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Enhancing Operational Efficiency in Oil and Gas Through I4.0-Enabled Condition-Based Maintenance

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Abstract

The oil and gas industry, marked by its intricate infrastructure and dependence on equipment reliability, progressively embraces Industry 4.0 (I4.0) technologies to drive operational excellence. This study presents a comprehensive framework for integrating I4.0 principles with Condition-Based Maintenance (CBM) strategies aimed at revolutionising maintenance practices in the sector. The research addresses recurring industry challenges, including equipment failures, production disruptions, and rising maintenance costs. It leverages a rigorous literature review, empirical data, and Delphi study to develop an innovative I4.0-based CBM framework designed to harness real-time diagnostics and predictive analytics. This framework provides a systematic, actionable roadmap for organisations looking to enhance equipment reliability, reduce downtime, and optimise maintenance expenditures. As part of the I4.0-based CBM framework, the study introduces an I4.0 Maturity Model and an online assessment tool, enabling maintenance professionals to gauge their readiness and progress in adopting I4.0-enabled CBM practices. The research culminates in the real-world application of the developed framework within an operational oil and gas organisation in Nigeria. This application demonstrates tangible enhancements in equipment reliability, production efficiency, and maintenance strategy optimisation. Insights from empirical deployment showcases the transformative potential of I4.0-enabled CBM in driving operational efficiency.
This research significantly contributes to the field of industrial operations management, offering a practical guide for organisations in the oil and gas sector and beyond. It presents a blueprint for leveraging I4.0 technologies to redefine maintenance paradigms, foster innovation, and enhance operational efficiency, paving the way for a sustainable and competitive future in the oil and gas industry.

Keywords
Industry 4.0, Condition-Based Maintenance (CBM), Oil and Gas Industry, Operational Efficiency, Predictive Analytics.

1. Introduction

Industry 4.0 (I4.0) signifies a transformative wave in manufacturing and sectors like the oil and gas, driven by technologies such as the Internet of Things (IoT), big data, and cloud computing. This shift enhances operational efficiency and performance through more intelligent, interconnected systems, as noted by researchers like Chen et al. (2017)), Frank et al. (2019), and Caiado et al. (2021). In the oil and gas, a sector plagued by high maintenance costs and equipment reliability issues, the integration of I4.0 is crucial yet challenging (Elijah et al., 2021; Lu et al., 2019). Industry 4.0 based Condition-Based Maintenance emerges as a proactive approach within this context, aiming to enhance equipment reliability and minimise downtime. It represents a shift from reactive to predictive maintenance, a change underscored by studies from Shin & Jun (2015) and Rastegari et al., 2017). However, the adoption of I4.0 into CBM in oil and gas is hindered by technological, operational, and organisational barriers (Morrison, 2019; Telford et al., 2011).

Despite the recognised potential of CBM to improve maintenance and equipment lifespan, industries show hesitance, often due to a mix of technical and cultural challenges (van de Kerkhof et al., 2016; Ingemarsdotter et al., 2021). There is a notable gap between the theoretical appeal and practical adoption of advanced CBM techniques, with professionals cautious about fully embracing predictive maintenance (Tiddens, 2018; Veldman et al., 2011). These challenges prevent the full realisation of operational efficiency advantages.

This article explores the integration of I4.0 technologies into CBM strategies in the oil and gas industry, considering the benefits, challenges, and potential paths forward. It aims to provide a clearer understanding of how to navigate the complexities of adopting Industry 4.0 into CBM, ultimately enhancing operational efficiency in a critical global sector.

1.1 Objectives

Adopting an Industry 4.0-driven Condition-Based Maintenance (CBM) framework in the practical setting of the oil and gas upstream sector (referred to as the oil and gas industry throughout this study) will significantly enhance operational efficiency. In this study showcasing the implementation of a developed I4.0-based CBM framework, the implementation not only enhances operational effectiveness by pinpointing areas for improvement but also supports a detailed evaluation and approval of the framework, serving as an additional layer of validation for the newly developed I4.0 based CBM framework.

This study aims to apply a developed Condition-Based Maintenance (CBM) framework within the oil and gas upstream sector to enhance operational efficiency by combining Industry 4.0 technologies with CBM. Following a comprehensive Delphi study, the research seeks to validate the framework through action research in a developing nation's oil and gas sector. The main goal is to transform maintenance practices, address challenges like equipment failure and high maintenance costs, improve equipment reliability, reduce downtime, and optimize maintenance expenses, thereby setting new standards for maintenance and operational excellence in the oil and gas industry.

2. Literature Review

Many scholarly contributions have significantly enriched the burgeoning discourse on Condition-Based Maintenance (CBM) and Industry 4.0 (I4.0) within the realms of manufacturing and operational efficiency. These insights collectively illuminate the challenges and opportunities inherent in integrating cutting-edge technologies and maintenance strategies within industrial settings, particularly within the oil and gas sector. This literature review meticulously synthesises these contributions, underscoring the transformative potential of employing an Industry 4.0 Maturity Model to integrate Industry 4.0 technologies to CBM and use I4.0 readiness or maturity level assessments to determine readiness or maturity level on I4.0 implementation. Such approaches are instrumental in addressing existing gaps in knowledge and practice, especially in the oil and gas industry.

Shin & Jun (2015) spotlight the increasing adoption of avant-garde technologies by manufacturing companies. Their findings emphasise the critical role of real-time intelligence in enabling CBM, thereby preventing catastrophic asset failures. This transition, they note, requires a profound organisational shift towards more sophisticated and technologically advanced paradigms.

Morrison (2019) highlights the prerequisites for effective CBM assimilation, including workforce upskilling and understanding the financial and operational intricacies involved. Similarly, Bengtsson (2006) andRastegari & Bengtsson (2014, 2015)delve deeper into the CBM assimilation process, proposing a work process for its implementation. They advocate for a comprehensive approach considering organisational, economic, and technical factors, emphasising the criticality of decision-making and asset selection based on tools like RCM or FMEA.

Van de Kerkhof (2020) contributes to this discourse by developing a CBM Maturity Model, an evaluative tool designed to assess capabilities in deploying CBM. This model, derived from a meticulous mapping of existing maturity models, addresses a gap in the literature by providing a structured assessment instrument tailored for asset owners and maintenance managers.

The significance of CBM in enhancing operational reliability and preventing asset failures is further corroborated by the foundational work of Peng et al. (2010) and complemented by the observations of Rastegari et al. (2013) and Bengtsson et al. (2004). The latter highlights the paradox of CBM systems' nascent maturity stages and proposes the incorporation of Artificial Intelligence techniques to navigate complex diagnostics.

