

EVALUATING THE EFFECTIVENESS OF CHOSEN MAINTENANCE STRATEGIES FOR CANNING CO2 BUBBLE BREAKERS



BEng Mechanical and Manufacturing Engineering

Plant and Asset Engineering (ACMA6007)



Report Submitted by **Benjamin James**



University of Wales
Trinity Saint David

1) Table of Contents

1)TITLE PAGE	1
2)TABLE OF CONTENTS	2
3)LIST OF ILLUSTRATIONS/TABLES	3
4)INTRODUCTION	4
5)CRITICAL REVIEW OF CURRENT MAINTENANCE PRACTICES	5
5.1)UNDERSTANDING AND INTERACTION WITH THE BUBBLE BREAKER:	5
5.2)IDENTIFIED GAPS AND THEIR IMPLICATIONS:	5
5.3)RECOMMENDATIONS FOR IMMEDIATE ACTION:	6
6)EVALUATING AND ENHANCING MAINTENANCE PRACTICES	7
6.1)EVALUATION OF CURRENT MAINTENANCE PRACTICES	7
6.2)UNDERSTANDING AND INTERACTION WITH THE BUBBLE BREAKER	7
<i>i)Advanced Training and Educational Initiatives:</i>	7
<i>ii)Operational Technology Integration:</i>	7
6.3)EQUIPMENT HANDLING STANDARDIZATION	7
<i>i)SOPs and Procedural Clarity:</i>	7
6.4)PROACTIVE MAINTENANCE STRATEGY	8
<i>i)Data-Driven Scheduling and RCM Principles:</i>	8
<i>ii)Condition Monitoring Tools:</i>	8
6.5)CONTINUOUS IMPROVEMENT AND ENGAGEMENT	8
<i>i)Feedback Loop and Performance Monitoring:</i>	8
6.6)APPLICATION OF ANALYTICAL TOOLS	8
<i>i)P-F Curve and FMECA Integration:</i>	8
6.7)KEY COMPONENTS OF FMECA:	9
6.8)PURPOSE AND BENEFITS OF FMECA:	10
6.9)APPLICATION OF FMECA:	10
6.10)CONCLUSIVE EVALUATION	10
7)COSTS & RESOURCES: IMPLEMENTING CHANGES	11
7.1)FINANCIAL IMPLICATIONS AND ROI	11
<i>i)Initial Investment</i>	11
<i>ii)Potential Savings</i>	11
<i>iii)Return on Investment (ROI)</i>	11
7.2)RESOURCE REQUIREMENTS	11
<i>i)Additional Personnel</i>	11
<i>ii)Training Needs</i>	11
<i>iii)New Technology Acquisitions</i>	11
7.3)CHANGE MANAGEMENT IMPLICATIONS: A DISCUSSION	12
<i>i)Stakeholder Engagement: The Foundation of Transformation</i>	12
<i>ii)Process Reconfiguration: More Than Just Adjustments</i>	12
<i>iii)Navigating Transition Challenges: A Collaborative Approach</i>	12
7.4)LINKING DISCUSSION TO ACTION	12
<i>i)Immediate Actions for Bridging Knowledge Gaps</i>	12
7.5)CONCLUSION: A UNIFIED VISION FOR CHANGE	12
8)CONCLUSIONS/RECOMMENDATIONS	13
8.1)KEY FINDINGS:	13
8.2)RECOMMENDATIONS:	13
<i>i)Short-term (0-6 months):</i>	13
<i>ii)Medium-term (6-12 months):</i>	13
<i>iii)Long-term (1-3 years):</i>	13
8.3)STRATEGIC VALUE OF CONTINUOUS IMPROVEMENT:	13
9)REFERENCING	14

2) List of Illustrations/Tables

INTRODUCTION – PAGE 4

Figure 1 – The Magor Brewery in South Wales

INTRODUCTION – PAGE 4

Figure 2 – Setting Bubble Breaker Block Height with Stainless Steel Rule

Figure 3 – Adjusting Bubble Breaker Regulation of CO2 Pressure

INTRODUCTION – PAGE 4

Figure 4 – Design-Failure-Potential Failure-Failure Curve

3) Introduction

Budweiser Brewing Group UK&I, part of the global AB InBev family, operates one of its key facilities at the Magor Brewery in South Wales. As a leader in the brewing industry, the Group is committed to maintaining the highest standards of product quality and efficiency across its operations. Within the Magor Brewery, the canning department plays a critical role in this mission, especially in ensuring the longevity and taste of the beer through advanced packaging technologies. One such technology, pivotal to maintaining these standards, is the bubble breaker—a device designed to minimize the Total Packaged Oxygen (TPO) in canned beer.



Figure 1 – The Magor Brewery in South Wales

TPO is a crucial quality control parameter in the brewing industry, influencing the beer's shelf life and flavour stability. The presence of oxygen within packaged beer can lead to oxidation, which deteriorates the quality of the beer over time. The bubble breaker addresses this challenge by blowing CO₂ over open beer cans to eliminate oxygen bubbles before sealing. This process significantly reduces TPO levels, thereby enhancing the beer's shelf life and ensuring the consistency of its flavour profile.

