance Practices and Compliance relating to CBM within a Safety Critical Industrial Setting: Specifically how CBM can be harnessed to benefit both safety and cost.

This thesis will not look in detail at the Asset Management Lifecycle, Reliability, Availability and Maintainability assessment.

1.5 Motivation

The dilemma of putting safety before cost has plagued the commercial sector for years, with Engineers, Plant Managers and Finance Directors all wanting to meet their objectives, but few case studies from industry shared to academia.

The motivation behind this thesis is to formally capture whether or not CBM can positively impact site safety and cost, to enable stakeholders to make successful commercial decisions with little challenge.

1.6 Structure

This thesis is arranged into seven chapters.

1. Significance and identification of research problem.

Chapter one: provides an extended introduction into the thesis, providing a background into the report, defining scope and motivation behind the thesis.

2. Academic and Industrial Practices of CBM for Safety on Safety Critical Sites.

The Second Chapter: provides a brief history into maintenance and aims to inform the reader on what academic research has taken place, critically analysing the problem statement through reviewing academic papers and defining further the need for research.

3. Industrial Questionnaire

The Third Chapter: reviews the methods and results of this paper showing the methodology that was chosen to meet the research aims and objectives, reviewing its effectiveness and accuracy of implementing. This will then be used to present data using innovative methods to analyse the results.

4. Case Study

Chapter four: will consist of a case study from ABC Chemical Manufactures showing practically what tools are currently being used in industry.

5. Results

Chapter five: will review the results from the industrial questions and case study.

6. Discussion

The sixth chapter: will critically analyse the results, how reliable they were and review appropriate context of the work with findings from the secondary research conducted, reviewing appropriate context of both primary, secondary research, and the case study.

7. Conclusion and Future Recommendations

The seventh chapter will conclude the entire paper and provide recommendations for future research.

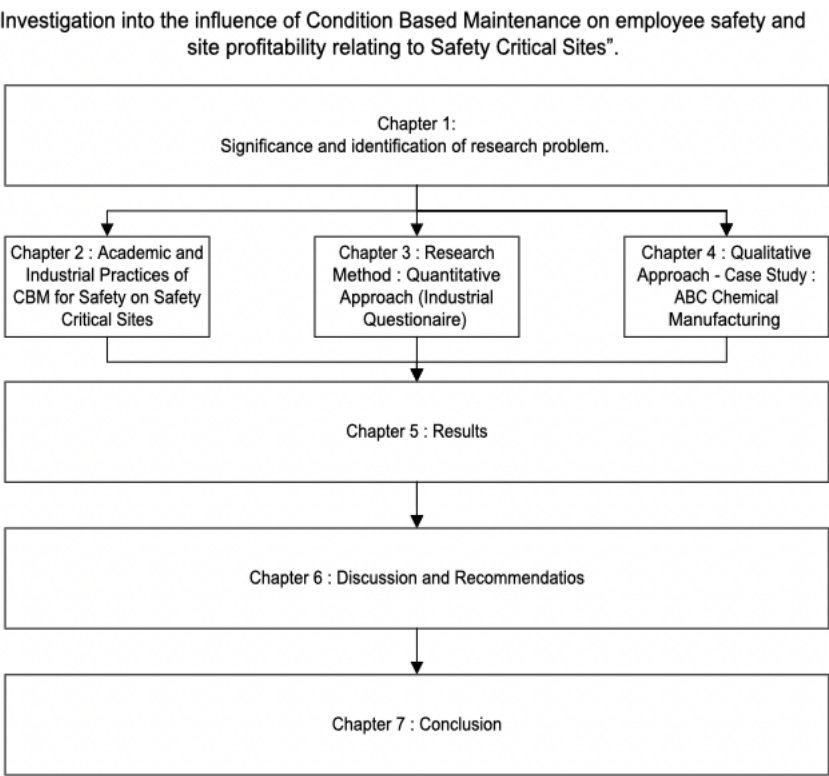


Figure 2 Schematic block-diagram showing thesis structure

2 Literature Review: Academic and Industrial Practices relating to CBM for Safety on Safety Critical Sites

The following chapter will identify the state of the art of the use of CBM within an industrial setting as noted by key theorists. It will provide a history into Maintenance, and Maintenance Management Strategies, reviewing the use of CBM, its challenges, limitations and barriers to execution. Furthermore, it will analyse the gaps in literature, to justify and underpin the problem statement.

2.1 What is maintenance

In order to understand if CBM can positively impact a site, it is important to understand what ‘maintenance’ is. The Oxford Dictionary (2025) describes Maintenance as “*sustaining a status*”, British Standards (2017, p.3) notes Maintenance to be “*the combination of technical and associated administrative actions*”, whereas Mobley (2002, p.8) stated that “*Maintenance is a Science*’.

No matter the exact definition, history has taught engineers assets breakdown and fail unless effectively maintained.

2.2 The Evolution of Maintenance

The history of Maintenance has been well documented over the years (Moubray (1992), Mobley (2002), Ben-Daya (2009), Richardson (2014). Whilst each theorist notes their own interpretation of history, the evolution of maintenance has organically grown throughout the years as technology, peoples’ understanding and apathy towards the difficulty in maintaining assets improves. Figure 3 shows the chronological timeline of the evolution of maintenance based on the above theorists.

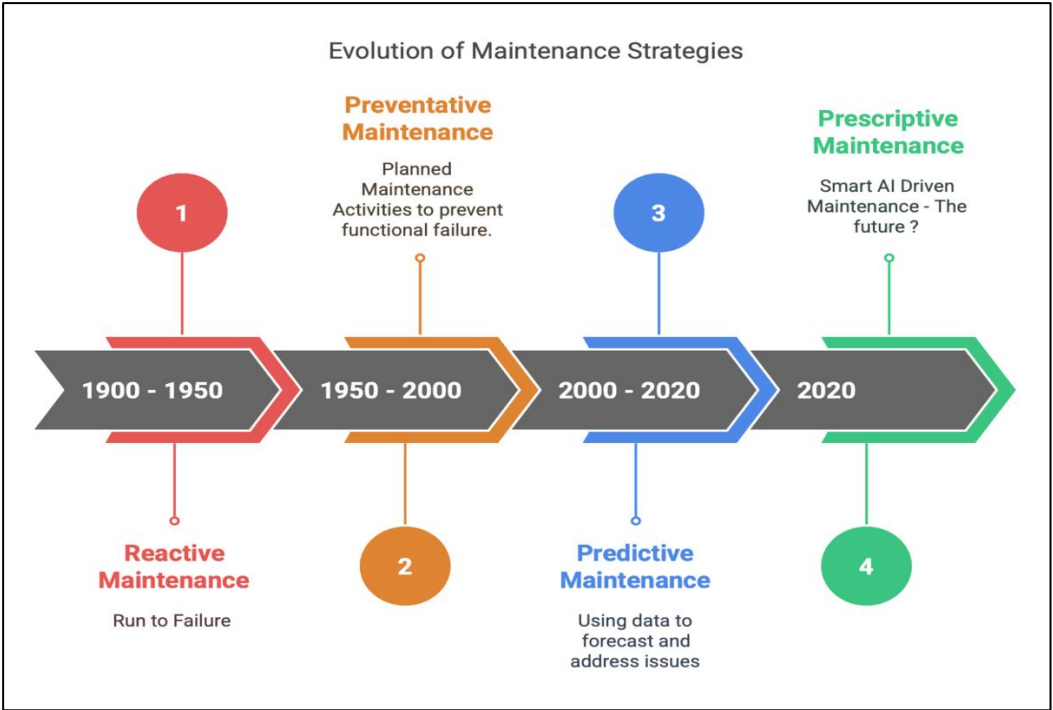


Figure 3 Evolution of Maintenance: Chronological Timeline (Image Generated through Authors text by (Napkin.AI (2025)

2.3 Reactive Maintenance

“Reactive Maintenance also known as Corrective Maintenance “(Department of Defence (1970, p.2) was the first known Maintenance Strategy. Running assets to failure required no downtime to maintain the asset and relied solely on the asset’s own inherent reliability. With asset replacement Capital Expenditure

(CapEx) costs increasing due to complex manufacturing, and the industrial revolution this strategy was not sustainable.

2.4 Preventative Maintenance

“Preventative Maintenance” (PM) (MOD (2022, p 2-9.) came about during the industrial revolution due to assets needing to be more reliable as a result of the higher levels of throughput. PM went through a period of growth during the World War era with the demand on assets increasing, through high reliability (Routledge (2021). Post war era PM theory was built upon and revolutionised through the use of reliability metrics (Toyota (Liker (2020). Technological advancements made it easier to capture historical information on a Computerised Maintenance Management Systems (CMMS), where Total Quality Maintenance (Bohoris et al (1995) was underpinned through data.

This supported by the Potential Failure (PF) Curve model (Figure 3) which supported earlier theories that it was in fact cheaper to fix before failure than to run to failure (Nowlan et al (1978)

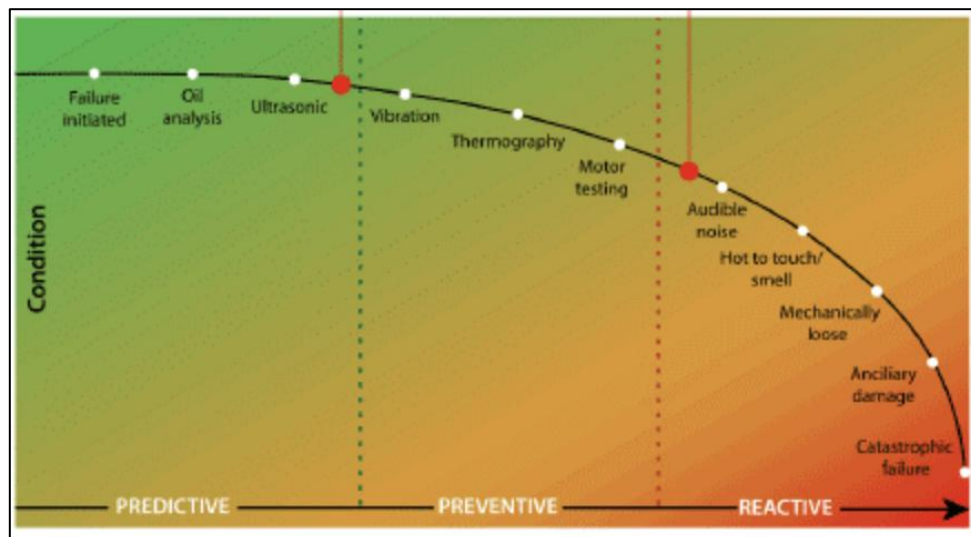


Figure 4 Nowlan et al (1978) Potential Failure Curve as depicted by (Bernet (2022)

2.5 Predictive Maintenance

Predictive Maintenance (PdM) (NASA (1994) was the next natural progression for Maintenance strategies to move into, collecting data in order assess potential failure modes. Reviewing historical data against current state it is possible to see

trends that enable an accurate prediction to form upon when failure will occur. CBM is a tool used within PdM spectrum.

2.6 Condition Based Maintenance

Nowlan's (1978.p 80) research notes an asset requiring CBM as *"a significant item is one whose failure could affect operating safety or have major economic consequences"*, mentioning both Safety and Cost as a key results. However, the limitations of his paper are led by the technological disadvantage due to modern equipment not being available at the time. Similarly, as there are no quantifiable cost savings in his results this limits the usefulness of the paper.

Theorist such as Sylvester (2022) (2020) note the successful use of CBM through specific Case Studies, not just reviewing the technical aspects of failure against the P-F Curve but analysing the potential failure modes against costs. (Doing so by using technology to define the failure modes and articulate failures using quantative data). Sylvester follows the high-level requirements set out in British Standards (2012) and International Standards Organisation (ISO). However, the results from Sylvester's work are limited due to commercial sensitivity and not being able to see costs associated with rectification.

Similar to Nowlan and Sylvester, the Ministry of Defence (MOD (2022), through Defence Standards, mentions how reliability can improve asset availability, showing increased availability as a result. However, the paper is constrained by political agenda, as Cost is mentioned more times than Safety. Whilst it is useful to see how the MOD utilised reliability concepts, cost savings are not quantified. This is likely as a result of the MOD's reluctance to share failure modes due to the security concerns. Rami et al (1996) however does share the cost information but doesn't describe the safety aspects of conducting CBM.

The above papers are examples of a mixture of conceptual usage of CBM with some practical implementation. The remainder of the literature review will look at specific technologies used with CBM following the downward PF Curve, to catastrophic failure.