The intricate relationship between CBM and Industry 4.0 is epitomised by the work of BAUR & WEE (2015), Deloitte (2015) and Koleva (2018), who elucidate the profound implications of I4.0 in terms of automation, data exchange, and digital transformation. They underscore the need for vertical and horizontal systemic integration to realise the full potential of I4.0 in enhancing operational efficiency and customising product offerings.
The criticality of assessing an organisation's readiness to embrace I4.0 is articulated by Rafael et al., (2020) and Sony & Naik, (2019). They advocate for the use of Maturity Models as systematic methods to evaluate and enhance operational processes in line with I4.0 integration. As explored by Axmann & Harmoko (2020) and Agca et al. (2017), these tools provide structured methodologies for companies to autonomously or externally assess their preparedness for the fourth industrial revolution.

In the specific context of the oil and gas sector, scholars like Mitchell (2011), Telford et al. (2011), and (Elijah et al., 2021) have explored the growing yet increasing adoption of CBM and I4.0 technologies. They emphasise sector-specific challenges and advocate for meticulously curated CBM programs and early adoption frameworks to navigate the oil and gas industry's complex operational and maintenance landscapes.

In synthesising these scholarly endeavours, it is evident that the integration of CBM and I4.0 holds immense potential for transforming the operational efficiency of the oil and gas sector. However, the literature also reveals a significant gap in the form of a comprehensive, industry-specific maturity model and readiness assessment tool. Such a tool would measure an organisation's readiness to integrate I4.0 technologies into CBM practices and provide tailored recommendations for phased integration towards full maturity. This gap represents a critical juncture for research and practical application, promising enhanced operational reliability, cost efficiency, and strategic agility in an increasingly complex and competitive industrial landscape.

3. Methodology

3.1 Action Research

Action research as a methodology is particularly well-suited for a research study as it offers a systematic and reflective approach to solving real-world problems through iterative cycles of planning, acting, observing, and reflecting. This method aligns with the goal of enhancing operational efficiency in the oil and gas sector by allowing for the practical application and continuous improvement of the I4.0-enabled CBM framework in a real-world industrial case study and so was selected for this study.

The selection of the oil and gas sector, particularly its upstream echelons, for this study is strategic. This sector is known for its volatile dynamics, complex supply chains, and high demands for technological adaptability. These characteristics make it an ideal environment for the application of sophisticated I4.0 solutions. The case study in this research serves two primary purposes: firstly, to demonstrate the practical application of the validated CBM framework, which includes the I4.0 maturity model for CBM and an assessment tool. This reaffirms the relevance of expert validations from the Delphi panel and provides empirical evidence of the framework's applicability and effectiveness in an operational setting. The results of the Delphi survey have been previously published in the authors' work by Onyeme & Liyanage (2023). Secondly, the case study helps observe the tangible effects and influences of the I4.0 CBM framework, offering insights into its contribution to operational efficiency and the evolution of the I4.0 integration roadmap for CBM in the oil and gas sector.

Coghlan & Brannick (2014) emphasise that action research is intricate and requires a systematic and reflective approach. The cyclical nature of action research is particularly beneficial in this study as it allows for continuous learning and improvement of the CBM framework. Choosing a single-case design for this research is justified by the work of Yin (2014) and Siggelkow (2007), who argue that single case studies can provide deep, nuanced insights that are often missed in broader statistical studies. This approach is particularly suited for testing and deploying a well-articulated framework like the one at the centre of this research. The Condition-Based Maintenance (CBM) framework, based on Industry 4.0 principles, presents a clear set of propositions tailored for CBM in the oil and gas sector. The aim is to move beyond mere application to an immersive understanding of the framework's operational dynamics within its natural setting. Authors like George & Bennett (2005) and Stake (1995) further support the use of single-case designs for scrutinising a concept within its native environment and for understanding and interpreting a particular case.

Engaging with a single organisation in the complex sector of oil and gas in Nigeria amplifies the synergy between the researcher and the subject, enabling a depth of interaction crucial for this research. The selection of the organisation was based on criteria such as senior management's engagement, the operational profile in the oil and gas sector, and existing CBM practices. This careful selection ensures that the organisation is a fitting representative for testing the CBM framework's adaptability and alignment with I4.0 principles.

Action research as the methodology for this work is well-aligned with the goal of enhancing operational efficiency in the oil and gas sector through I4.0-enabled Condition-Based Maintenance. The systematic and reflective nature of action research, combined with a well-chosen single-case study in a relevant sector, provides a robust structure for testing, validating, and refining the I4.0 CBM framework. This approach contributes to the academic field and offers practical insights and a realistic roadmap for integrating emerging technologies into maintenance strategies for operational excellence in complex, high-stakes industries like the oil and gas.

3.2 The Case Study - Participating Organization and Production Asset at a Glance

The organisation is an oil field operated by an oil and gas corporation within the Niger Delta Region, an area endowed with substantial crude oil deposits, was selected for an action research study following the stated research objectives. This selection was predicated on the fervent interest exhibited by the organisation’s management team, their readiness to integrate and enhance asset integrity and their existing robust approach to Condition-Based Maintenance (CBM). Moreover, their eagerness to exploit the potential of digitalisation and the principles of Industry 4.0 in refining their maintenance strategies was pivotal in this choice. Owing to the sensitive nature of the data pertaining to the organisation, its stakeholders, and its maintenance strategies, confidentiality was maintained throughout the research, in line with ethical considerations and a consensus with the organisation's senior management. Consequently, this entity was designated as “Organisation A” within the scope of the study.

Organisation A oversees an extensive network of pipelines, flowlines, flow stations, and natural gas plants, encompassing numerous producing crude oil wells. The production operations are primarily focused on the tangible extraction of petroleum. The facilities within the production ambit are categorised into distinct fields, and for this study, the chosen field, which will be referred to as “Production Unit A”, manages two oil stabilisation facilities, commonly referred to as "Flow stations." The flow station is responsible for receiving and managing crude oil from the reservoir, processing it to a stable state suitable for further handling at a crude oil terminal—a separate entity—before its sale as stabilised oil. A vital feature of the participating organisation is its long years of operation in Nigeria and its large oil and gas company footprint within and oustside the country.