The purpose of this assignment is to undertake a comprehensive evaluation of the maintenance strategies employed for the bubble breaker at the Magor Brewery. This involves a critical review of the current maintenance practices, an assessment of their effectiveness, and the exploration of potential improvements to enhance the device's performance and reliability. The evaluation will also consider the costs and resources required to implement these improvements, aiming to provide actionable recommendations that align with the brewery's goals of product quality and operational excellence.

By focusing on the bubble breaker, this report seeks to contribute to the broader objectives of Budweiser Brewing Group UK&I, emphasizing the importance of maintenance excellence in sustaining high-quality brewing processes. Through a structured approach that includes literature review, analysis of current practices, and strategic recommendations, this evaluation aims to offer insights into optimizing maintenance practices for critical brewing equipment, thereby supporting the Group's commitment to excellence and innovation in beer production.

4) Critical Review of Current Maintenance Practices

4.1) Understanding and Interaction with the Bubble Breaker:

The bubble breaker's role as a key component in reducing Total Packaged Oxygen (TPO) and preserving beer quality is not fully understood by the operational staff at Budweiser Brewing Group's Magor Brewery. It has become evident that there is a significant gap in knowledge regarding the function and proper operation of the bubble breaker among operators. This lack of understanding extends to essential operational adjustments that can impact the effectiveness of the TPO reduction process, such as the adjustment of the bubble breaker's height and the regulation of CO2 pressure.



Figure 2 – Setting Bubble Breaker Block Height with Stainless Steel Rule



Figure 3 – Adjusting Bubble Breaker Regulation of CO2 Pressure

While some operators occasionally adjust the CO2 pressure to modulate the amount of CO2 dispensed, this practice is not uniformly applied, and the rationale behind such adjustments seems to be based on individual discretion rather than a structured approach or understanding of the equipment's optimal operation. Furthermore, the adjustment of the bubble breaker's height, a critical parameter for ensuring efficient CO2 blanket formation over the beer cans, is largely neglected. This oversight can lead to suboptimal oxygen displacement, affecting the quality of the product.

4.2) Identified Gaps and Their Implications:

The main issues identified from the current state of practice around the bubble breaker include:

- **Limited Operational Knowledge:** Operators' lack of comprehensive understanding about how the bubble breaker works—or its importance in the production process—highlights a critical gap in training and knowledge management within the brewery. This gap jeopardizes the quality of the final product and the efficiency of the production line.
- **Inconsistent Equipment Handling:** The absence of standardized procedures for adjusting the bubble breaker's settings (both height and CO2 pressure) indicates a piecemeal approach to equipment management. This

inconsistency can lead to variability in the beer's exposure to CO₂, directly impacting the effectiveness of TPO reduction.

- **Lack of Proactive Maintenance and SOPs:** The earlier noted absence of formal maintenance practices is compounded by the operators' limited engagement with the equipment's functional adjustments. The lack of SOPs not only affects the bubble breaker's maintenance but also its day-to-day operation, leading to inefficiencies and potential quality control issues.

4.3) Recommendations for Immediate Action:

Given these observations, several immediate actions are recommended to address the knowledge and operational gaps surrounding the bubble breaker:

1. **Development and Implementation of SOPs:** Create comprehensive Standard Operating Procedures that cover both maintenance and operational adjustments of the bubble breaker. SOPs should include guidelines on the optimal height and CO₂ pressure settings, informed by the equipment's design specifications and best practices for TPO reduction.
2. **Operator Training Program:** Initiate a targeted training program for operators, focusing on the importance of TPO reduction, the role of the bubble breaker in this process, and the practical skills needed to adjust and maintain the equipment properly. This program should aim to build a solid understanding of the equipment's operation and its impact on product quality.
3. **Regular Knowledge Refreshment Sessions:** To combat knowledge attrition and ensure the continuous competency of the workforce, implement regular refresher courses that keep staff updated on operational best practices and any new developments related to the equipment or the production process.
4. **Monitoring and Feedback Mechanism:** Establish a monitoring system to track the performance of the bubble breaker and the consistency of its operation across different shifts. This system should be coupled with a feedback mechanism that allows operators to report issues or suggest improvements, fostering a culture of continuous improvement and engagement.

Addressing these gaps through structured training, standardized procedures, and active monitoring will significantly enhance the bubble breaker's maintenance and operation. This strategic approach will not only improve the equipment's reliability and efficiency but also reinforce the brewery's commitment to maintaining the highest quality standards in its products.

5) Evaluating and Enhancing Maintenance Practices

5.1) Evaluation of Current Maintenance Practices

Upon meticulous examination of the existing maintenance protocol for the bubble breaker at Budweiser Brewing Group's Magor Brewery, it becomes apparent that the practices in place are insufficiently equipped to tackle the challenges presented by modern production demands. The identified gaps in operational knowledge, inconsistent equipment handling, and a lack of proactive maintenance strategies underscore the urgent need for a more sophisticated and integrated approach. Addressing these shortcomings through the development and implementation of comprehensive training, the adoption of advanced technologies for condition monitoring, data-driven maintenance scheduling, and the establishment of robust feedback mechanisms is essential. This integrated strategy aims to significantly advance the brewery's maintenance operations, enhancing the reliability, efficiency, and product quality of the bubble breaker. By consolidating these enhancements into a cohesive plan, the brewery can ensure that it not only addresses the critical gaps identified in the current maintenance strategy but also sets a foundation for sustained operational excellence (**Kumar & Saini, 2023; Ozbiltekin-Pala et al., 2022; Pansare et al., 2022**).