2.6.1 Ultrasound

British Institute of Non-Destructive Testing (BINDT) notes the use of Ultrasonic as a non-intrusive technique for identifying failures. This is achieved in two ways; through monitoring “*time of flight*” Mugyerwa (2013, p.2) also known as “Airborne (AB)” British Standards (2018, p.5) or through “Structure-borne” (British Standards (2018, p.6). Roberts et al (2010) notes the use of Ultrasound to identify fault within space industries, but his paper is limited through its technical information vs information which is relevant to industry. Whereas Bandes (2014) shares (through a whitepaper) the successful implementation of AB Ultrasound to identify leaks to improve “*Safety Conditions*” and to “locate safety hazard” Bandes (2014, p.3), alongside sharing specific industrial cost savings. Bandes’ paper (which was written on behalf of UE Systems, a retailer of AB/SB Technology) shares Safety and Cost examples, but is written as a sales paper, which comes across as a sales pitch and which could question the accuracy of the information.

2.6.2 Vibrational Analysis

The use of Vibrational Analysis (VA) is a method of monitoring sine waves recorded from an asset’s natural resonance. (Saavedra (2004) Zafer (2023), Srivastava (2017) Islam (2024) all note fantastic usage of VA from a technical perspective, but nothing within their technical papers notes the usage of VA from a cost saving perspective. This makes the papers technically beneficial but without the cost analysis it makes it difficult to articulate the benefits of using CBM.

2.6.3 Thermography

Yang et al (2020) notes the use of Thermography to identify structural defects, within their paper. The paper includes lots of technical data and it does discuss the structural safety concerns should catastrophic failure occur, although there are no quantitative costs included.

However, Sylvester (2022) does provide case study examples but with limited cost analysis; likely due to commercial sensitivity. Sylvesters common sense approach to reliability aids the reader to implement similar ideas.

2.6.4 Acoustic Analysis

Jiang (2008), Galicia (2007) and Cristobal (2014) all note the successful use of Acoustic Analysis (AE) to identify failure modes. Specifically, Cristobal mentions the use of multiple CBM techniques to enable successful identification of failure modes. Rønsch et al (2022) – builds upon Cristobal's works mentioning safety and cost, can be impacted through using dual techniques, i.e. utilising two CBM tool to identify faults.

2.7 Gaps in Literature

The above section has shown that the history of maintenance is well documented, with many theorists and authors willing to put their slant on the progression of maintenance to date. However terminology has become warped between large companies trying to put their own take on what they *perceive* the definition of maintenance to be institutions such as Department of Defence, the Ministry of Defence, NASA, British Standard Institute.

Research into CBM is growing with pace, however research into the applicational impact on Safety and Cost is limited. Research papers that cover this are written by Technical Sales Managers, vs academia. This is likely due to theorist research being heavily technically focused, and less operationally focus. The continuation down this path with grow the gap between academia and industrial practices.

Noting in the papers there was no information specifically relating to CBM tools on COMAH Sites. Whilst some papers mentioned cost savings, few were willing to share the actual fiscal costs (and associated benefits). Whilst its understandable that companies may not want to share commercial sensitive data. The lack of sharing stifles innovation.

Similarly, the terminology for maintaining assets used by the HSE (2015, pp. 33-40) notes *“Necessary measures”* , *“through operating good maintenance practices”* and *“demonstrating that safety and reliability have been taken into*

account, where a Major Accident could occur”. However, there is no prescribed method into how this should be carried out at a regulatory level. At which point Engineering and Maintenance practitioners will look towards standards to ascertain how work should be conducted. Yet standards give no potential costs savings, which makes it difficult to quantify when trying to articulate the benefits of CBM to a Board Directors.

This research aims to bridge these gaps.

3 Research Methods

3.1 Introduction

The methodology utilised in the research for this thesis follows a mixed-method approach (Cresswell (2010)). The literature review identified the state of the art from an academic perspective, enabling gaps in academic research to be addressed through the use of a online survey collecting quantitative data. To substantiate the literature reviews state of the art, alongside an industry wide survey, a qualitative case study has been investigated to understand if CBM can impact Safety and Profitability.

3.2 Hypothesis

Table 1 shows the Hypothesis of this research; noting three Hypothesis exists for this paper. Figure 5 shows how the Hypothesis interlink between the research conducted and potential output.

Hypothesis	Discription
H1.	Conducting CBM on Critical Assets positively impacts downtime and sites Profit and Loss.
H2.	Conducting CBM on Critical Assets directly impacts Lost Time Injuries, and Sites Safety
H3.	Conducting CBM reduces stress and in turn workload on Engineering Teams.

Table 1 Research Based - Hypothesis

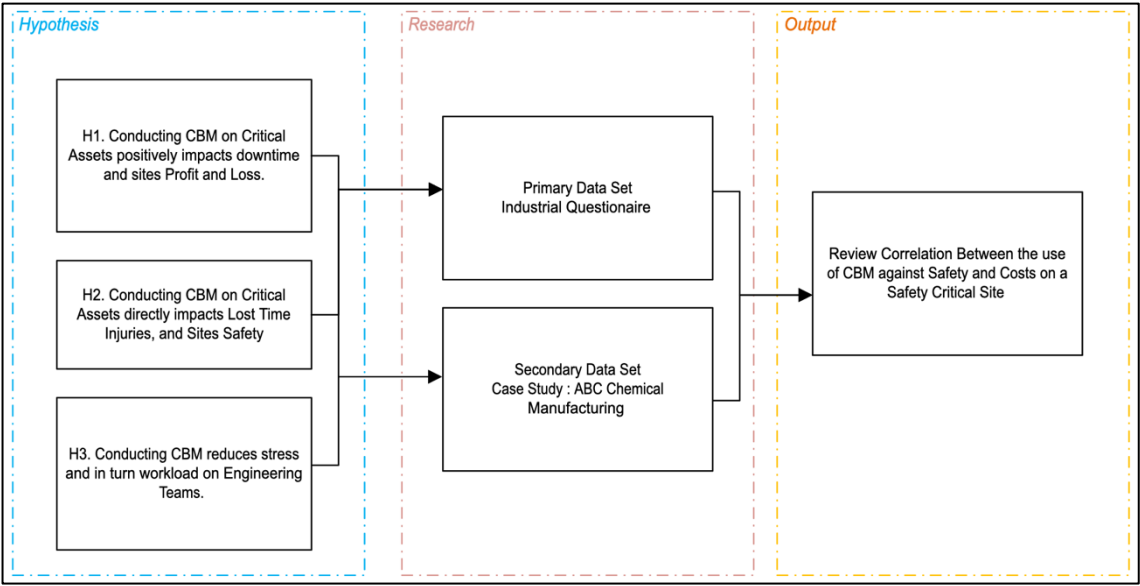


Figure 5 Research Model

3.3 Quantitative Approach – Online Survey

Following successful approval by Cranfield Universities Ethics team (Appendix A), a survey was submitted using Survey Planet (2025) and shared to the author’s professional network on LinkedIn (2025) and around the authors professional workplace on 5th March 2025.

The survey data set was collected over a four week period. The specific questions can be found in Appendix B.

According to Saunders (2009) questionnaires are easily influenced, specifically relating to how the questions are asked. Through Open and Closed questions, it is hoped to get a varied response, and in turn a true reflection of how the industry utilised PdM tools.

The purpose of the online survey questions was to question the gaps following the literature review. In order to understand how industry is utilising CBM. This is in support of the objectives identified in section 1.

4 Qualitative Approach – Case Study : ABC Chemical Manufacturing

From the information gained during the literature review the author utilised a number of PdM techniques within ABC Chemical Manufacturing, to see if there is added value in employing these to impact sites safety and profitability.

4.1.1 ABC Chemical Manufacturing

Note. Section 3.4.1 - The introduction into ABC Chemical Manufacturing has been previously published in BINDT Condition Monitoring Papers (Watkinson et al (2024). But is a direct reflection of the case study.

ABC Chemical Manufacturing is sited in the United Kingdom. It manufactures a variety of Solvent Based Flammable Materials, which are shipped across the Globe.

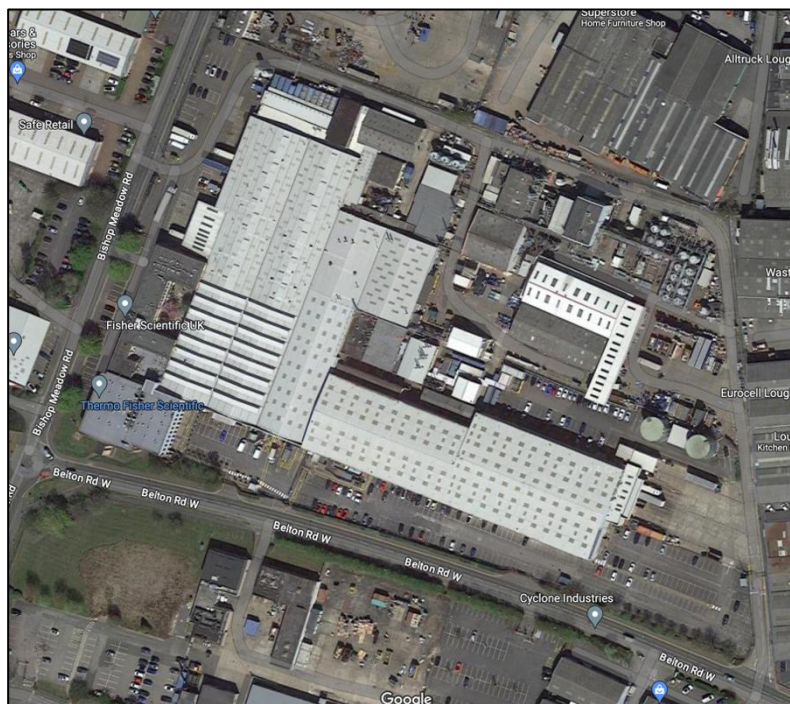


Figure 6 Aerial View of ABC Chemical Manufacturers (Google Maps(2025)

Manufacturing is conducted across three key processes.

- Manual Bottling of Bulk Chemicals (Where no distillation or mixing process is required)
- Distillation of Chemicals then sending them to the Manual Bottling Facility

- Mixing of Multiple Chemicals then sending them to the Manual Bottling Facility.

The manufacturing infrastructure dates back to the mid 1970s, with more modern warehouse facilities added at a later date to support stock holdings and manufacturing growth.

The Site is closely regulated by the United Kingdom's (UK) Health and Safety Executive, specifically regulated under Control Of Major Accidents and Hazards (Lower Tier Site) Regulations (HSE (2015)). This is due to the number of flammable materials manufactured and stored within the Site Hazardous Chemical Tank Farm (Figure 7), and the associated impact in the event of an abnormal incident.



Figure 7 LCD : ABC Manufacturing Chemicals Tank Farm

4.1.2 Safety Record and Fiscal Costs

Due to commercial sensitivity, it is not possible to publish full profit and loss detail of ABC Chemical Manufacturing. Section 4 will however go into detail around Operating Cost of Goods Sold (OCOGS), how savings relating to OCOGS can reduce the cost of goods sold, which in turn can be shown as a profit.

4.1.3 Condition Based Maintenance – Tools Utilised by ABC Chemical Manufacturing.

Prior to writing this report ABC Chemical Manufacturing conducted CBM through Contracted resource only. To date the Engineering department utilises six different tools to identify failure modes, noting that two of these techniques are contracted out externally.

ABC Chemical Manufacturing PdM Equipment Overview						
PdM technique	Ultrasonic (SB)	Ultrasonic (AB)	Acoustic	Thermography	Motion Amplification	Vibration Analysis
Manufacture	Wintact	UE Systems	UE Systems	Hikmicro	RMS	Emerson
Model	WT100A	FLIR SI-2	Ultra-Probe 100	BX20	Irs M	AMS 2140
In-house/External	In- house	In house	In House	In house	External	External
Cost of Equipment	92.78	8878	1095	1654.8	34000	22,000

Table 2 CBM tools utilised by ABC Manufacturing

5 Results

This section will review the results from the Industry Questionnaire and three case studies from the author’s workplace.

5.1 Survey Results

As mentioned in section 2 the purpose of the online survey questions was to question the gaps following the literature review in order to understand how industry is utilising CBM. This is in support of the objectives identified in section 1.3.

5.1.1 Respondent demographics and response rate

The survey was published online on 3rd March 2025 and was open for four weeks until 31st March. In total there were 71 Respondents from across the globe. Figure 8 shows the global locations.