The selected Production asset (Production Unit A) is located in the Niger Delta region of Nigeria has a manning of 75 workers, including 30% maintenance technicians specialised in various disciplines (more of Mechnical, Electrical, Instrumentation). The asset operates through a two-stage oil production system (High-Pressure and Low-Pressure) within a flow station equipped with separators, a flare knock-out drum, a surge vessel, centrifugal pumps, and a pipeline leading to a Terminal for further processing. Additional systems include Fuel Gas, Metering, Free Liquid Knock-out pumps, an Open Drain System, Flare Stacks, and utilities like generators, air compressors, and fire water pumps. An illustrative flow diagram provides a simplified overview of the facility's equipment and layout, as shown in Figure 1.

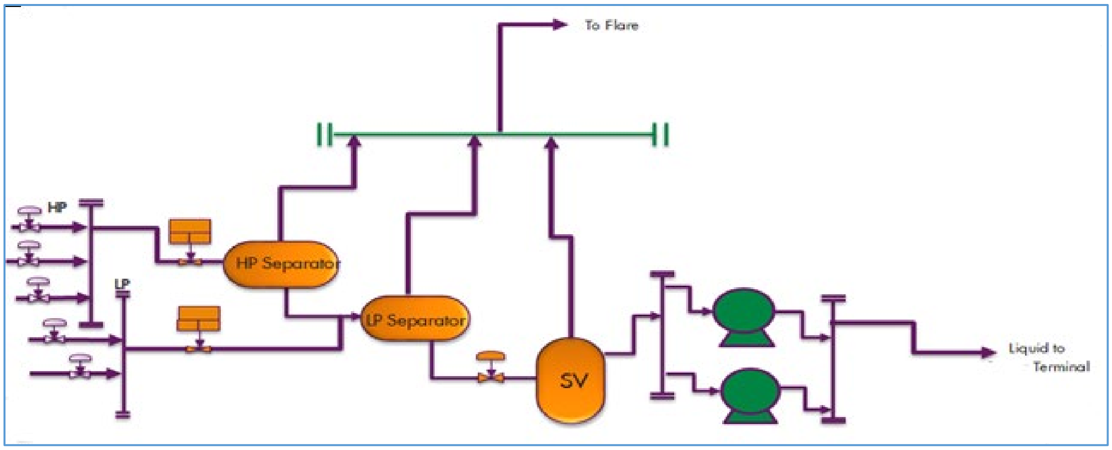

Figure 1. Flow diagram of the crude production facility

3.3 Data Collection and Analysis

In pursuing empirical rigour, the researcher employed a hierarchical approach within the action research paradigm, interfacing primarily with the echelons of the production unit's team leadership to enlist participation from two distinct operational strata within the maintenance domain. This hierarchical engagement commenced with the leadership tier, encapsulating the facility manager, the maintenance team leader, and the discipline-specific supervisors for the Mechanical, Electrical, and Process Automation and Control sectors. Subsequently, the approach encompassed the technician tier, which included a delegate from each of the aforementioned technical disciplines.

The assemblage comprised 11 individuals, each contributing to the operationalisation of the framework. Their collaboration spanned several critical phases: the discernment of maintenance imperatives, the evaluation of extant maturity levels utilising the designated online assessment tool, and the critical appraisal of the derived outcomes to inform the progression along a strategically formulated roadmap.

Table 1 presents a synthesised compilation of pertinent data regarding the participant cadre, encapsulating their roles, responsibilities, and age for contributions to the research initiative. This data forms the empirical substrate from which the action research study derives its foundational insights and operational directives.

Table 1. Framework Validation Participants

S/N	Role	Discipline/Background	Number	Age
1	Facility Manager	Mechanical Engineering	1	47
2	Team Leader (Maintenance)	Electrical/Electronic Engineering	1	35
2	Team leader (Operations)	Industrial/Production Engineering	1	49
3	Electrical Supervisor	Electrical Engineering	1	55
4	Mechanical Supervisor	Mechanical Engineering	2	48
5	Process, Automation and Control Supervisor	Electrical/Electronics Engineering	2	49
6	Electrical Technician	Electrical Engineering	1	47
7	Mechanical Technician	Mechanical Engineering	1	46
8	Process, Automation and Control Technician	Instrumentation and Control	1	34

The researcher's participation, entrenched within the action research paradigm, was executed with the utmost professionalism and an ethos of collaborative inquiry, encompassing candid dialogues with Production Unit A's leadership and meticulous observational record-keeping of the framework's application in situ. The analytical process was fortified by employing thematic synthesis to extract and consolidate the total insights from the qualitative corpus, as explicated in the study by Braun & Clarke (2006) and Thomas & Harden (2008).
In concert with this, quantitative evaluative measures were enacted to ascertain the deployment stage of I4.0 in CBM practices in the industry. This quantification was facilitated via an online Assessment Tool, which synthesised the

collective maturity levels across various dimensions and sub-dimensions, predicated upon consensual responses tendered by the Production Unit A team members. The assessment was operationalised with the researcher providing essential facilitation throughout the evaluation procedure.

4. The CBM Framework– I4.0 Maturity Model and the Readiness Assessment tool

This comprehensive framework is designed to elevate operational efficiency in the oil and gas industry by seamlessly integrating Industry 4.0 (I4.0) technologies into Condition-Based Maintenance (CBM). Central to this framework are two pivotal components: the I4.0 Maturity Model and the I4.0 Readiness Assessment Tool, each intricately designed to align with the primary objective of augmenting operational efficiency.

The I4.0 Maturity Model is an intricate structure comprising five principal dimensions (People; Organisation; I4.0 Solutions; Process, Operations and Maintenance; Environment) and 27 sub-dimensions (Figure 2), developed after a thorough review of existing literature and models (Marx et al., 2012; Pöppelbuß & Röglinger, 2011). These dimensions encompass key facets of condition-based maintenance, including data acquisition, analysis, prognosis, diagnostics, and decision support. Each dimension is further broken down into sub-dimensions that reflect specific areas within CBM and Industry 4.0 integration.