5.2) Understanding and Interaction with the Bubble Breaker

i) Advanced Training and Educational Initiatives:

- Develop an interactive, in-depth training program focused on the bubble breaker's operational principles, emphasizing its crucial role in reducing Total Packaged Oxygen (TPO) and ensuring beer quality.
- Organize workshops with the equipment's manufacturers to deepen technical knowledge and practical skills in bubble breaker operation and maintenance.
- Utilize augmented reality (AR) technology for hands-on simulation experiences, enabling operators to visualize the bubble breaker's impact on the production process and understand the criticality of precise adjustments (**Bryan, 2006; Sisson, 2019**).

ii) Operational Technology Integration:

- Equip the bubble breaker with IoT sensors to monitor performance parameters continuously. Use this data to facilitate immediate adjustments and pre-emptive maintenance actions.
- Implement a centralized control dashboard that provides real-time feedback on the bubble breaker's operational settings, enhancing decision-making and precision (**Shehadeh et al., 2016; Muazu & Tasmin, 2019**).

5.3) Equipment Handling Standardization

i) SOPs and Procedural Clarity:

- Create detailed Standard Operating Procedures (SOPs) for the bubble breaker, covering both routine maintenance and operational adjustments, such as optimal height and CO2 pressure settings (**Pinto Junior & Mendes, 2017**).
- Conduct practical workshops to ensure familiarity with these SOPs, emphasizing their importance in maintaining consistent product quality.

5.4) Proactive Maintenance Strategy

i) Data-Driven Scheduling and RCM Principles:

- Integrate machine learning algorithms with the brewery's data management systems to analyse historical performance data, enabling a shift from calendar-based to condition-based maintenance scheduling.
- Conduct a Reliability-Centred Maintenance (RCM) analysis to prioritize maintenance tasks based on the bubble breaker's specific needs, focusing on critical components and their potential failure modes through a detailed Failure Mode Effects Analysis (FMEA) (**Leelasarada et al., 2017; Elnaga & Imran, 2013**).

ii) Condition Monitoring Tools:

- Deploy a suite of condition monitoring tools, including vibration sensors, thermal cameras, and ultrasonic detectors, tailored to the bubble breaker's operational requirements. This will enable real-time monitoring and early detection of potential issues (Pellissier, 2009).

5.5) Continuous Improvement and Engagement

i) Feedback Loop and Performance Monitoring:

- Launch a digital platform for real-time reporting of operational issues and suggestions for improvement, accessible via mobile devices to encourage active participation from operators.
- Implement a regular review cycle to evaluate feedback, discuss performance metrics, and identify continuous improvement initiatives. Celebrate achievements to motivate staff engagement (Found et al., 2018).

5.6) Application of Analytical Tools

i) P-F Curve and FMECA Integration:

- Apply the P-F Curve analysis to identify early warning signs of wear or failure, enabling timely maintenance interventions before operational impact (Zhang & Chu, 2010).