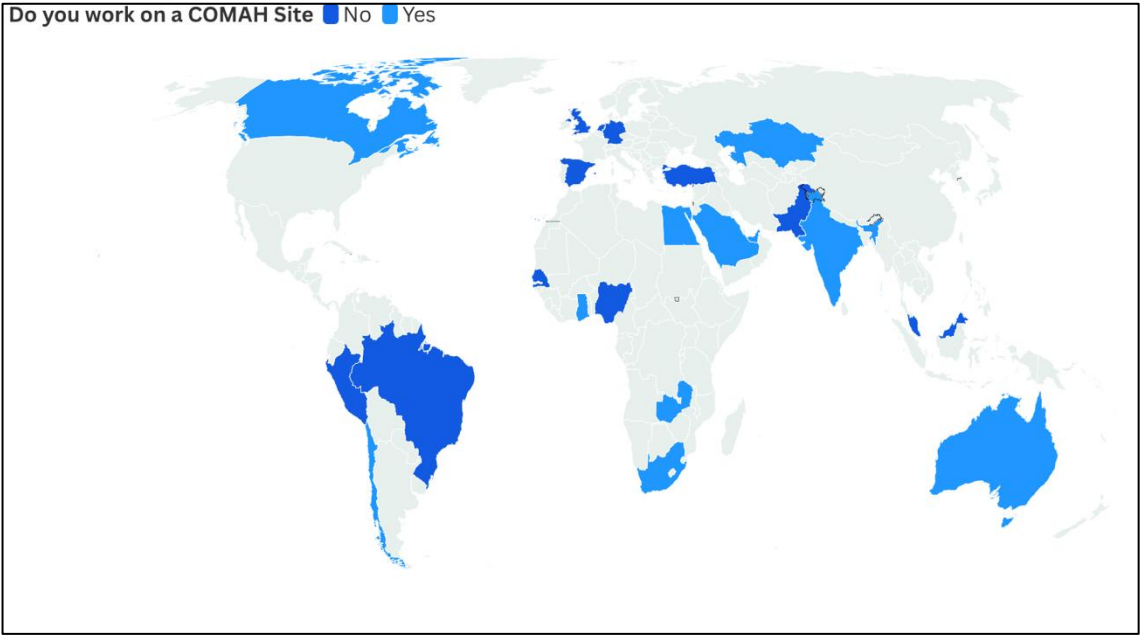


Figure 8 Questionnaire Respondents by Location (Image generated questionnaire data utilising flourish (2025)

Out of the 71 respondents they held a variety of roles; with the majority employed in managerial or hands on based roles.

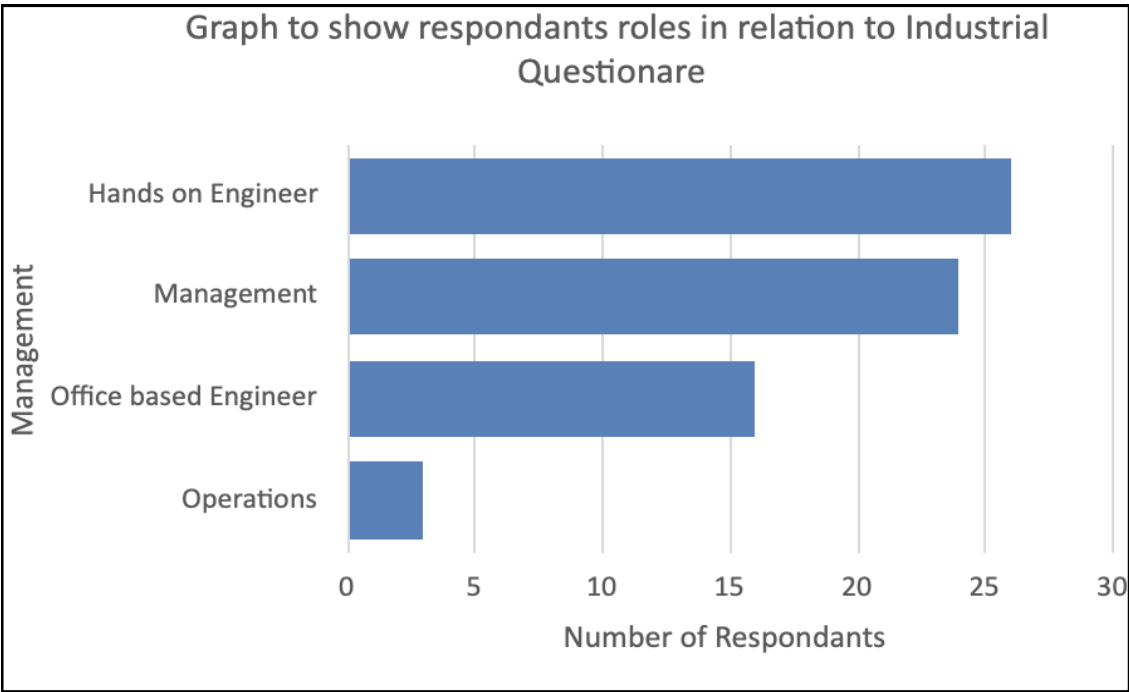


Figure 9 Graph to show respondents roles in relation to industrial questionnaire

The questionnaire was generated and shared on a number of different platforms, including LinkedIn and the author's internal work platform. It is predicted that a total of one thousand people engaged with the post, with 71 responding to the survey. According to Fincham (2008) the response rate percentage is 7.1 % (Equation 1)

$$\text{Response Rate} = \left(\frac{71}{1000} \right) \times 100 = 7.1 \%$$

Equation 1: Response Rate according to Fincham (2008)

Holtom (2022) notes surveys with a response rate of above 4% are to be deemed as "good". It should be noted that there were no incentives tied to the response.

5.1.2 Response Themes

The questions set were designed around the literature review to capture any gaps within industry. With a focus on COMAH Sites the questionnaire was based on five themes. These were Safety, Cost, Maintenance Strategies, PdM tools, and Employee Stress. Noting that 58.6 % of total responders worked on COMAH Sites, there is an accurate representation of the industry.

5.1.2.1 Maintenance Strategies: Maintenance Strategies and In house vs Contracted Maintenance.

Question 3 (figure 10) shows how maintenance strategies are utilised across industry, it indicates that over half of the respondents utilise a mixed maintenance strategy.



Figure 10 Pie Charts to show respondents questions what type of Maintenance strategies their site utilised, alongside whether CBM is contracted out.

Similarly Question 4 showed a mixture of business models with the majority of sites choosing a mixture of conducting CBM in house alongside outsourcing.

5.1.2.2 PdM tools: Types of CBM techniques, perceptions and challenges

Question five (figure 12) showed a mixture of CBM tools being utilised, with the majority of respondents noting they use Vibrational Analysis and Thermography. Question Six (figure 13) complimented the use of these tools showing 54.9% confidence in the effectiveness of these tools, with 42.3% showing some confidence. There were however 2.8% of the respondents who felt these tools were not effective after all.

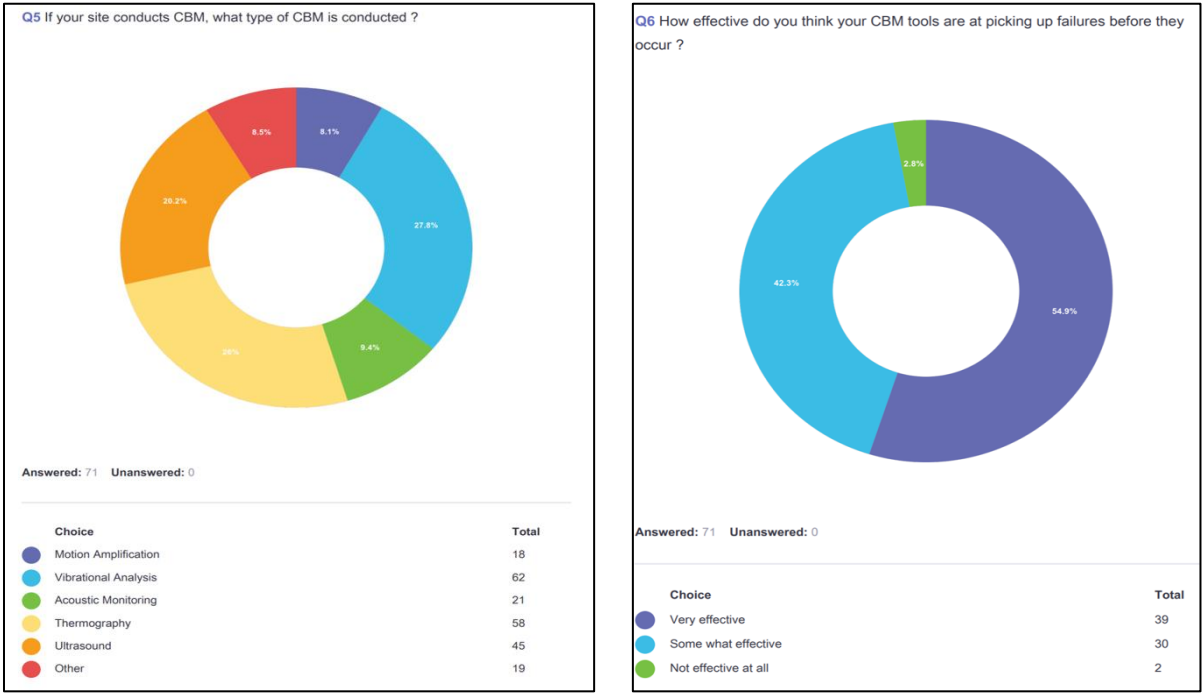


Figure 12 Pie Charts to show CBM Techniques utilised by industry and the perceived effectiveness of CBM tools

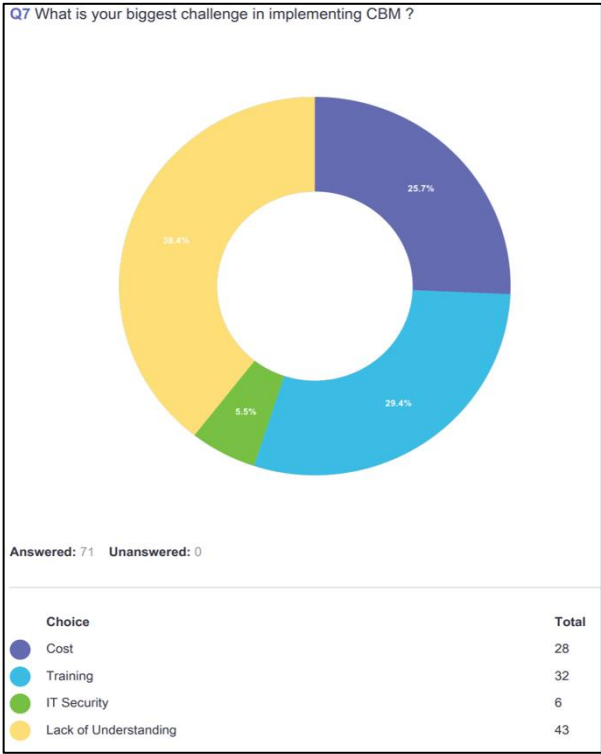


Figure 11 Pie Chart to show challenges in the implementation of CBM

Question seven (Figure 11) focused on the biggest challenges in implementing CBM with 39.4% of the respondents stating a lack of understanding as one of their biggest challenges, with 29.4% stating a lack of training, followed by 29.4% struggling with costs to execute.

5.1.2.3 Safety : Impact of CBM on Safety and associated risk mitigation.

Questions 8 (figure 15) and 9 (figure 16) focused on the impact that CBM can have on site safety. It noted that 78.6 % of respondents saw a reduction in the number of safety incidents on site through the use of CBM. Question 9 shows most safety incidents that were identified were down to structural failures being found (53.3%). With 27.2% of safety issues found related to flammable gases.



Figure 13 Pie Chart to show if CBM has reduced the number of safety incidents on site. Alongside what types of safety risks have been mitigated by the use

5.1.2.4 Employee Retention: Impact of CBM Engineering/Maintenance Teams Stress Levels

Question 10 (figure 17) focused on employee stress showing that 37 of the responders 52.1% found their teams to be less stressed through the implementation of CBM. However 40.8% found the implementation of CBM didn't impact their stress levels, but note more structure and being less reactive.