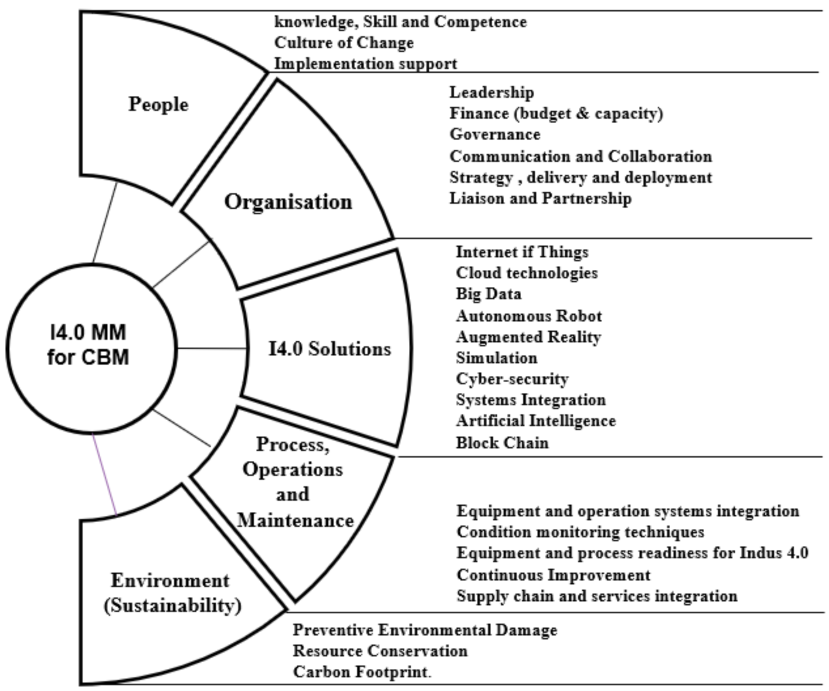

Figure 2 – The Dimensions and Subdimensions for the I4.0 MM for CBM

The model operates on a scale from Level 0 to Level 4, with each level representing a progressive stage in the organisation's maturity regarding the integration of I4.0 elements into their CBM strategies. This gradation allows organisations to understand their current position and identify areas needing enhancement, thereby enabling targeted improvements and strategic planning for advancing their 4.0 maturity. Complementing the Maturity Model is the I4.0 Readiness Assessment Tool, a user-friendly and insightful instrument for organisations to evaluate their preparedness to embrace I4.0 in their CBM practices (Agca et al., 2017; Sheen & Yang, 2018). This interactive online self-assessment tool allows maintenance teams to critically appraise their operational readiness and receive prescriptive advice for future actions. It operationalises its assessments through a scoring system based on meticulously established criteria for each pertinent sub-dimension, ranging from a score of "0" indicating minimal readiness to a score of "4" denoting maximal maturity. The tool employs visualisation aids such as grids, graphs, and radar plots to enhance comprehensibility, offering a clear snapshot of the organisation's current standing and the strategic actions required for advancing maturity levels.

The framework, with its I4.0 Maturity Model and Readiness Assessment Tool, is tailored to meet the specific demands of CBM in the oil and gas sector. It recognises the industry's unique operational challenges and the critical role CBM plays in maintaining equipment reliability and reducing downtime. By providing a structured pathway for the phased integration of I4.0 technologies into CBM systems, the framework aims to guide organisations from their current state to a future where I4.0 and CBM are seamlessly integrated, achieving enhanced operational efficiency.

The framework was informed by a Delphi process, which enabled initial validation, after an exhaustive review of scholarly literature and an in-depth analysis of the architecture and thematic content of extant maturity models. Each stage of the framework, from recognising maintenance objectives to proposing a strategic blueprint for CBM augmentation through I4.0 integration, is designed to ensure that the organisation has a clear direction and understands the practical steps required for enhancing its operational efficiency through I4.0-based CBM. The framework, with its focus on the I4.0 Maturity Model and Readiness Assessment Tool, provides a robust methodology for oil and gas companies to navigate the complexities of I4.0 integration into CBM. It offers a validated and tailored approach, ensuring that organisations can assess their current state and receive guided recommendations for advancing their operational efficiency through strategic CBM and I4.0 integration. Figure 2 shows only the dimensions and their subdimensions, while Table 2 shows an excerpt of the model (a sub-dimension of one of the five dimensions).

Table 2 – Excerpt from I4.0 Maturity Model for CBM in the O&G Industry

Dimension 1 - Organization					
Sub-dimension (Assessment criteria)	Readiness level				
	Level 0	Level 1	Level 2	Level 3	Level 4
Leadership	The leadership team do not recognize the value of Industry 4.0 investment in CBM.	The leadership team are investigating potential Industry 4.0 benefits to the system.	The leadership team recognises the financial benefits of Industry 4.0 and is developing plans to integrate Industry 4.0 into CBM.	There is support from the leadership on the integration of Industry 4.0 in CBM. The strategy documents adopted and integrated. Follow-ups, reviews and provision of additional resources is as required.	There is widespread support and commitment for Industry 4.0 by the leadership team and across the maintenance discipline of the organization. Industry 4.0 is fully operationalized.
Finance (Budget and capacity)	There is no budget plan for Industry 4.0, and no consideration has been given.	There is no sizeable Industry 4.0 investment in CBM, Funds are allocated selectively as per request in piece meals.	There is an ongoing cost/benefit analysis review for Industry 4.0 investment. Basic funding available for low-level investment	Investments have been made for I4.0 integration into CBM in selected facilities after pilot studies, there is an annual cost/benefit analysis of Industry 4.0 investment.	I4.0 investment made for I4.0 integration across all facilities, and there is a more frequent cost/benefit analysis of Industry 4.0
Governance	No governance is available for I4.0 integration into CBM	There is an idea of how the I4.0 integration into CBM would need to be governed and reported. The right standards and guidelines, stakeholders as well as formal requirements and agreements, data rights	There is a clear procedure on how to manage the integration of I40 to CM moments, which has been captured in the organizational governance standards. The standards have	A business model for accountability, associated industry-specific standards and guidelines is in place and endorsed at the leadership level. I4.0 stewards are establishing the	The business model for accountability, associated industry-specific standards and guidelines endorsed at the leadership level. I4.0 is deployed across all facilities. I4.0 integration with CBM

4.1 Application of Framework

During scholarly dialogues with the operational team, a critical analysis was conducted concerning established Key Performance Indicators (KPIs) pertinent to the reliability and efficacy of the equipment within the flow stations of Production Unit A. These dialogues were precisely oriented towards enhancing performance and productivity, mainly through the lens of the Condition-Based Maintenance (CBM) strategy implemented for the major equipment within the flow station.

The consensus reached with the leadership of the participating production unit centred on a strategic focus on the CBM approach as it pertains to the research agenda and the organisation's broader maintenance philosophy for critical equipment. The conversations culminated in a collective understanding that the CBM framework, under the scope of this study, would serve as a foundational impetus for the integration of Industry 4.0 (I4.0) technologies into the pre-existing CBM schema. This integration is anticipated to precipitate significant strides in efficiency, effectiveness, and productivity within the operational domain, a comprehensive evaluation of the incumbent CBM strategy and the identification of potential intersections for the application of I4.0 innovations.