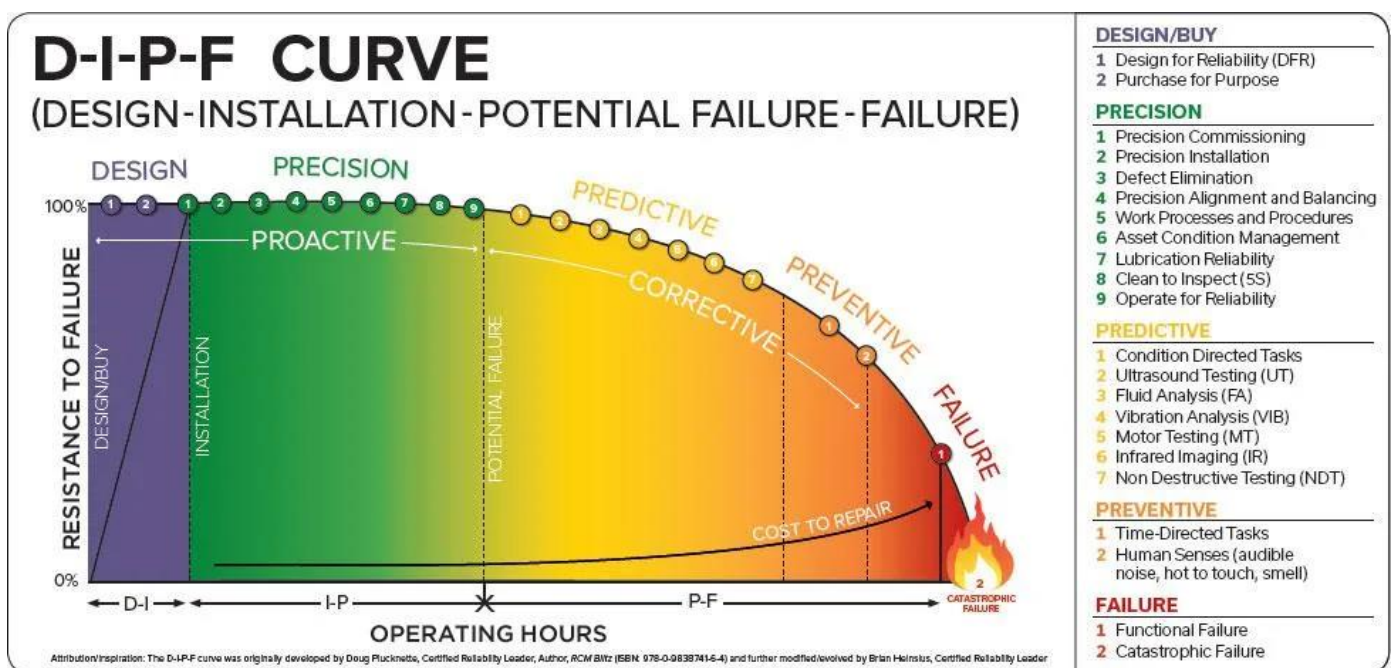


Figure 4 – Design-Failure-Potential Failure-Failure Curve

The D-I-P-F curve, commonly known as the P-F curve in maintenance and reliability engineering, is a conceptual graph that illustrates the stages of failure in a piece of equipment or component over time. It helps in understanding how a failure develops and provides insights into detecting and addressing potential failures before they occur. The curve is divided into four key segments: D (Design), I (Installation), P (Potential Failure), and F (Functional Failure). Here's a breakdown of each segment (Mobley, 2002):

1. **D - Design:** This initial point or phase represents the condition of the equipment immediately after its design and manufacture, presumed to be at its peak performance and reliability. The equipment is expected to operate as intended without any degradation or loss of function.
2. **I - Installation:** This phase represents the equipment's condition after installation and during its operation. Even with the best design and manufacturing processes, the performance of equipment can be significantly influenced by how well it is installed, commissioned, and integrated into the operational environment. Improper installation can lead to premature wear or failure.
3. **P - Potential Failure:** This is a critical point on the curve where a potential failure can be detected but has not yet resulted in a complete loss of function. It is the stage where condition monitoring and predictive

maintenance techniques are most valuable. Identifying signs of potential failure (such as abnormal vibrations, unusual noises, or increased heat) allows for intervention before the equipment fails. The interval between P and F is known as the P-F interval, offering a window of opportunity for corrective action to prevent or mitigate the impact of the failure.

4. **F - Functional Failure:** This stage occurs when the equipment no longer performs its intended function or has degraded to a point where it is considered failed. The goal of maintenance strategies, particularly predictive maintenance, is to identify and rectify issues before reaching this point.

The D-I-P-F curve underscores the importance of regular monitoring and maintenance to detect early signs of deterioration. By acting within the P-F interval, maintenance teams can plan and execute maintenance activities more effectively, reducing unplanned downtime and extending the lifespan of the equipment. This approach contrasts with reactive maintenance, which only addresses failures after they have occurred, often resulting in higher costs and longer downtime.

- Conduct a comprehensive FMECA to assess the potential failure modes of the bubble breaker and their impact on operations, prioritizing maintenance tasks based on criticality and likelihood (**Sherwin, 2000**).

Failure Modes, Effects, and Criticality Analysis (FMECA) is an extension of Failure Modes and Effects Analysis (FMEA), a systematic method used to identify and evaluate the potential failure modes of a product or process, understand the causes and effects of these failures, and prioritize the actions needed to mitigate or eliminate the risk of these failures. FMECA adds an additional layer of analysis by assessing the criticality of each failure mode, allowing organizations to focus their efforts on the most significant issues that could impact system performance, safety, reliability, and regulatory compliance (**Stamatis, 2003**).

5.7) Key Components of FMECA:

1. **Failure Modes:** The ways in which a process, design, product, or system can fail. Failures are classified according to their impact on the operation or functionality.
2. **Effects Analysis:** The process of identifying the consequences of each failure mode on the system, product, or process. This includes considering the impact on the end-user, the environment, and compliance with regulations.
3. **Causes of Failure:** Identifying the root causes that could lead to each failure mode. This might include material defects, design flaws, human error, or environmental conditions.
4. **Criticality Analysis:** An assessment of the severity and likelihood of each failure mode, which helps in prioritizing the failure modes that need immediate attention or mitigation. Criticality is typically evaluated based on the impact on safety, system performance, and regulatory compliance, among other factors.
5. **Risk Priority Number (RPN):** A numerical value that ranks the risk of each failure mode by considering its severity, occurrence (likelihood), and detectability. This helps in prioritizing which failure modes to address first.