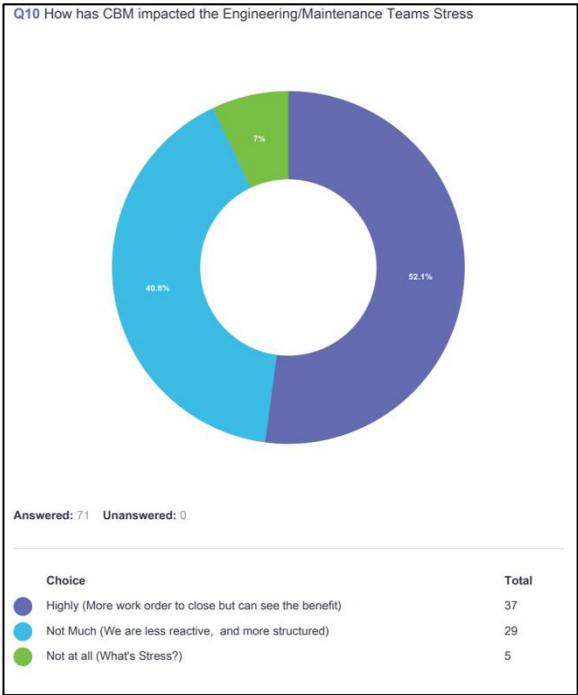


Figure 14 Pie Chart to show if CBM can impact employee stress levels.

5.1.2.5 Cost : Investment and Future outlook

Questions 11, 12 and 13 were all based around the investment opportunity when utilising CBM. Question 11 (figure 17) showed that 70% of respondents spend >£10,000 on implementing CBM, with 24.3% of respondents spending between £5,000 and £10,000 on CBM, and with 5.7% saying they spend less than £5,000 on CBM. Question 12 (Figure 16) showed the majority of the responders (88.7%) saw a positive impact on site through the implementation of CBM, with 93% (Figure 19) stipulating that CBM provides a good ROI on investment, and that CBM will become more widely adopted in the next five years (figure 20)

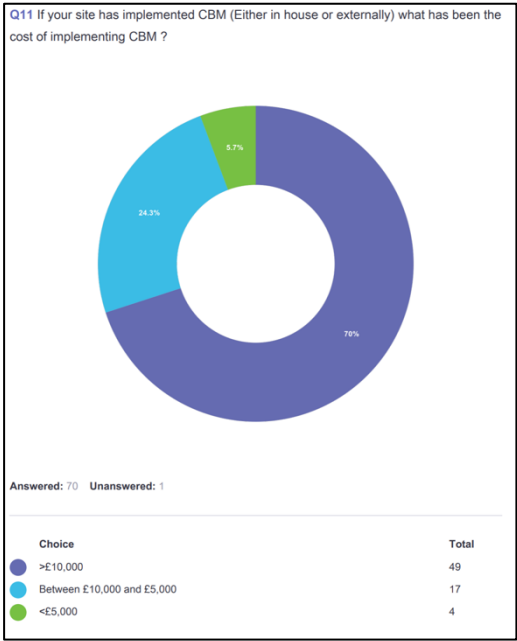


Figure 17 Pie Chart to show implementation costs of CBM

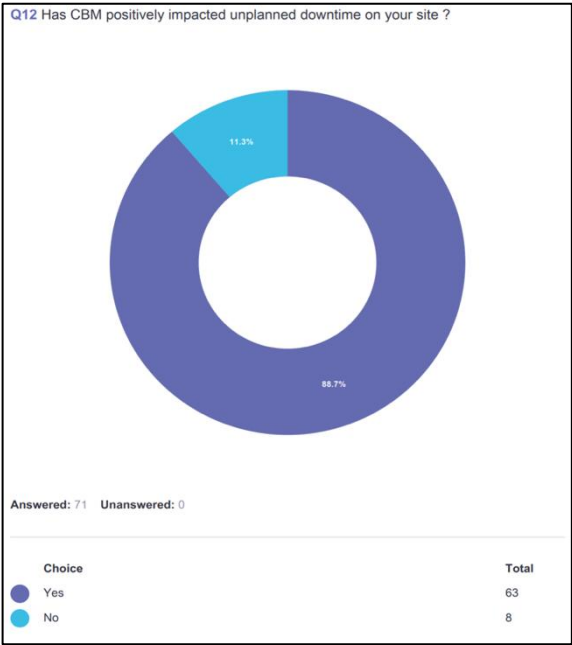


Figure 16 Pie Chart to show how CBM has impacted unplanned downtime on the responders' sites

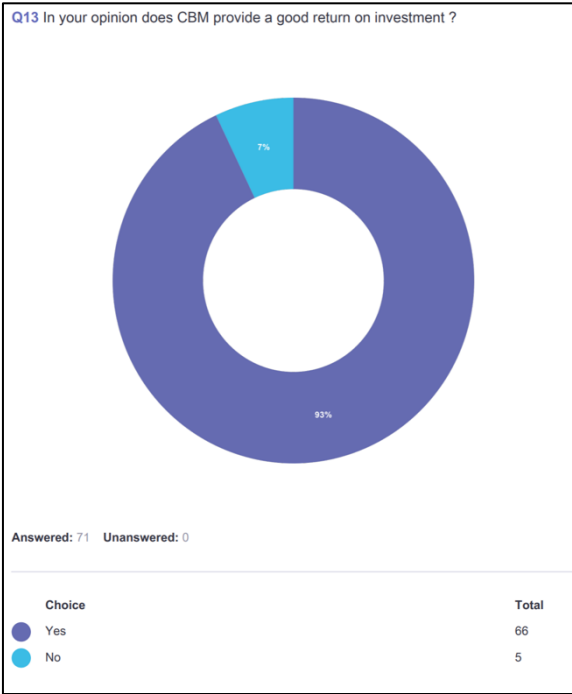


Figure 15 Pie Chart to show responders opinion on whether or not CBM is a good return on investment.

5.1.3 Survey Summary

Collectively the results from the Survey showed that CBM is being adopted across industry. However, there are challenges relating to cost and budget. But this could be outweighed by the positive impact on safety, downtime and employee stress levels, with future trends suggesting that CBM is the future and provides a good ROI.

5.2 Case Study : ABC Manufacturing

This section will review three case studies from ABC Chemical Manufacturing. The case studies are conducted utilising the equipment shown in table 2, through both in-house engineering resource and external resource. The timeline for this case study dates from September 2024 through to May 2025.

5.2.1 Case Study 1 : Utilising Ultrasonic (AB) to identify air leaks.

5.2.1.1 Situation

ABC Chemical Manufacturing relies on pneumatics to operate Air Actuated Valves (AAV). It utilises over forty Air Operated Double Diaphragm (AODD) pumps to move solvent based chemicals around their facilities. The AODD and AAVs are pneumatically supplied by three compressors strategically located around the manufacturing site. Alongside this the site has a number of hazardous gases on site such as Nitrogen and Argon.

5.2.1.2 Problem

One of the primary failure modes to pneumatically supplied systems is a major loss in air, resulting in functional failure. However, site employees note that small air leaks have been perceived as the norm, due to asset being able to perform their functional tasks, albeit at a cost to the business.

5.2.1.3 Impact

UE Systems (2025) stipulates for every 8m² of compressed air lost it costs 1 Kwhr of Energy. At ABC Chemical Manufacturing the cost of 1Kwhr is £0.26 - Noting that the compressors are not turned off and are on 24/7, 365 days of a year.

5.2.1.4 Solution

Utilising a Flir Si-2 (Figure 22) which used Ultrasonic AB principles, alongside leak detection tags, the site rolled out internal air Leak detection and monitoring (figure 20), following (British Standards (2018, p.15) methodology to detect air leaks.

This is conducted on a Bi-Weekly Basis through a Planned Preventative Maintenance work order, generated from the sites CMMS. Figure 24 Maps out this process.



Figure 19 Flir Si-2 and leak detection tags



Figure 18 Apprentice at ABC Chemical Manufacturing carrying out AB Ultrasonic Testing



Figure 20 Flir SI-2 Screen Visual

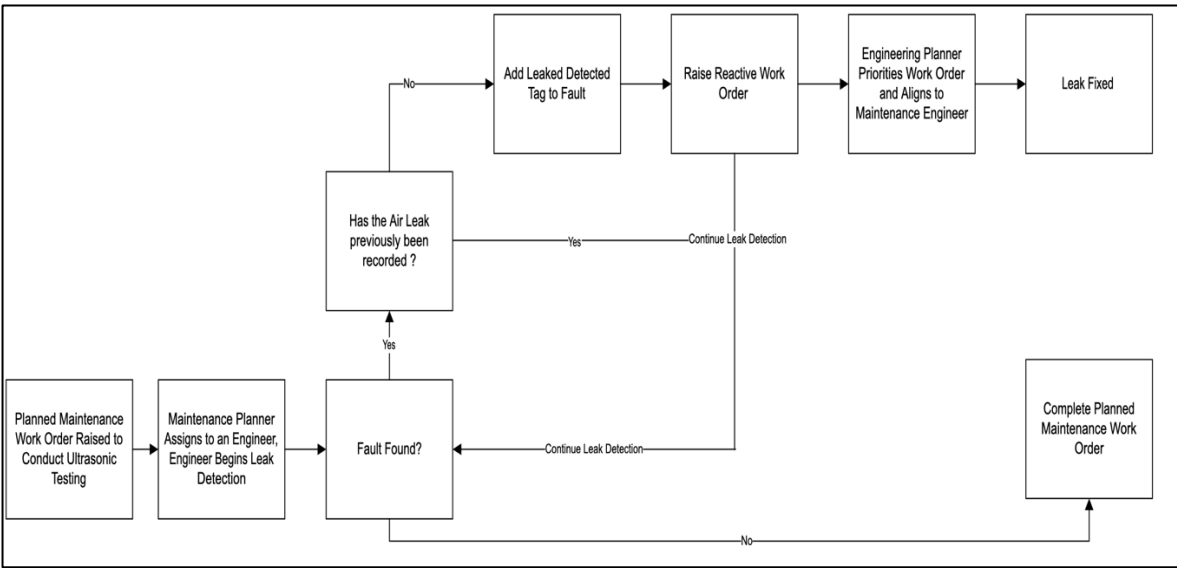


Figure 21 ABC Chemical Manufacturing Leak Detection Process

As depicted in figure 23 the process relies on “Plan, Do, Check, Act” (Slack et al (2022) process. To support and highlight the leaks found the team utilised visual indicator tags (figure 24) to show a leak had been found. Once rectified these

were place on a business visual management board alongside updating a digital tracker (figure 25).