The application of the framework within the context of the action research was methodically executed through a tripartite process. Initially, the procedure entailed a comprehensive identification of Production Unit A’s principal maintenance priorities and objectives. This was followed by a meticulous evaluation of the organisation's maturity and preparedness for Industry 4.0 integration. The culminating phase involved a thorough review and analysis of the outcomes derived from the Industry 4.0 maturity model assessment tool, alongside a concise summarisation of the findings. This structured approach facilitated a systematic exploration of the organisation's maintenance framework and provided a nuanced understanding of its readiness and potential areas for enhancement in the context of Industry 4.0. The outcomes of the assessment are showcased and discussed in Section 5.

5. Results and Discussion

The I4.0 maturity assessment conducted in this study provides a comprehensive evaluation of the organisation's current state and readiness to integrate Industry 4.0 technologies into its CBM practices. The results, categorised into an overall summary and detailed individual dimensions, offer a strategic foundation for developing targeted interventions to bridge the gap between the current state and the envisioned future state of I4.0 integration. This approach aligns with the research's goal of enhancing operational efficiency, ensuring that the assessment's outcomes are a starting point for continuous improvement and sustainable I4.0-based CBM practices.

5.1 Overall Industry 4.0 Maturity or Readiness Level

The organisation's readiness evaluation indicates a nascent adoption stage with an overall weighted average of 1.2 as seen in Figure 3. This reflects a preliminary integration of Industry 4.0, with some structured processes established. Specifically, the "Industry 4.0 Solutions" dimension is at Level 1, revealing a need for more systematic integration strategies. The "Organisation" dimension is slightly more advanced at Level 2, indicating a partial implementation with formal processes. The "People" and "Processes, Operations, and Maintenance" dimensions are at Level 1, suggesting initial awareness and adoption but lacking formalisation and advanced integration. Similarly, the "Sustainability (Environment)" dimension is at Level 1, highlighting early efforts to align sustainability with Industry 4.0 initiatives.

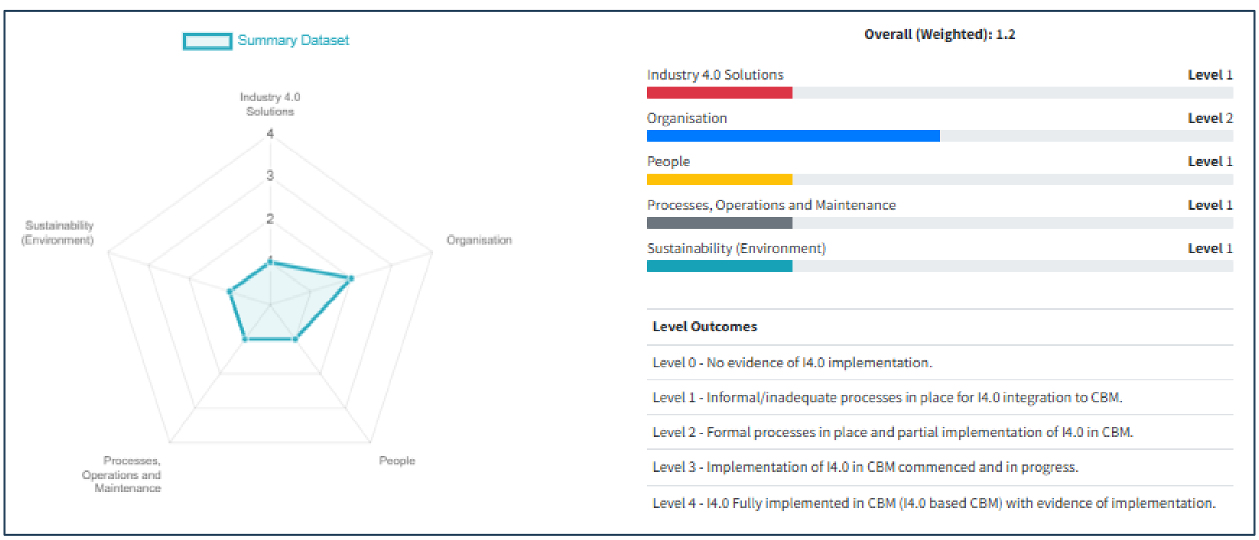

Figure 3. Overall I4.0 Maturity Assessment Outcome for all the dimensions

The organisation should concentrate on evolving its capabilities uniformly across all dimensions. Utilising the relative strength in organisational processes as a foundation, the focus should be on formalising and sophisticating procedures in all areas. This includes advancing training and development programs, enhancing system integration, aligning sustainability objectives with Industry 4.0 technologies, and actively implementing actions and recommendations derived from the Industry 4.0 maturity assessment tool. By doing so, the organisation can ensure a cohesive and comprehensive adoption of Industry 4.0 principles, leading to enhanced operational efficiency and a robust CBM framework. The following section looks in more detail at the outcome under each dimension with recommendations to support I4.0 integration to CBM for operational efficiency enhancement.

5.2 Overall Industry 4.0 Maturity or Readiness Level for each dimension

Organisation: The assessment of the "Organisation" dimension on Industry 4.0 (I4.0) readiness for Condition-Based Maintenance (CBM) indicates the organisation is in the initial stages of I4.0 integration, with an overall weighted average of 2.3 (Figure 4). This situates the organisation between the early phases of I4.0 implementation and having formal but partially implemented processes. Specifically, areas like communication, governance, liaison, and partnership show some structured approaches at Level 2, suggesting partial implementation of I4.0. However, finance, leadership, and strategy delivery are at Level 1, highlighting a need for more strategic and structured approaches in budgeting, leadership, and overall I4.0 strategy implementation.