5.8) Purpose and Benefits of FMECA:

- **Risk Management:** Helps identify and prioritize the risks associated with failure modes, focusing resources on mitigating the most critical issues.
- **Improves Reliability and Safety:** By addressing the most critical failures, FMECA contributes to the overall reliability and safety of a system, product, or process.
- **Supports Decision Making:** Provides a structured framework for decision-makers to identify, prioritize, and implement corrective actions.
- **Cost Reduction:** Prevents costly downtime and repairs by proactively identifying and mitigating potential failures.
- **Regulatory Compliance:** Assists in meeting safety and reliability standards set by regulatory bodies.

5.9) Application of FMECA:

FMECA is widely used in various industries, including aerospace, automotive, manufacturing, and healthcare, to ensure products and processes are as fail-safe as possible. It is particularly valuable in complex systems where failures could have catastrophic consequences. By systematically analysing potential failures and their impacts, organizations can develop more reliable, safe, and efficient products and processes (**Bowles & Peláez, 1995**).

5.10) Conclusive Evaluation

Adopting this holistic strategy for enhancing the maintenance practices of the bubble breaker at Budweiser Brewing Group's Magor Brewery represents a significant step towards not only addressing the immediate challenges identified in the current maintenance regime but also setting a robust foundation for sustained operational excellence and product quality. By integrating advanced training programs, leveraging cutting-edge condition monitoring technologies, implementing data-driven maintenance scheduling, and fostering a culture of continuous improvement through structured feedback mechanisms, the brewery is poised to achieve a remarkable transformation in the maintenance and operation of its critical equipment.

This comprehensive approach ensures that the bubble breaker operates at peak efficiency, directly contributing to the brewery's core mission of producing beer of the highest quality by minimizing Total Packaged Oxygen (TPO) levels, which is crucial for maintaining the beer's flavour stability and shelf life (**Bamforth, 2008; Hough et al., 1982**). The emphasis on education and hands-on experience will bridge the existing knowledge gaps among operators, empowering them with a deep understanding of their role in the production process and the impact of their actions on product integrity. The adoption of condition-based maintenance scheduling, underpinned by the principles of Reliability-Centred Maintenance (RCM) and informed by predictive analytics, marks a transition from reactive to proactive maintenance strategies, optimizing resource allocation and minimizing unplanned downtime (**Moubray, 1997**).

Moreover, the establishment of a feedback loop and the integration of analytical tools such as the P-F Curve and FMECA into the maintenance strategy underscore the brewery's commitment to leveraging data for informed decision-making and prioritizing maintenance activities based on their potential impact on operations (**Mobley, 2002**). This not only enhances the reliability and performance of the bubble breaker but also aligns maintenance efforts with the brewery's broader operational goals and sustainability initiatives.

In conclusion, the strategic enhancements proposed for the bubble breaker's maintenance practices embody a forward-thinking approach that transcends traditional maintenance methodologies. By fostering a culture of innovation, continuous learning, and operational excellence, Budweiser Brewing Group's Magor Brewery is setting a new standard for maintenance practices within the industry. This initiative not only underscores the brewery's dedication to product quality and operational efficiency but also demonstrates a commitment to its workforce's development and well-being, paving the way for a future where the brewery continues to thrive in an ever-evolving market landscape.

6) Costs & Resources: Implementing Changes

6.1) Financial Implications and ROI

i) Initial Investment

The **initial investment** includes costs associated with acquiring new condition monitoring technologies, such as IoT sensors and AR for training, as well as the development and implementation of a comprehensive training program. This also covers investments in software for data-driven maintenance scheduling and the integration of feedback mechanisms. The financial outlay will vary based on the scale of implementation and the specific technologies adopted but can be expected to run into several hundreds of thousands of pounds, considering both hardware, software, and personnel training aspects (**Parida & Chattopadhyay, 2007**).

ii) Potential Savings

Potential savings come from reduced downtime, lower maintenance costs, improved efficiency, and extended equipment lifespan, and a notable decrease in consumer complaints. Implementing condition-based maintenance can reduce maintenance costs by 20-25%, while predictive maintenance strategies can further enhance savings by reducing unplanned downtimes by up to 50% (**Swanson, 2001**). Additionally, the reduction in TPO levels can improve product quality, potentially increasing market share and revenue. Significantly, the reduction in consumer complaints not only enhances brand reputation but also leads to savings in customer service and warranty claims, further contributing to the overall financial benefits of the proposed changes.

iii) Return on Investment (ROI)

ROI is calculated by comparing the net savings (total savings minus initial investment) to the initial investment, over a certain period, typically 3-5 years for industrial investments. Given the expected savings, the ROI for the proposed improvements could be significant, with break-even points potentially within the first two to three years post-implementation, depending on the specific costs and savings realized (**Tsang, 2002**).

6.2) Resource Requirements

i) Additional Personnel

Implementing the proposed changes may require hiring additional maintenance staff or reallocating existing employees to specialized roles. This includes technicians skilled in IoT technologies and data analysis, as well as training coordinators for ongoing educational programs.

ii) Training Needs

A substantial part of the resource allocation will go towards **developing and delivering training programs**. This involves not only the creation of materials and resources for AR-based and hands-on training but also potentially hiring external experts or consultants to facilitate workshops and sessions.

iii) New Technology Acquisitions

Acquisition of new technologies encompasses IoT sensors, AR equipment for training, software for data analytics and maintenance scheduling, and possibly new tools or devices for improved condition monitoring and diagnostics.