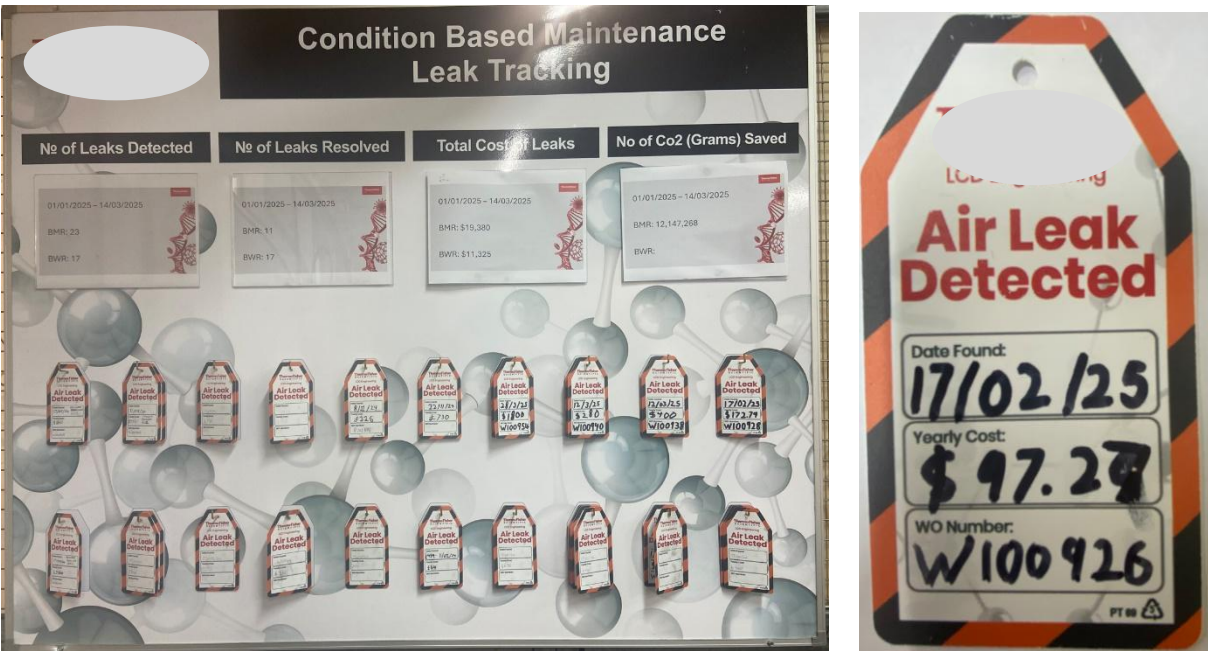


Figure 22 ABC Chemical Manufacturing Leak Detection Process and Visual Mapping

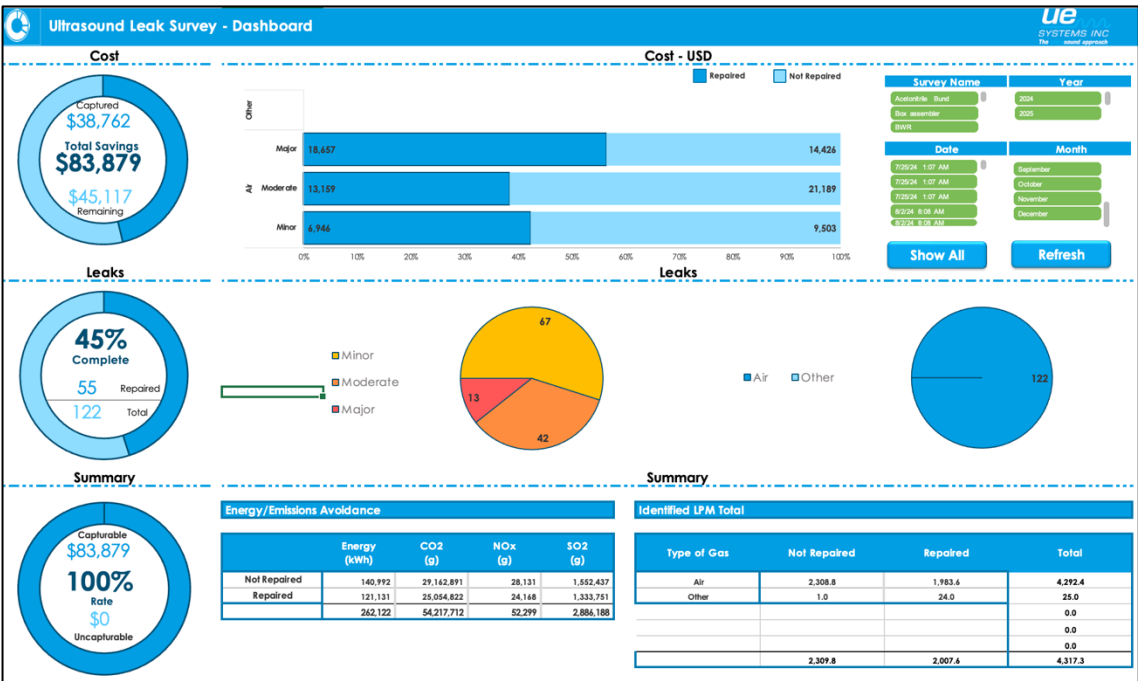


Figure 23 ABC Chemical Manufacturing Digital Dashboard

5.2.1.5 Key Findings

Figure 25 shows the results after eight months' of leak detection, showing a total of 122 leaks found, which were costing \$83,879 per annum, \$45,117 of which have been repaired. 121 leaks were specifically relating to compressed air however one leak was Nitrogen based. Whilst the Nitrogen leak was small and in an open environment, if this had been in a confined space or an area when an employee was working, the impact could have been different.

From a Return On Investment (ROI) perspective the savings in air leaks recovered the cost of the equipment \$16,000, leaving a total saving of \$67,879/£50,761.66. This included the sustainability savings, which showed in excess of 25,054g of Co2 per annum.

The benefit of repairing the cost of air leaks was also noticeable on the site electricity usage (figure 28) shown in Kwhr). Note the levelling of energy usage from week 35. Note the reduction in electrica from weeks 13 through to 32 in the data set is due to heating not being utilised as much due to warmer months.

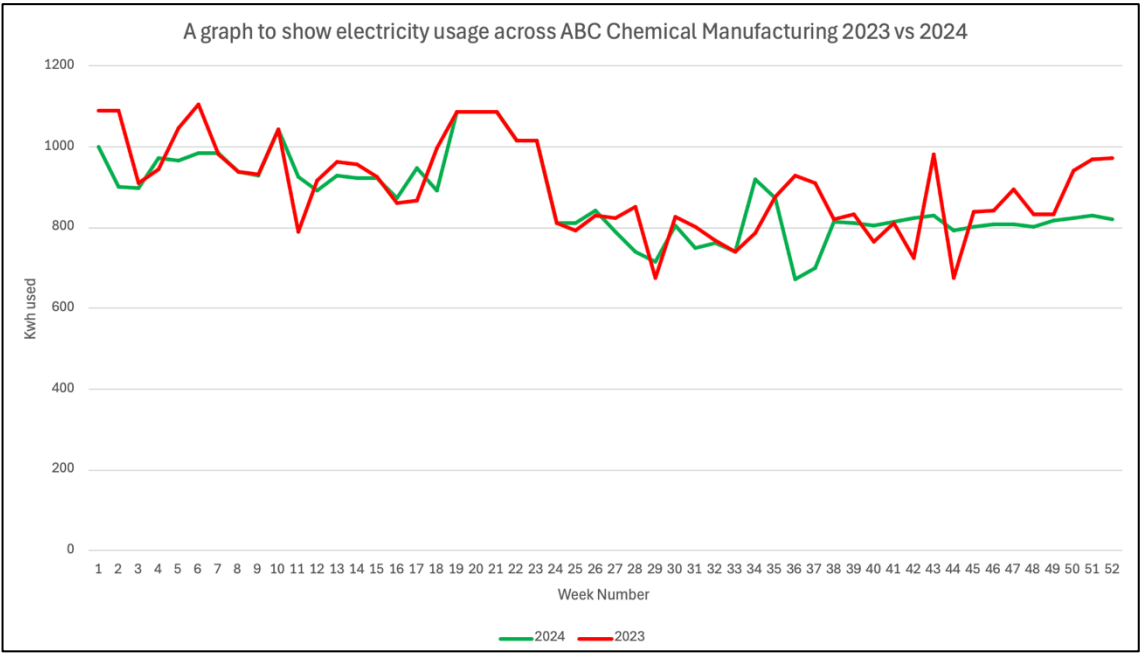


Figure 24 A graph to show electricity usage across ABC Chemical Manufacturing

This cost directly impacts the OCOGS which makes manufacturing costs cheaper and more sustainable.

5.2.2 Case Study 2 : Distillation Vessel: Ultrasonic and Vibration Analysis

5.2.2.1 Situation

In October 2024 during a routine operation, an employee heard an acoustic noise (Figure 27) and raised a Reactive Maintenance ticket for Distillation Vessel 302 (V302).

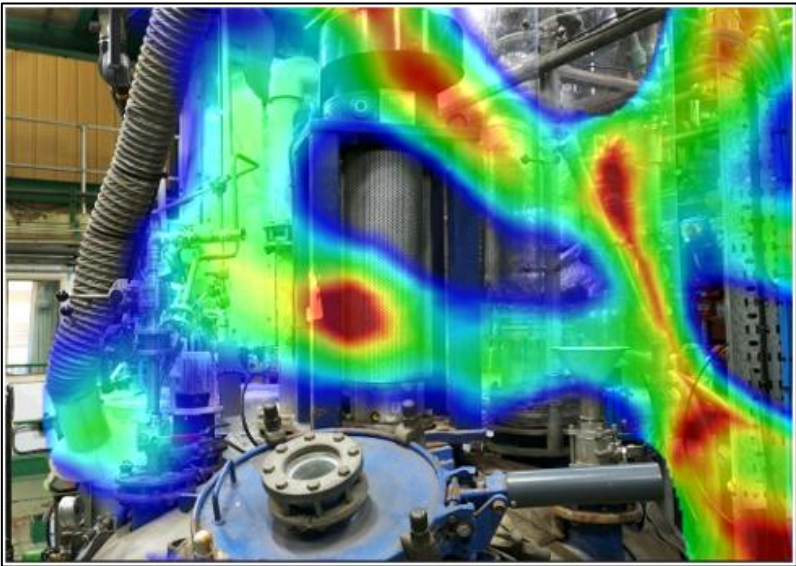


Figure 25 A picture of the level of acoustic noise around V302. i.e what the operator heard.

Noting that the Site Engineering Team employees PdM on all Production Critical Assets, the team reviewed the Condition monitoring data: Vibrational Analysis (VA) (figure 29) and noted that, since September 2024 (figure 31), the asset had been producing abnormal vibration data. (Note Aug 24 vessel was under-load). Initial baseline data started in June 2025.

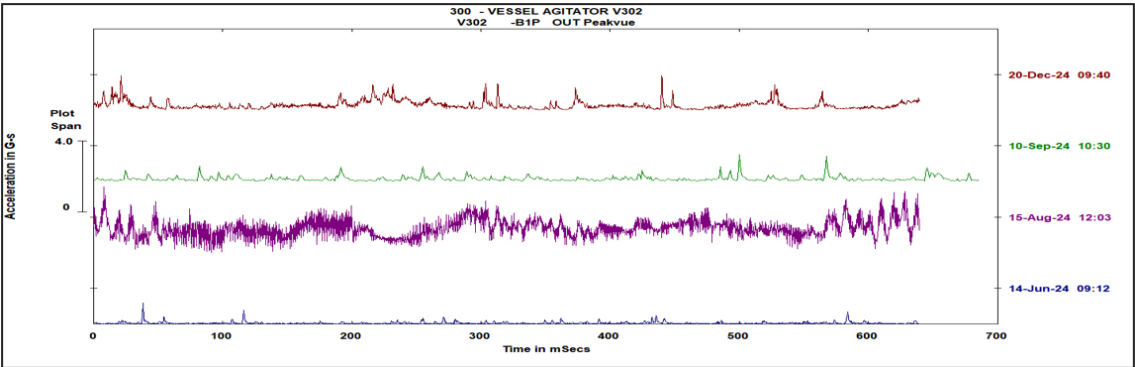


Figure 26 VA data from V302

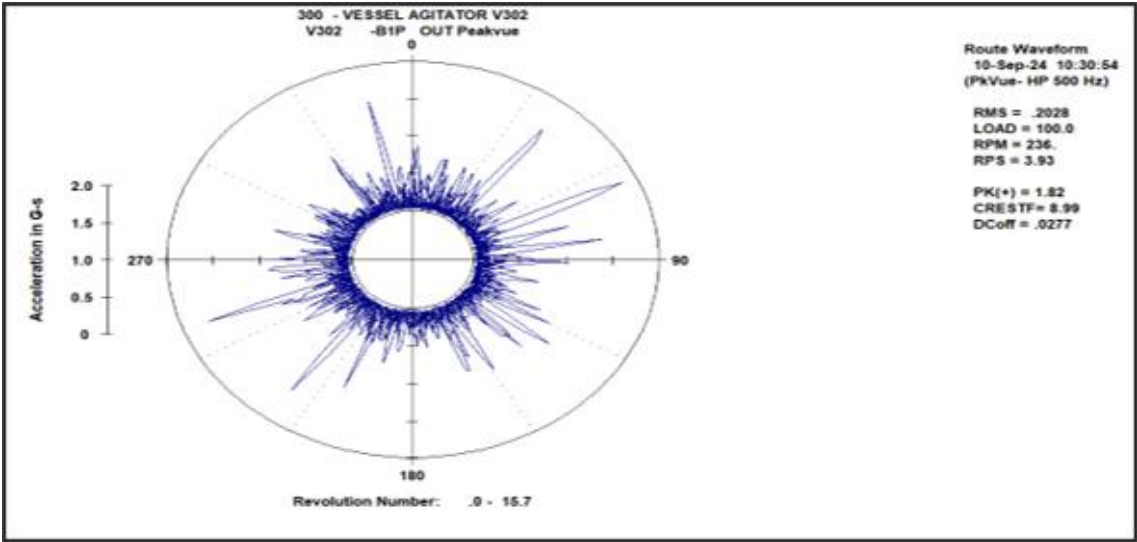


Figure 27 VA Data September 2024

To substantiate the VA findings the team used an acoustic tester to pinpoint the failure mode location (figure 30), noting the potential failure mode in the seal housing location.