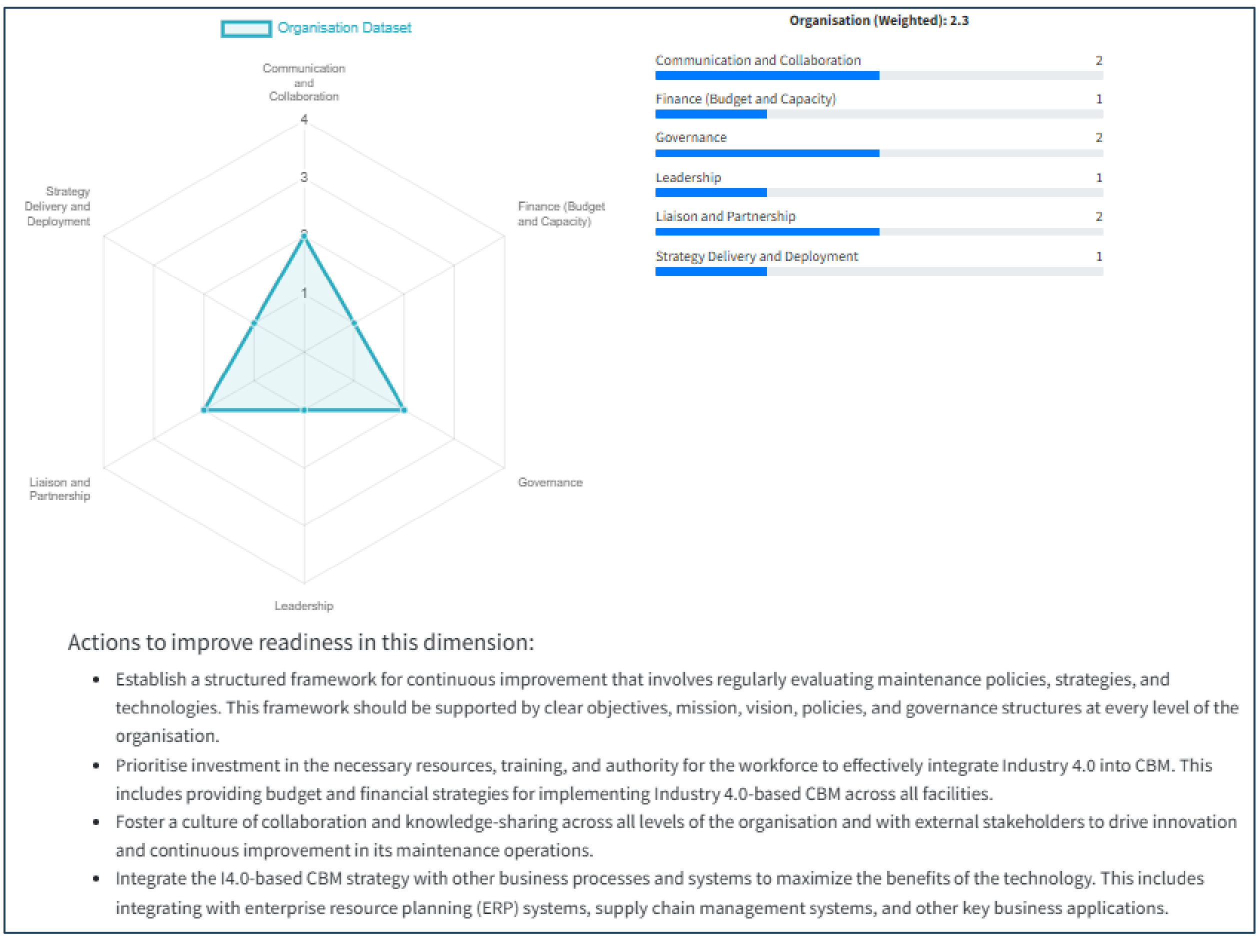

Figure 4. I4.0 Maturity Assessment Outcome for the dimension “Organisation.”

The recommendation provided by the tool as seen in Figure 4 is to establish a clear, structured framework that supports I4.0 at every level. This includes allocating sufficient budget and resources, promoting effective leadership, fostering collaboration and knowledge sharing, and ensuring a strategic approach to deploying and delivering I4.0 initiatives. By addressing these areas, the organisation can advance its I4.0 integration, thereby enhancing operational efficiency using an industry 4.0-based CBM approach.

Industry 4.0 Solutions: The "Industry 4.0 Solutions" dimension assessment outcome for I4.0 integration readiness or maturity shows that the organisation is in the early stages of adopting various technologies, with an overall readiness score of 0.8 (Figure 5). Key technologies like Artificial Intelligence, Autonomous Robots, Blockchain, and Simulation have not been implemented (Level 0), indicating a significant gap in integrating advanced solutions into maintenance processes. Meanwhile, technologies like Augmented Reality, Big Data and Data Analytics, Cyber Security, and Systems Integration are only at the initial stage of adoption (Level 1), with informal or inadequate processes. On a more positive note, Cloud Technologies and the Internet of Things are at a more advanced stage (Level 2), suggesting some formal processes and partial implementation.