6.3) Change Management Implications: A Discussion

i) Stakeholder Engagement: The Foundation of Transformation

Engaging stakeholders effectively is paramount. In the context of Budweiser Brewing Group's Magor Brewery, where the operation of the bubble breaker and its significance in reducing Total Packaged Oxygen (TPO) levels is not fully appreciated, engaging every level of the organization becomes a critical first step. This engagement isn't just about informing but also about creating a dialogue. Regular updates and forums for feedback become platforms for sharing insights into how the bubble breaker's optimization directly impacts beer quality, addressing the gap in understanding its operational principles. Such discussions can catalyse a shift in perception, making the stakeholder see the value in the proposed changes, beyond the mere operational adjustments, towards enhancing the product's integrity.

ii) Process Reconfiguration: More Than Just Adjustments

The necessity for process reconfiguration transcends the mere introduction of new technologies or practices; it's about rethinking how we interact with our tools and equipment. Given the inconsistent handling and adjustment of the bubble breaker's settings, reconfiguring processes must involve a holistic understanding of the equipment's role in quality control. This discussion involves not just the technical teams but also the operators, encouraging a shared responsibility in maintaining optimal TPO levels. By mapping out current processes and identifying integration points for new technologies and SOPs, we foster an environment where operational adjustments are not based on individual discretion but on a collective understanding of best practices.

iii) Navigating Transition Challenges: A Collaborative Approach

The transition to enhanced maintenance practices is fraught with potential resistance, not least because of the identified gaps in knowledge and the inconsistent application of adjustments to the bubble breaker. Addressing these challenges requires a strategy that's inclusive, one that recognizes the complexity of integrating new technologies while respecting the learning curve involved. Phased rollouts and pilot testing offer a path to gradually introduce changes, allowing for real-time feedback and adjustment. This approach not only mitigates resistance but also builds competency and confidence among the staff, ensuring that the transition is as much about learning and adaptation as it is about enhancement and efficiency.

6.4) Linking Discussion to Action

i) Immediate Actions for Bridging Knowledge Gaps

The critical review highlighted immediate actions necessary to bridge the knowledge and operational gaps. These actions, including the development of SOPs and targeted operator training programs, are not just tasks to be completed. They represent a commitment to elevating the understanding and interaction with the bubble breaker. The discussion around these actions should emphasize their role in not just correcting inefficiencies but in building a foundation for continuous improvement and engagement.

6.5) Conclusion: A Unified Vision for Change

The integration of advanced training, condition monitoring technologies, and a culture of continuous improvement represents a holistic strategy to address the immediate challenges identified. However, the success of this strategy hinges on our ability to manage change effectively. Through active stakeholder engagement, thoughtful process reconfiguration, and a collaborative approach to navigating challenges, we can ensure that these enhancements lead to a significant transformation in maintenance practices. Ultimately, this strategy is about more than just operational efficiency; it's about fostering a culture of innovation, learning, and quality that positions Budweiser Brewing Group's Magor Brewery at the forefront of the industry.

7) Conclusions/Recommendations

7.1) Key Findings:

The critical review of current maintenance practices for the bubble breaker at Budweiser Brewing Group's Magor Brewery has unveiled a series of inefficiencies. These include gaps in operational knowledge, inconsistent equipment handling, and a noticeable absence of proactive maintenance strategies. Such shortcomings hinder the effective reduction of Total Packaged Oxygen (TPO), which is paramount for preserving beer quality. The findings underscore the necessity for a more sophisticated and integrated approach to maintenance, leveraging advanced technologies and structured training to bridge the knowledge gap and standardize equipment handling.

7.2) Recommendations:

i) Short-term (0-6 months):

Standard Operating Procedures (SOPs): Develop and implement comprehensive SOPs for the bubble breaker's operation and maintenance. These SOPs should detail optimal settings and adjustments, informed by manufacturer specifications and best practices for TPO reduction, ensuring consistency in equipment handling (**Pinto Junior & Mendes, 2017**).

Operator Training Program: Roll out an extensive training program focused on the bubble breaker's role in TPO reduction and beer quality. Utilize AR technology for interactive learning experiences, enabling operators to gain a hands-on understanding of the equipment's impact on the production process (**Bryan & Sisson, 2006**).

ii) Medium-term (6-12 months):

Technology Integration: Integrate IoT sensors and a centralized control dashboard for continuous monitoring and real-time feedback on the bubble breaker's performance. This technology will facilitate immediate adjustments and pre-emptive maintenance actions, enhancing decision-making and precision (**Shehadeh et al., 2016**).

Knowledge Refreshment Sessions: Implement ongoing refresher courses to maintain and update the operational knowledge of the staff. These sessions will ensure that the workforce stays informed about best practices and any new developments related to the equipment or production process (**Found et al., 2018**).

iii) Long-term (1-3 years):

Feedback Loop and Performance Monitoring: Establish a digital platform for real-time reporting of operational issues and suggestions for improvement. This system should promote active participation from operators and support a culture of continuous improvement, allowing for regular review cycles to evaluate feedback and celebrate achievements (**Found et al., 2018**).