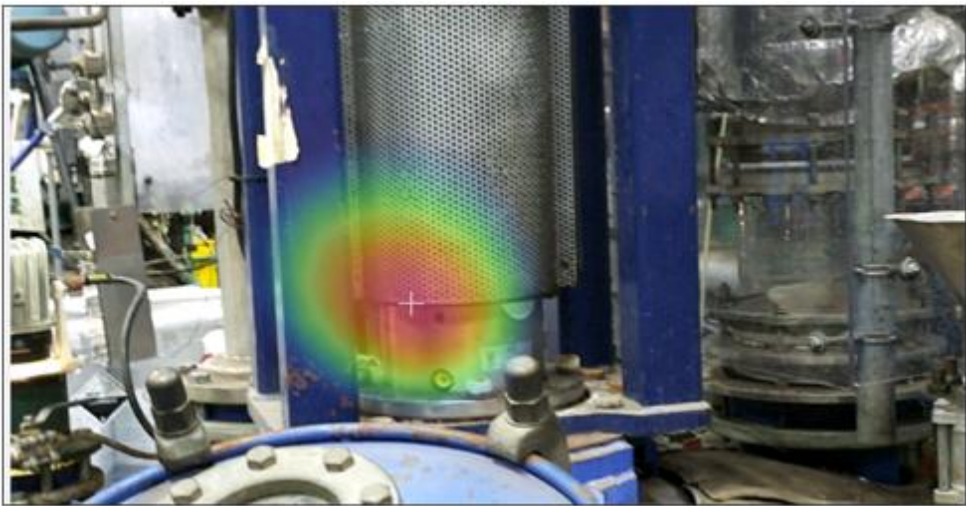


Figure 28 Pinpointing the acoustic noise.

5.2.2.2 Problem

Utilising CBM tools it showed that the acoustic noise was coming from the vicinity of the nitrogen seal as shown in figure 31.

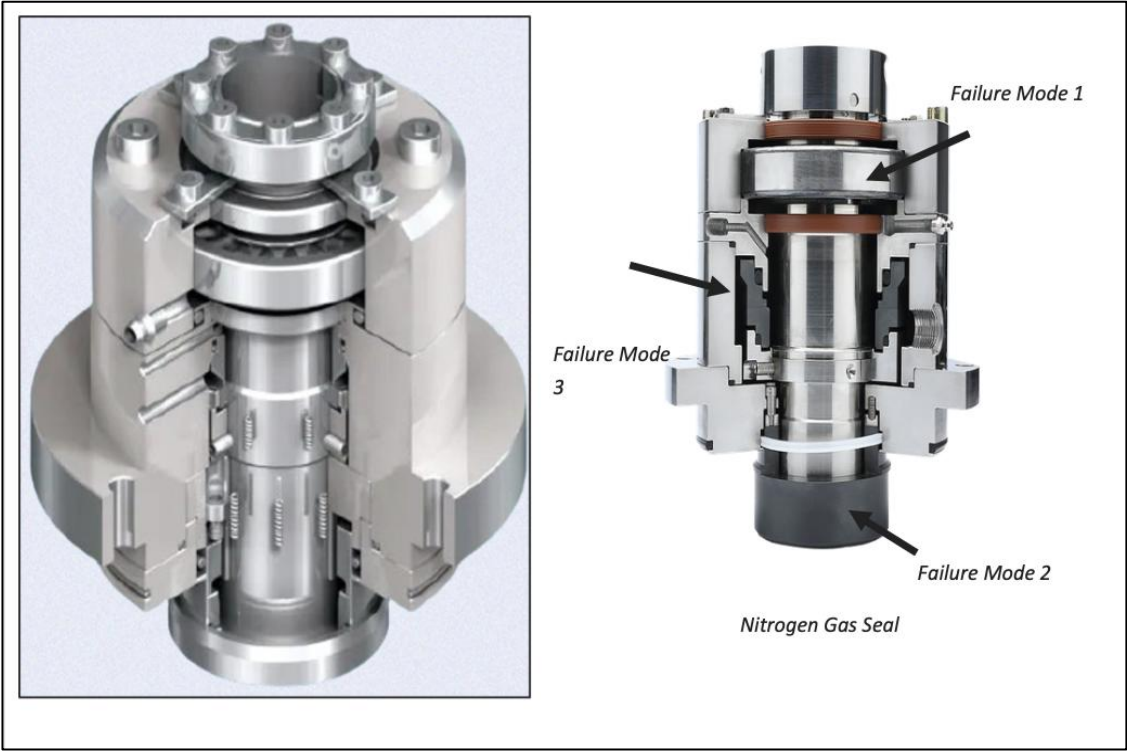


Figure 29 Nitrogen Seal – Diagram

Failure Mode Analysis on V302	
	Potential Cause
Failure Mode 1	Bearing Failure
Failure Mode 2	Loss of Nitrogen Around Seal
Failure Mode 3	Shaft Misalignment

Table 3 Failure Mode Analysis on V302

Irrelevant of the specific failure modes, the high peak values from the VA showed increased acceleration readings (figure 32) it was *assumed* the asset was edging towards functional failure by December. Note (threshold at which failure occurred was assumed).

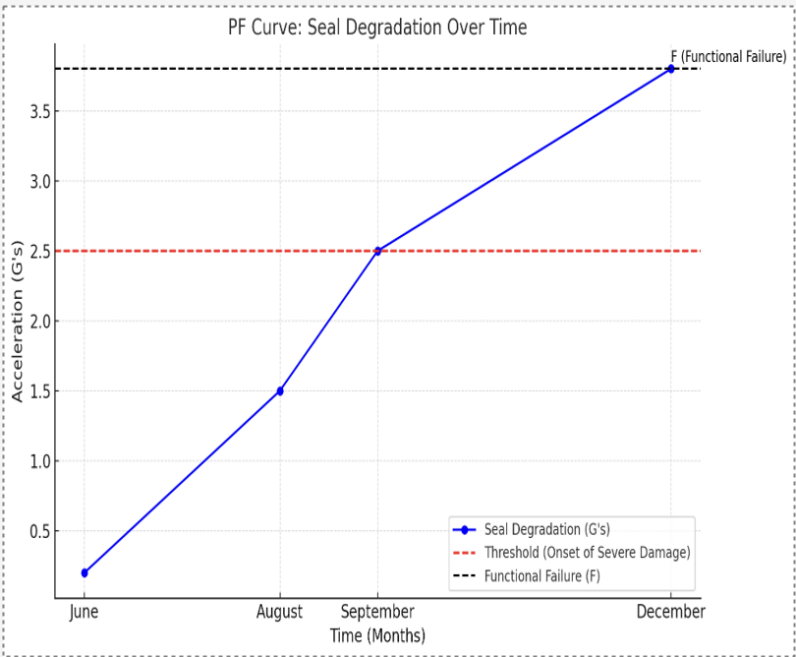


Figure 30 Seal degradation assessment

5.2.2.3 Impact

The use of the agitator was stopped, and production was reduced to 50% of overall capacity, whilst a repair was sought. By turning off the agitator it was risk assessed that chemicals which didn't require agitation could be manufactured.

5.2.2.4 Solution

After 12 weeks of waiting for a new nitrogen seal the asset was repaired. (Figure 33)



Figure 31 Pictorial storyboard of V302 repair

5.2.2.5 Key Findings

Due to the commercial impact of the assets reduced operating capacity an internal review was carried out by the author. The output of this is shown in figures 34 and 35 identifying the failure modes and route causes.



Figure 32 V302 Failure Mode 1



Figure 33 V302 Mode 2

Noting the root cause of the initial acoustic noise was due to lack of lubrication around nitrogen seal causing carbon seal failure. This was due to no nitrogen ever been supplied to the seal. It was assumed the seal was a dry mechanical seal due to no drawings being available.

5.2.2.6 Cost and Impact.

If the operator had not raised the concern around the noise of the asset, and engineering team not had historic data (all be it brief), the asset could have achieved complete function failure. The cost of functional failure is estimated to be £309,296 (\$389 713.96). Figure 39 shows how this has been calculated.

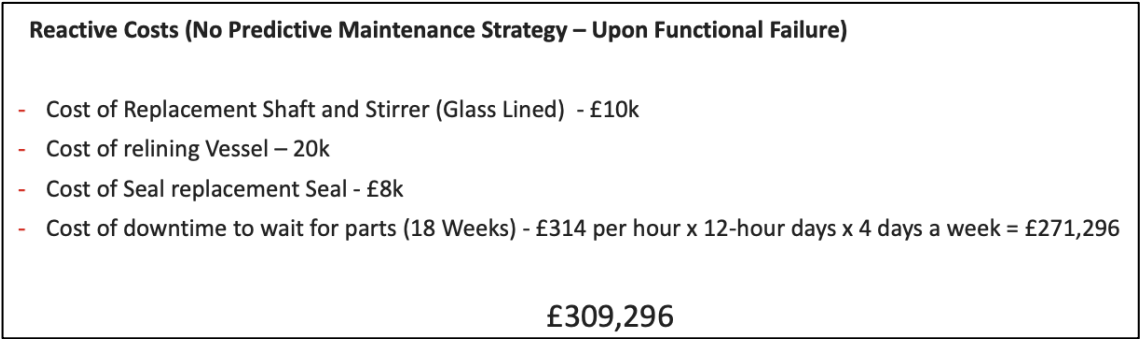


Figure 34 V302 : Cost of Functional Failure Calculation

However, due to the operator’s due diligence and the historical VA data, the proactive strategy cost the business £98,004.60 (\$123,485.79).

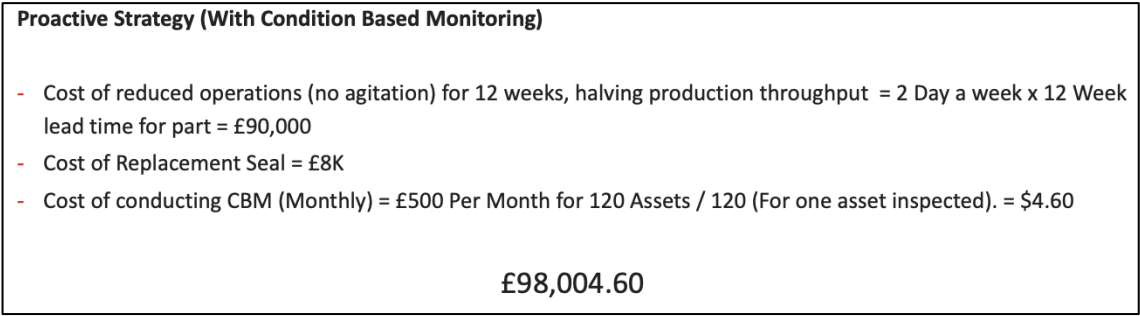


Figure 35 V302 : Cost of Proactive Strategy

Therefore, the total savings of utilising a PdM regime is £211,291 (\$266,227.16) - shown in equation -

$$£309,296 - £211,291.40 = £211,291.40$$

Equation 2 Cost of Functional Failure Vs Proactive Strategy

5.2.3 Case Study 3 : New Manufacturing Plant : Motion Amplification Analysis

5.2.3.1 Situation

ABC Manufacturing is currently expanding production. To enable this several contractors have been employed independently of each other to build a new production facility. The contractors of the Mechanical, Electrical and Plumbing (MEP) installation are adhering to British Standards for Commissioning and handover.

5.2.3.2 Problem

Current commissioning standards look at immediate causes for concern, not longer term problems such as failures caused by onset of vibration induced fatigue. This is a concern as the facility operates with AODDs which cause vibration.

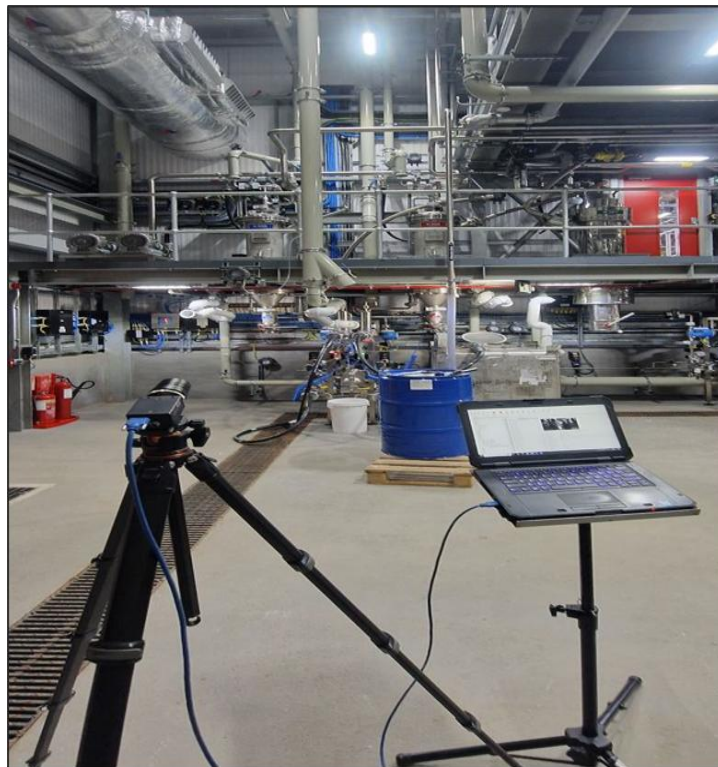


Figure 36 MA set up at ABC Chemical Manufacturing

5.2.3.3 Solution.

Conduct Motion Amplification (MA) study in line with API 571 and mitigate any identified failure modes using Energy Institutes Avoidance of Vibration Induced Fatigue Failure in Process Pipework, 2nd Ed, 2008.