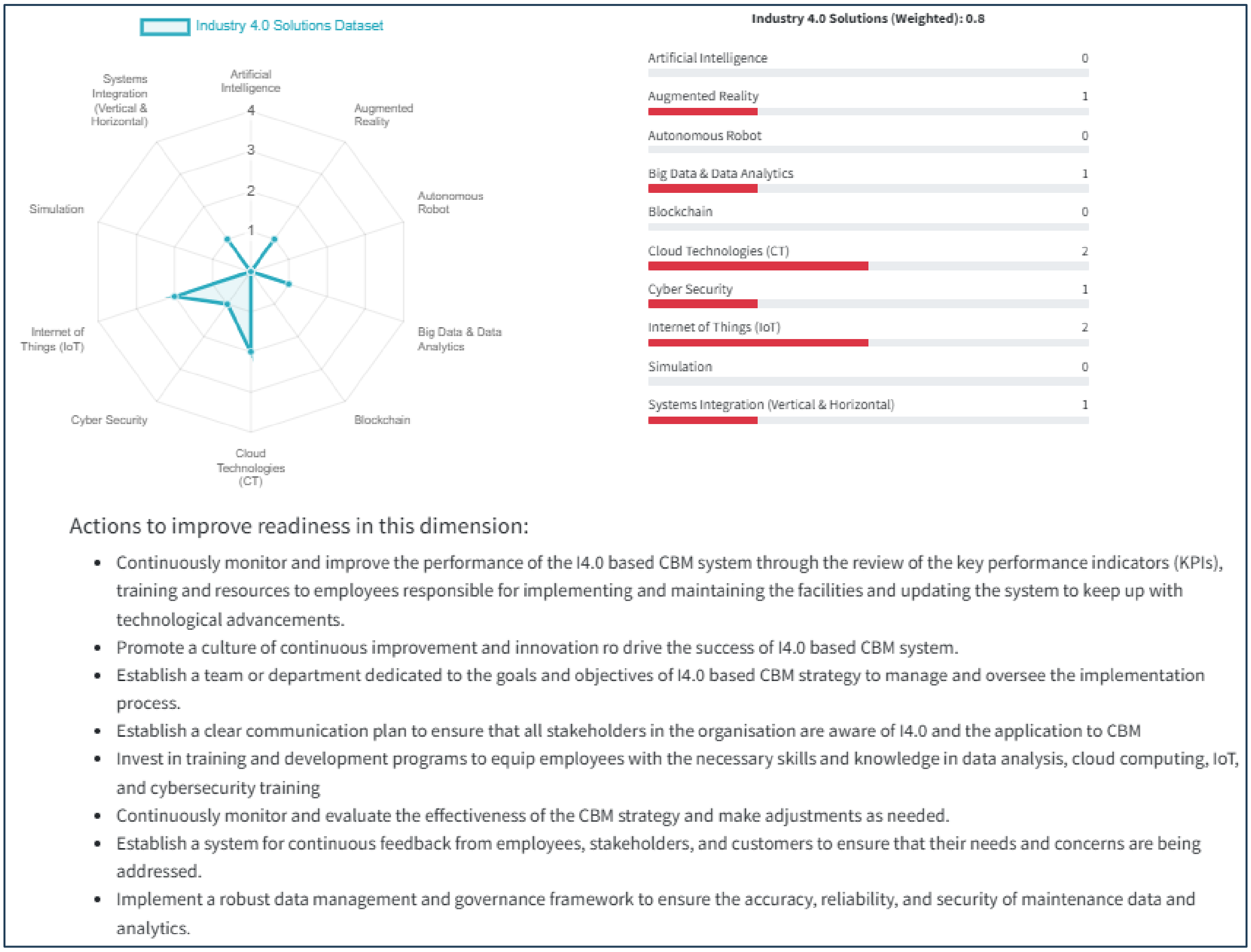

Figure 5. I4.0 Maturity Assessment Outcome for the dimension "Industry 4.0 Solutions"

To enhance operational efficiency through Industry 4.0-based CBM, the organisation should focus on maturing its technological capabilities. This involves establishing a dedicated team for Industry 4.0 objectives, promoting thorough communication of these technologies' benefits, and aligning sustainability with Industry 4.0 efforts. By doing so, the organisation can advance beyond the initial stages of technology adoption, optimise the use of advanced technologies in CBM, and realise significant improvements in operational efficiency.

Processes, Operations and Maintenance: The "Process, Operation & Maintenance" dimension assessment for Industry 4.0 (I4.0) readiness in Condition-Based Maintenance (CBM) reveals the organisation is at an early adoption phase, with an overall weighted score of 0.8 (Figure 6). This proximity to Level 1 indicates that the organisation recognises the potential of I4.0 but lacks formal processes and complete integration strategies. Key areas such as Continuous Improvement, Equipment and Process Readiness, Measurement and CM Techniques, Supply Chain, and Services Integration are at Level 1, reflecting awareness but inadequate formalisation and implementation. Equipment and

Operation System Integration is at Level 0, indicating a significant gap in machine-to-machine integration critical for leveraging I4.0 in CBM.

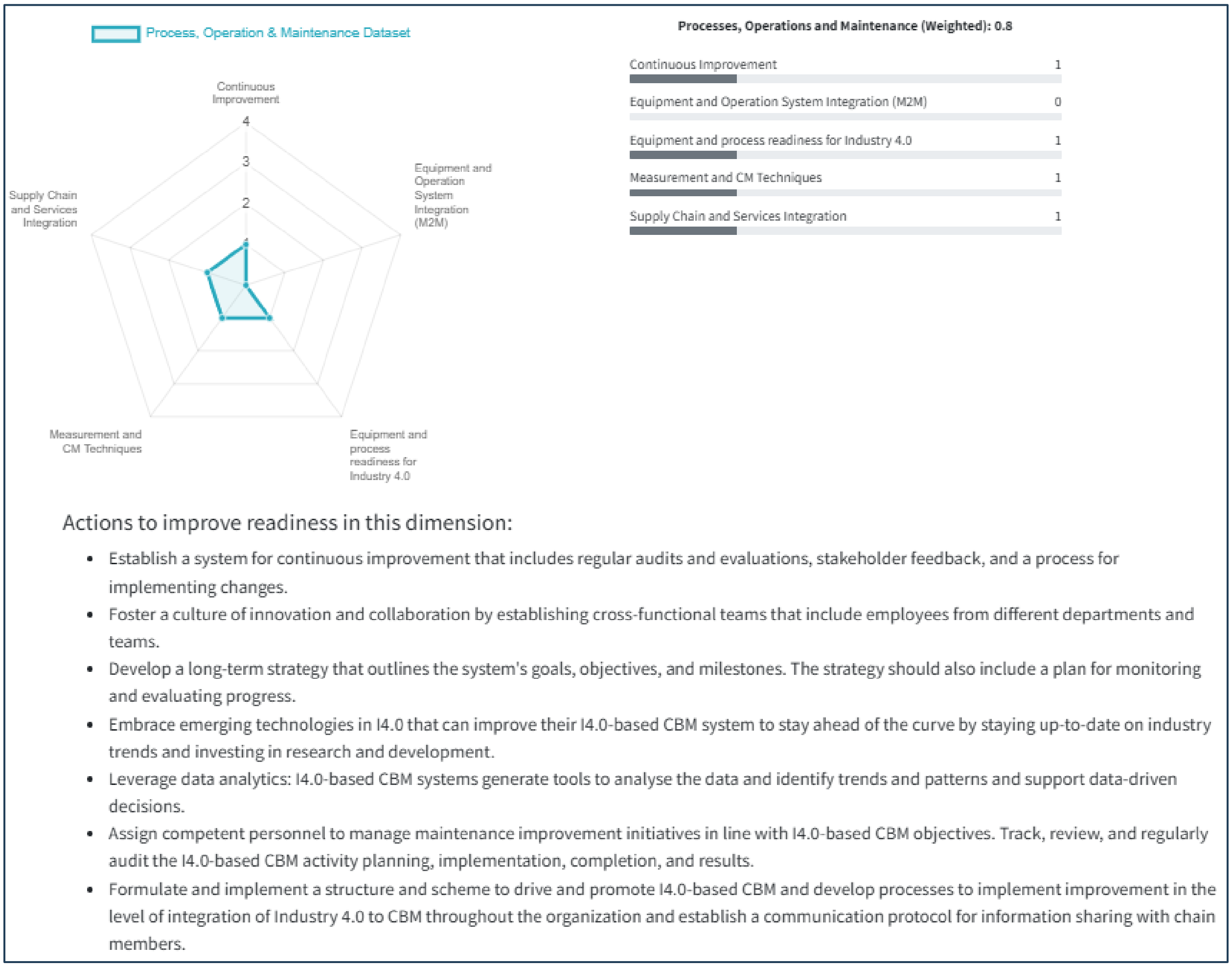

Figure 6. I4.0 Maturity Assessment Outcome for the dimension “Process, Operations and Maintenance”