P-F Curve and FMECA Integration: Apply P-F Curve analysis to identify early warning signs of equipment wear or failure, enabling timely maintenance interventions. Additionally, conduct a comprehensive FMECA to assess the potential failure modes of the bubble breaker and prioritize maintenance tasks based on their criticality and impact on operations (**Zhang & Chu, 2010; Sherwin, 2000**).

7.3) Strategic Value of Continuous Improvement:

Integrating these recommendations into the maintenance strategy will not only address the immediate challenges but also lay the groundwork for sustained operational excellence. Emphasizing continuous improvement and the strategic value of data-driven decision-making will ensure that the brewery remains adaptable and responsive to evolving production demands. By fostering a culture of innovation and learning, Budweiser Brewing Group's Magor Brewery can enhance equipment reliability, product quality, and ultimately, operational efficiency.

8) Referencing

1. Achouch, M., Dimitrova, M., Ziane, K., Sattarpanah Karganroudi, S., Dhouib, R., Ibrahim, H., & Adda, M. (2022). On Predictive Maintenance in Industry 4.0: Overview, Models, and Challenges. *Applied Sciences*. Accessed on 14th March 2024, 14:45. Link: <https://www.mdpi.com/2076-3417/12/16/8081>
2. Adryan, F., & Sastra, K. W. (2021). Predictive Maintenance for Aircraft Engine Using Machine Learning: Trends and Challenges. *AVIA*. Accessed on 18th March 2024, 09:30. Link: https://www.researchgate.net/publication/357458578_Predictive_Maintenance_for_Aircraft_Engine_Using_Machine_Learning_Trends_and_Challenges
3. Bamforth, C.W. (2008). *Beer: Tap into the art and science of brewing*. Oxford: Oxford University Press.
4. Bowles, J.B. & Peláez, C.E. (1995). Application of FMEA to a computer-based system. *IEEE Transactions on Reliability*, 44(4), pp.561-564.
5. Bryan, L.A., & Sisson, N. (2006). Using augmented reality for operational staff training. *Journal of Workplace Learning*, 18(4), 240-250. Accessed on 22nd March 2024, 11:00. Link: https://www.researchgate.net/publication/376378496_USING_VIRTUAL_REALITY_AND_AUGMENTED_REALITY_FOR_TRAINING_FOR_HEALTHY_AND_SAFE_WORK
6. Cinar, Z., Nuhu, A. A., Zeeshan, Q., Korhan, O., Asmael, M. B. A., & Safaei, B. (2020). Machine Learning in Predictive Maintenance towards Sustainable Smart Manufacturing in Industry 4.0. *Sustainability*. Accessed on 6th March 2024, 16:15. Link: <https://www.mdpi.com/2071-1050/12/19/8211>
7. Drakaki, M., Karnavas, Y. L., Tzifettas, I. A., Linardos, V., & Tzionas, P. (2022). Machine learning and deep learning based methods toward industry 4.0 predictive maintenance in induction motors: State of the art survey. *Journal of Industrial Engineering and Management*. Accessed on 10th March 2024, 10:50. Link: <https://www.econstor.eu/bitstream/10419/261786/1/1789452813.pdf>
8. Elnaga, A. A., & Imran, A. (2013). The Effect of Training on Employee Performance. *European Journal of Business and Management*.
9. Falekas, G., & Karlis, A. (2021). Digital Twin in Electrical Machine Control and Predictive Maintenance: State-of-the-Art and Future Prospects. *Energies*. Accessed on 28th March 2024, 17:05. Link: <https://ideas.repec.org/a/gam/jeners/v14y2021i18p5933-d638457.html>
10. Found, P., Lahy, A., Williams, S. J., Hu, Q., & Mason, R. (2018). Towards a theory of operational excellence. *Total Quality Management & Business Excellence*.
11. Hough, J.S., Briggs, D.E., Stevens, R., & Young, T.W. (1982). *The brewing of beer: Mashing and sparging*. Dordrecht: Springer.
12. Jain, M., Vasdev, D., Pal, K., & Sharma, V. (2022). Systematic literature review on predictive maintenance of vehicles and diagnosis of vehicle's health using machine learning techniques. *Computational Intelligence*. Accessed on 24th March 2024, 12:20. Link: <https://ouci.dntb.gov.ua/en/works/7P5EbLn4/>
13. Kotter, J.P. (1996). *Leading change*. Boston, MA: Harvard Business School Press.
14. Kumar, N., & Saini, D. S. (2023). Some Recent Stories of Operational Excellence in SMEs. *International Journal for Research in Applied Science and Engineering Technology*.
15. Leelasarada, V., Babu, B., & Kumar, B. (2017). The impact of training on organisation performance in manufacturing industry. *International journal of applied research*.
16. Lorenti, L., Dalle Pezze, D., Andreoli, J., Masiero, C., Gentner, N., Yang, Y., & Susto, G. A. (2023). Predictive Maintenance in the Industry: A Comparative Study on Deep Learning-based Remaining Useful Life Estimation. *2023 IEEE 21st International Conference on Industrial Informatics (INDIN)*. Accessed on 3rd March 2024, 15:30. Link: <https://arxiv.org/pdf/2312.16810.pdf>