5.2.3.4 Impact

MA enables the visualization of VA which is helpful to deduce where vibration is resonating from. This is something which VA can do but it takes longer to diagnose areas of concern due to not being able to visualize the issue.

ABC Manufactures contracted a 3rd party contractor to conduct MA study on the new plant. The contractor found several failings. Figure 39 contextualizes these failings.

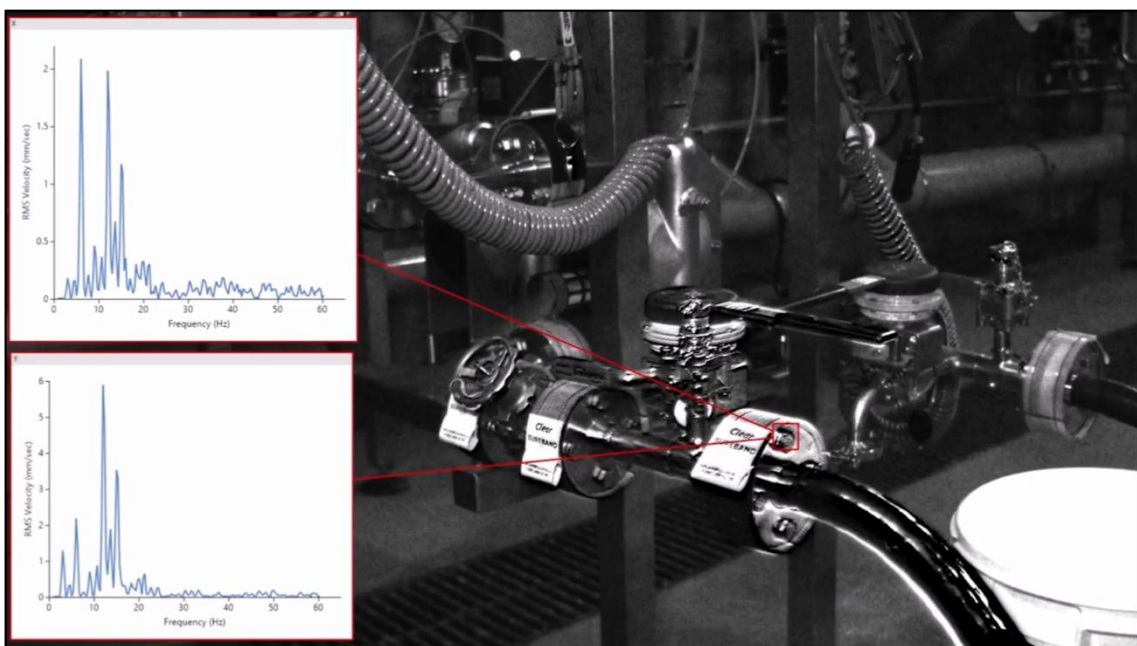


Figure 37 MA Results pre-remediation

Figure 39 shows that a section of pipework is vibrating at 6mm/sec, due to being not fully supported. Whilst it's unlikely to impact pipework integrity in the short term, over several years this could lead to a breach in primary containment. Noting this line carries solvent at 4ba the impact of failure could result in operator injury.

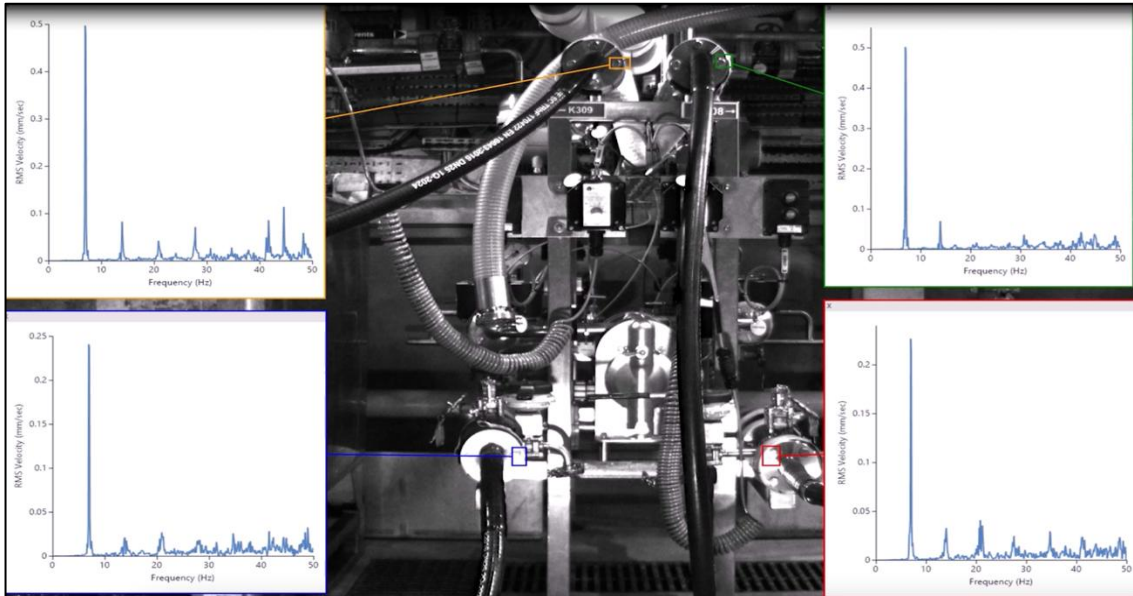


Figure 38 MA Results post remediation

The MEP company were tasked with reducing vibration along this section of pipework, after which time they braced the area of pipework which saw a reduction in vibration by 96% (figure 40).

The simplicity of bracing pipework has reduced the onset of early fatigue caused by vibration. This was achieved utilizing MA technology.

5.2.3.5 Cost and Impact.

The cost the MA survey cost £1200. With personal injury claims in the UK costing a total of £7.1 Billion and the average claim costing £21,500 (HSE(2023)). The total cost saved by conducting engineering diligence saved the company £19,800 (\$24,948) is fiscal costs and priceless amount in reputational damage should an employee or contractor have been injured.

5.2.4 Case Studies Summary

This section has reviewed three case studies showing safety risk mitigation and cost savings following the use of PdM. In total the collective cost saved, over 8 months of work, totals £281,853.06 (£281,854.32). This doesn't include the environmental impact in reduction of Co2 emissions and the irreplaceable company reputation should an injury occur.

6 Discussion

The purpose of this paper was to investigate the influence of Condition Based Maintenance on employee safety and site profitability relating to Safety Critical Sites. To investigate the state of the art a mix method approach was applied using an industrial questionnaire and a *real-world* case study from the authors workplace. This mix method sought out quantitative and qualitative information which will be discussed and critically analysed in this section.

6.1 Industrial Questionnaire

The industrial questionnaire which was published online (Survey Planet (2025)) saw seventy-one people answer 14 questions based around five themes: Safety, Cost, Maintenance Strategies, PdM tools, and Employee Stress.

6.1.1 Use of CBM and Respondents

The output of these questions shows initially that CBM is not just emergent technology but is actively being used in the work place with over half (58.6% - Table 1) reporting the use of a blended maintenance strategy across their assets. This was interesting given the geographical range of respondents which were from a total of 24 different countries; presenting a strong global representation in the use of CBM implementation.

This report however didn't look at the regional trends within the use of CBM. Out of the 71 respondents, the majority were from developed nations whilst some were from emerging CBM Markets. Out of the those who responded there is a need for further research to understand the perceived challenges in developed countries vs non developed due to higher technological advancements but similarly IT barriers to execution as shown in question 6.

Whilst the barriers to execution could develop into challenges, it was notable the perceived effectiveness of CBM with a combined 97.2% of respondents who believed CBM is effective. However this could be tainted by the respondents themselves, as notably they all clicked the link to answer the question sets. In

order to have answered there was already a sub-conscious interest in the impact that CBM has. This is the problem with non-incentivised questionnaires. There needs to be a base level of interest in order for the respondents to want to answer the question.

6.1.2 Impact to Safety

78.6% of the respondents believed that CBM could positively impact safety incidents on site. However, when asked what type of risks which could be mitigated only 85% responded. This could have been due to the types of risk in the question sets not being applicable to them. Conversely those that did response shown the biggest risks reduction was around structural integrity risks and flammable gas. Both of these could negatively impact a sites safety culture as seen in Buxton (Hobbs (2013) where a tank farm collapsed due to structural integrity checks not being carried out.

6.1.3 Impact to Cost and Challenges

Alongside the impact to cost there was a favourable ROI despite 70% of the respondents spending over £10,000 per annum on CBM. However, there is still a gap within the research due to the challenges to implementation; which were shown as a lack of overall understanding (39.4%), and training (29.4) both of which can be impacted through the spend. These challenges are perhaps the reasons why some engineering teams choose to conduct CBM through a third party as well as conducting some in house (50%).

This report however did not review the cost effectiveness of inhouse vs outsourced maintenance. This is an area for further research.

When reviewing the industrial questionnaire against the identified hypothesis, in Section 3 – Table 1, the data set shows favourable that to H₁ and H₂. however H₃ is difficult to ascertain due to stress being perception whilst there was a combined response of 92% stipulating that CBM does somewhat impact stress, this needs to be reviewed in line with the potential barriers to ensure an accurate representation of stress drives can be reviewed.

6.2 Case Study Summary

The three case studies from ABC chemical manufacturing provided substantial evidence towards the positive impact that CBM can have on COMAH sites, demonstrating that through mitigative data-driven decisions, potential latent risks can be addressed prior to functional failure occurring. This mirrors the information collected from the survey.

6.2.1 Case Study 1 - Compressed Air Leak Detection

The use of compressed air leak detection through the in house maintenance team saw a positive impact to safety through asphyxiation hazard caused by nitrogen leaks, alongside a positive impact to not just revenue but also sustainability through a reduction in electricity and in turn Co² emissions, saving >\$50,000 - showing a payback on the flir Si-2 in 4 months.

Whilst there was a potential asphyxiation hazard, the engineering team needs to ensure CBM doesn't become a substitute for process safety controls and that site follows the Institute of Chemical Engineering (IChemE) hierarchy of process controls (IChemE) 2025) which sees engineering controls in place to enable a sufficient Safe Systems of Work to be in place. For nitrogen the use of a personal gas monitor should be the first point of call. Not Bi-monthly CBM checks.

This tool should continue to be used not just to ensure site safety and costs are stabilised, but also as a tool to ensure quality maintenance is being carried out.

6.2.2 Case Study 2 - Vibration Analysis and Ultrasound

Case Study 2 showed that using Vibration and Ultrasonic detection to mitigate functional failures from occurring stopped significant downtime to the business, through averting a potential primary containment breach.

This example was ultimately driven through the operator's knowledge of plant and human element that something wasn't right. This shows that operators are an essential part of asset reliability, and that the driver to replace wasn't solely down to the use of CBM.

6.2.3 Case Study 3 - Motion Amplification

The use of MA to validate 3rd party commissioning proved to be useful by identifying resonance issues within chemical pipework. This resonance had the capacity to induce vibration fatigue. The cost of the MA (£1200) vs potential personal injury claim (£21,500) shows the additional work was of benefit not just from a fiscal benefit but also due to the potential reputational damage should an incident occur.

Whilst MA is a useful tool there are little KPIs to validate the “go/no go” criteria for fault rectification.

There is a single standard from the energy institute, for avoidance of vibration induced fatigue in process pipework (Energy Institute (2008)). This is complemented through British Standards acceptability of flaws in metallic structure guidelines (British Standards (2013)).

However both documents note the dependability of failure to be down to usage and the environment. Therefore, the guidelines should be used as guides only and not black and white usable information.

6.2.4 Case Study Impact to Cost and Challenges

Whilst the case study showed significant cost savings of >£282,00 (>\$355,320) there is a notable difference in the type of savings.

Most Manufacturing sites operate a yearly planned Cost and OCOGs model.