17. Mobley, R.K. (2002). An introduction to predictive maintenance. Oxford: Elsevier Science & Technology.
18. Moubray, J. (1997). Reliability-centred maintenance. New York: Industrial Press Inc.
19. Muazu, M., & Tasmin, R. (2019). Operational Excellence and the Implications for Health, Safety and Environmental Performance in the Oil and Gas Industry. *Journal of Technology Management and Business*. Accessed on 12th March 2024, 09:15. Link: <https://www.semanticscholar.org/paper/Operational-Excellence-and-the-Implications-for-and-Muazu-Tasmin/60dca4ad59c79d55dbf692d116f392975a3ec4a1>
20. Ozbiltekin-Pala, M., Kazançoğlu, Y., Kumar, A. K., Garza-Reyes, J., & Luthra, S. (2022). Analysing critical factors of strategic alignment between operational excellence and Industry 4.0 technologies in smart manufacturing. *The TQM Journal*. Accessed on 26th March 2024, 16:45. Link: <https://repository.derby.ac.uk/item/9q8vx/analysing-critical-factors-of-strategic-alignment-between-operational-excellence-and-industry-4-0-technologies-in-smart-manufacturing>
21. Pansare, R., Yadav, G., & Nagare, M. (2022). Integrating operational excellence strategies with Industry 4.0 technologies through reconfigurable manufacturing system practices. *The TQM Journal*. Accessed on 20th March 2024, 14:30. Link: <https://scholar.google.com/citations?user=Lh4UcrwAAAAJ&hl=ja>
22. Parida, A., & Chattopadhyay, G. (2007). Development of a multi-criteria hierarchical framework for maintenance performance measurement (MPM). *Journal of Quality in Maintenance Engineering*, 13(3), 241-258.
23. Pellissier, R. (2009). Innovation in operational excellence in a complex environment. PICMET '09 - 2009 Portland International Conference on Management of Engineering & Technology. Accessed on 15th March 2024, 17:20. Link: <https://www.semanticscholar.org/paper/Innovation-in-operational-excellence-in-a-complex-Pellissier/344b4dbeb948ca8ef68108b993ef71ae80a19316>
24. Pinto Junior, M. J. A., & Mendes, J. V. (2017). Operational practices of lean manufacturing: Potentiating environmental improvements. *Journal of Industrial Engineering and Management*.
25. Ran, Y., Zhou, X., Lin, P., Wen, Y., & Deng, R. (2019). A Survey of Predictive Maintenance: Systems, Purposes and Approaches. *ArXiv*. Accessed on 7th March 2024, 10:00. Link: https://www.researchgate.net/publication/337971929_A_Survey_of_Predictive_Maintenance_Systems_Purposes_and_Approaches
26. Sahal, R., Breslin, J., & Ali, M. (2020). Big data and stream processing platforms for Industry 4.0 requirements mapping for a predictive maintenance use case. *Journal of Manufacturing Systems*. Accessed on 19th March 2024, 11:45. Link: <https://www.growkudos.com/publications/10.1016%252Fj.jmsy.2019.11.004/reader>
27. Sharma, J., Mittal, M. L., Soni, G., & Keprate, A. (2023). Explainable Artificial Intelligence (XAI) Approaches in Predictive Maintenance: A Review. *Recent Patents on Engineering*. Accessed on 25th March 2024, 12:10. Link: <https://benthamscience.com/article/130973>
28. Shehadeh, R. M., Maqableh, M., Al-Zoubi, M. O., Akhorshaideh, A. H., & Al-Shami, M. K. (2016). Review the Operational Excellence Factors of Service Firms: A Literature Review. *European Journal of Business and Management*.
29. Sisson, J. (2019). Maturing the lean capability of front-line operations supervisors. *International Journal of Lean Six Sigma*. Accessed on 17th March 2024, 16:00. Link: https://www.researchgate.net/publication/328227089_Maturing_the_lean_capability_of_front-line_operations_supervisors
30. Stamatis, D.H. (2003). Failure Mode and Effect Analysis: FMEA from Theory to Execution. Milwaukee: American Society for Quality.
31. Swanson, L. (2001). Linking maintenance strategies to performance. *International Journal of Production Economics*, 70(3), 237-244.
32. Tsang, A.H.C. (2002). Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering*, 8(1), 7-39.

33. Vollert, S., Atzmueller, M., & Theissler, A. (2021). Interpretable Machine Learning: A brief survey from the predictive maintenance perspective. 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). Accessed on 11th March 2024, 13:55. Link: <https://dl.acm.org/doi/10.1109/ETFA45728.2021.9613467>
34. Zhang, W., & Chu, J. (2010). Early warning methodologies for equipment failure and maintenance strategies. Mechanical Systems and Signal Processing, 24(5), 1503-1517. Accessed on 5th March 2024, 15:40. Link: https://www.researchgate.net/publication/290632134_Early-warning_model_oriented_to_maintenance_procedures