The purpose of this is to accurately predict the impact to sites revenue and where necessary increase or decrease site production demands to meet costs (if demand allows).

To save against the cost in the OCOGs model, the cost needs to be against planned spend. ABC Chemical manufacturing aligns some spend to productional losses caused by lack of asset availability. But it is not possible to guess planned downtime.

This is a challenge as if OCOGS did predict downtime on a yearly basis the cost of goods sold would increase which could impact consumer pricing.

This challenge could be frustrating to engineering teams, as they aren't seeing the real-world cost savings. But their work is having a real world impact.

However, an area for teams to review would be increasing the asset depreciation life caused by extending the life of asset through the use of CBM. This would need to be done on a case-by-case basis through multiple stakeholder management (operations/finance and engineering).

6.2.5 Summary of Case Study and Industrial Survey

When reviewing the case study and industrial survey; there is a synergy between the two and the literature review.

Academically technical CBM challenges are well document through white papers, utilising known CBM techniques. The industrial survey and case study cement this knowledge further proving there are benefits to be had through utilising CBM on COMAH sites.

However, there are clear gaps in training and understanding.

Outside the engineering department, there is little training for the general manufacturing population to be made aware of the use of CBM, its practicalities, and its effectiveness on impacting a business's safety culture and profitability.

Similarly, engineering apprentices are not taught at a grass roots level what CBM is. They are trained on how things fail, and how to repair asset, with no focus in the current apprentice syllabus on PdM techniques.

Similarly at a Graduate level: Graduates base line of education doesn't include a module on CBM. This is reflected in the gap and lack of understanding shown through the case study.

It is therefore the engineers' and engineering teams' ethical and professional responsibility to be the stewards of PdM. To articulate and educate its use and benefits.

Through understanding the known unknowns, it is possible to reduce and mitigate risk.

The articulation of CBM within the case study makes it palatable for those not educated within an engineering setting through clear figures, showing cost depreciation. This creates a mutual understanding of the benefits of PdM but not necessary how it should be implemented.

6.2.6 Analysis of Hypothesis

Table 4 shows an evaluation of the initial Hypothesis, providing reasoning behind the acceptance criteria.

Summary of Hypothesis		
Hypothesis	Accept/Reject	Reasoning
H ₁ : Conducting CBM on Critical Assest positively impacts downtime and sites profit and loss.	Accept	From the industrial questionnaire over 79% of respondants confirmed that CBM has had a positive impact on Safety and downtime. In turn impacting P&L. This is supported in the case study which provided "real world evidence" that CBM mitigates safety incidents and downtime.
H ₂ : Conducting CBM on Critical Assets directly impacts Lost Time Injuries and Site Safety	Partially Accept	The information gained from the industrial questionnaire showed that 93% of respondants noted a positive ROI, and the case study a mixture of £282,000 in savings. However these savings cannot be benefited and claimed. Whilst the case study and industry questionnaire showed favourable to safety incidents, this research did not review Lost Time Injuries specifically.
H ₃ : Conducting CBM reduced stress and in turn workload on Engineering Teams	Accept	The industrial questionnaire showed that 92.9% respondants believed that CBM had <i>some effect</i> on stress and in turn work load. However organisations need to be mindful of the challenges of implementing CBM as this in itself could become stressful.

Table 4 Table to show summary of hypothesis

H₁ and H₃ have been accepted based upon the conclusive evidence collected from both the industrial questionnaire and the multiple case studies. H₂ has been partially accepted due to the positive response. However, whilst it is assumed there was little evidence from research to stipulate it directly impacted LTOIs.

6.2.7 Limitations of findings

Whilst the case study and paper have provided a positive output, its use is limited due to the validation of the case study, which focused on a single site. Whilst there were benefits to be found through the implementation.

To generalise this, without acknowledgement would be naive.

Some sites may have less impact utilising CBM, due to either cost constraints, run to failure business model or through having sufficient maintenance practices already in place.

Similarly, a different site could be much worse than the case study.

On reflection this paper showed multiple case studies in a single site. This could have been better described if used multiple sites were chosen.

6.3 Recommended Framework through implementing CBM and the Future

6.3.1 Recommended Process Flow and Framework

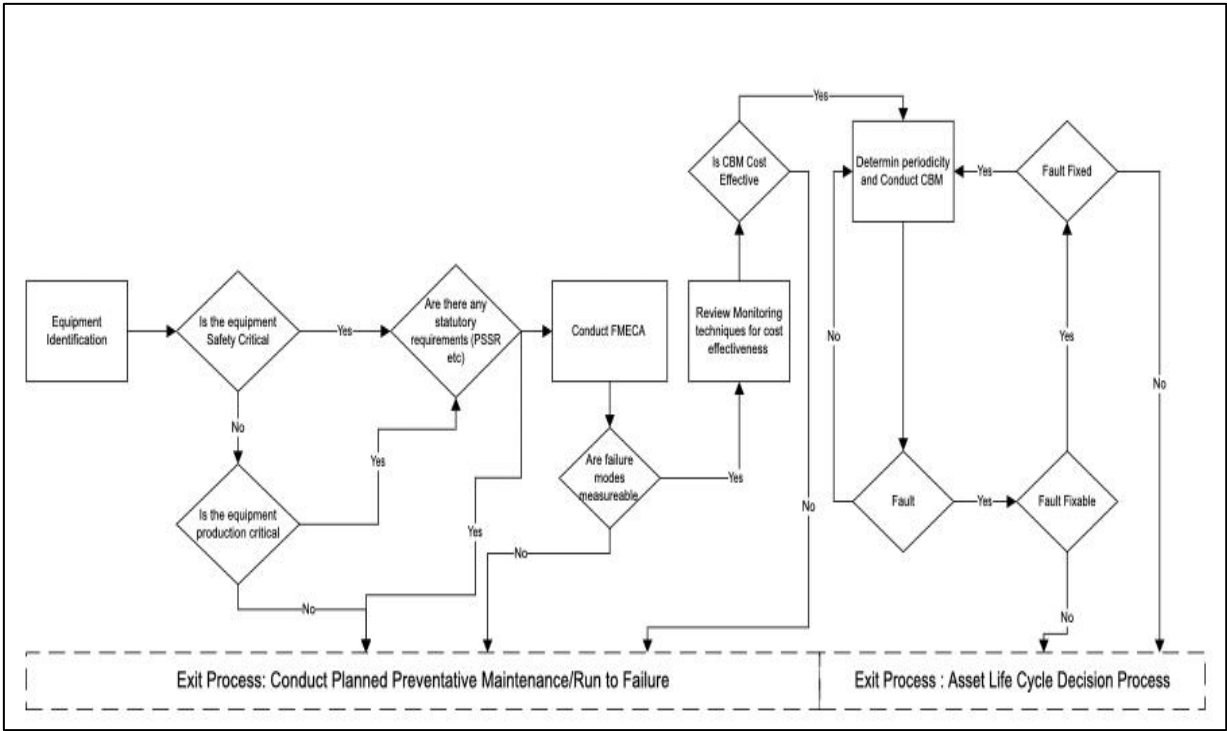


Figure 39 Authors recommendation of CBM Framework for COMAH Sites

Figure 41 shows the recommended framework for COMAH sites, this process identifies the need through an equipment identification process. Going on to select the equipment based on Safety criticality and production critical thereafter.

Conscious of the perception that CBM can somehow override the legal statutory requirements such as PSSR/LOLER/LEV the framework points the user to ensure these are sufficiently planned via scheduled planned maintenance.

Thereafter the identification of failure modes through a Failure Modes Critical Effects analysis. The purpose of this is to identify whether the failure modes are even measurable. If measurable; CBM takes place on a Plan Do Check Acts Cycle.

However, this process flow needs to be underpinned by a high-level framework. Figure 42 showing the principles of CBM implementation on a COMAH site. Noting that at the base of the pyramid is the sites culture followed by the investment in people. Doing this before purchasing the tool will save money. Through investing in people using a competency-based frameworks this will ensure a base level of competence.

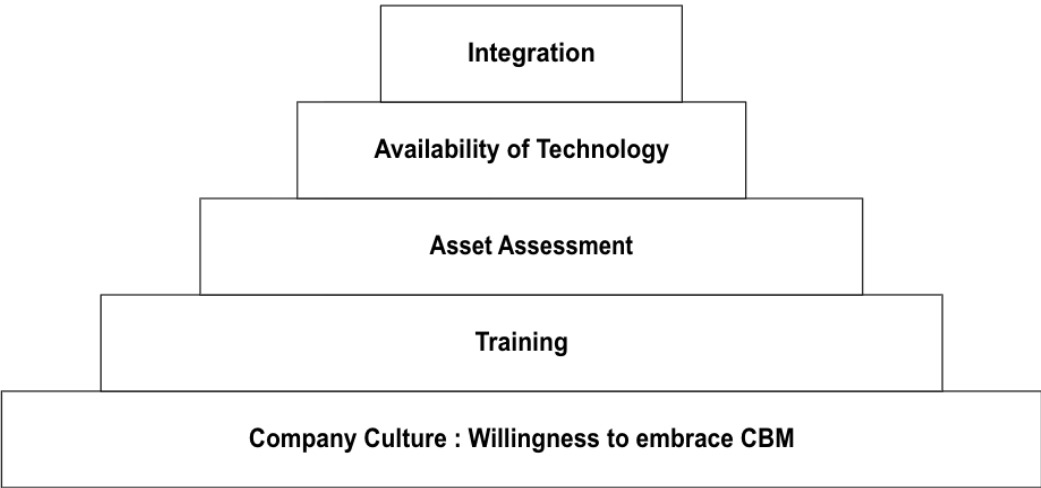


Figure 40 Authors recommendation for principles of CBM Implementation on a COMAH Site

6.3.2 The Future

Future research should include multi-site research and the use of synchronised metrics to enable cross learning to take place.

Using this information to create an AI digital twin which could enable prescribe predetermined maintenance regimes to mitigate failure mode. At an industrial scale.

Whilst concurrently using base line industrial data sets to train engineers at a grass route level on what CBM is will fill the competence-based gap.

Similarly, a study in its self could be done on LTOIs and non-LTOIs reviewing the ratio and to metricise whether or not CBM could have mitigated the incidents.

6.3.3 Discussion Summary

This section has discussed the mixed methods approach to this paper demonstrating that CBM when implemented effectively at a single site level can have a positive impact to both site Safety and Profitability.

It has provided a framework for future site Engineering teams to implement similar CBM Campaigns. Whilst also suggesting where future research could positively impact wider industry.

7 Conclusion

Following extensive research; this paper is an academic first, investigating the influence that CBM can have on site safety and profitability. It has bridged that gap between industry perception and academic papers through quantifying costs and risk reduction rather than using perception.

It has achieved the aim of this paper through investigating both from a qualitative and quantitate data. Where findings showed through a monetised case study that when CBM is utilised by competence engineering teams it can impact Safety and Cost.

However, the success of CBM is reliant on the conditions that it is set in, in an environment where successful maintenance practices are not already in place. If engineering maturity is already in place through a successful planned maintenance regime and commercially this model works. It is suggested not to impact a successful model.

Although CBM is likely to be the future and will be integrated into modern technologies it is recommended that employees are trained on the use and benefits.

This paper has shown that CBM is not a “plug and play” solution and the acceptance criteria for which assets CBM should be applied to is critical.

When aligned to safety and costs, it has showed that the two pillars are not mutually exclusive of each other. Instead, both areas converge to mutually reinforce asset risk mitigation, showing how the importance in sufficient risk mitigation for safety critical assets.

Academic papers throughout the literature review provided excellent examples of where data driven decisions can be utilised to improve asset performance, through the use of algorithms to drive asset performance. Where academia is lacking is the human element that is needed through the selection process and the on the ground employee knowledge.

An employee knowing something isn't right is the base level of asset performance. This is a culture that can be trained, but asset husbandry in some sites can take years to adopt.

The framework and process flow can be used as guidelines to help the journey with initial challenges around cost to implement being impacted through easy wins such as leak detection. Directly impacting a sites fiscal performance, enabling that money to be then invested into CBM to drive the longevity of assets.

To summarise, the use of CBM on COMAH sites is proven to have a positive impact. The knowledge to drive the change can be taught, however the desire to drive change needs to be driven from a point of passion to enable successful implementation.

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Appendix A Ethical approval letter



5 March 2025

Dear Mr Watkinson ,

Reference: CURES/24486/2025

Project ID: 27898

Title: "Investigation into the influence of Condition Based Maintenance on employee safety and site profitability relating to Safety Critical Sites".

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/24486/2025 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team