To enhance efficiency in operations through I4.0-based CBM, the organisation should focus on advancing its initial recognition of I4.0's value into actionable strategies. This involves forming cross-functional teams dedicated to integrating I4.0 technologies with existing processes, fostering a systematic approach to continuous improvement, and developing robust measurement and monitoring frameworks. Additionally, prioritising machine-to-machine integration and a proactive approach to risk assessment can significantly improve the effectiveness and efficiency of CBM systems. By actively developing and implementing these strategies, the organisation can move beyond the initial stages to achieve higher levels of integration and operational efficiency with I4.0 technologies.

Sustainability (Environment): The "Sustainability (Environment)" readiness assessment indicates that the organisation is at a foundational level of integrating sustainability into its Condition-Based Maintenance (CBM) operations with an emerging recognition of its importance as shown in Figure 7. However, it lacks a fully integrated and formalised approach, particularly in leveraging Industry 4.0 (I4.0) technologies for enhanced sustainability practices. Specifically, Carbon Footprint and Preventive Environmental Damage are both at Level 1, reflecting a nascent stage with informal processes and an ad-hoc approach to sustainability efforts. In contrast, Resource Conservation is at a more advanced Level 2, showing some formal processes and partial implementation of I4.0, indicating initial steps towards resource-efficient practices.

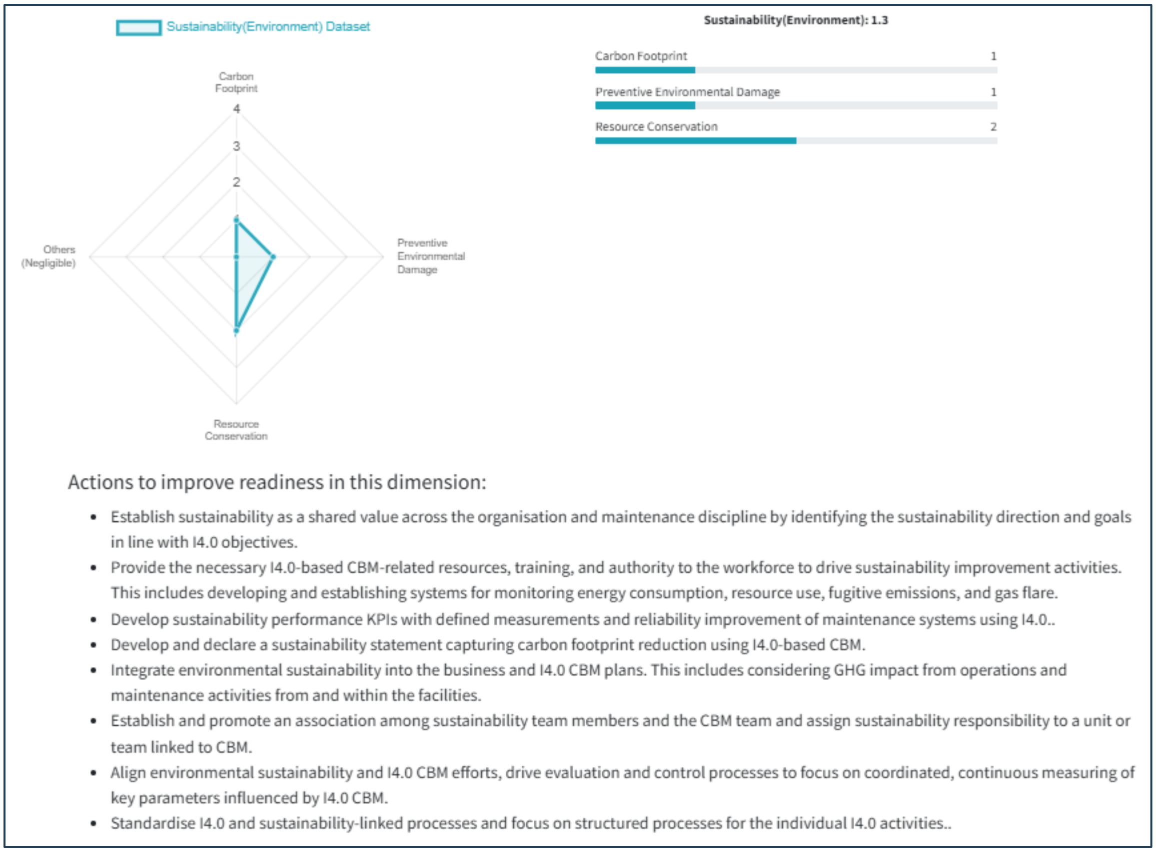

Figure 7. I4.0 Maturity Assessment Outcome for the dimension “Sustainability.”

The organisation is advised to focus on structuring and formalising its sustainability efforts. This includes leveraging I4.0 technologies to optimise resource use, reduce carbon footprint, and prevent environmental damage more effectively. The organisation can ensure a more comprehensive and efficient approach by promoting sustainability awareness within the workforce, standardising processes that integrate I4.0 and sustainability, and developing Key Performance Indicators (KPIs) to measure sustainability initiatives' effectiveness. This strategy enhances operational efficiency and aligns CBM practices with broader environmental sustainability objectives, creating a more resilient and responsible organisation.

People: The "People" dimension assessment for Industry 4.0 (I4.0) readiness in reveals that the organisation is at an initial stage of readiness, with all three assessed subdimensions—Culture of Change, Implementation Support, and Knowledge, Skills, and Competence Availability—rated at Level 1 (Figure 8). This level indicates a recognition of the need for a supportive culture, implementation support, and necessary competencies for I4.0 but without formalised processes or a systematic approach to development in these areas.

The organisation must focus on advancing the "People" dimension by cultivating a culture that actively embraces change and innovation, integrating comprehensive support systems for I4.0 implementation, and systematically developing the knowledge, skills, and competencies required for effective I4.0 integration. By fostering creativity and idea generation among employees, assigning skilled personnel to lead I4.0 initiatives, and providing structured competency development programs, the organisation can improve its readiness level.

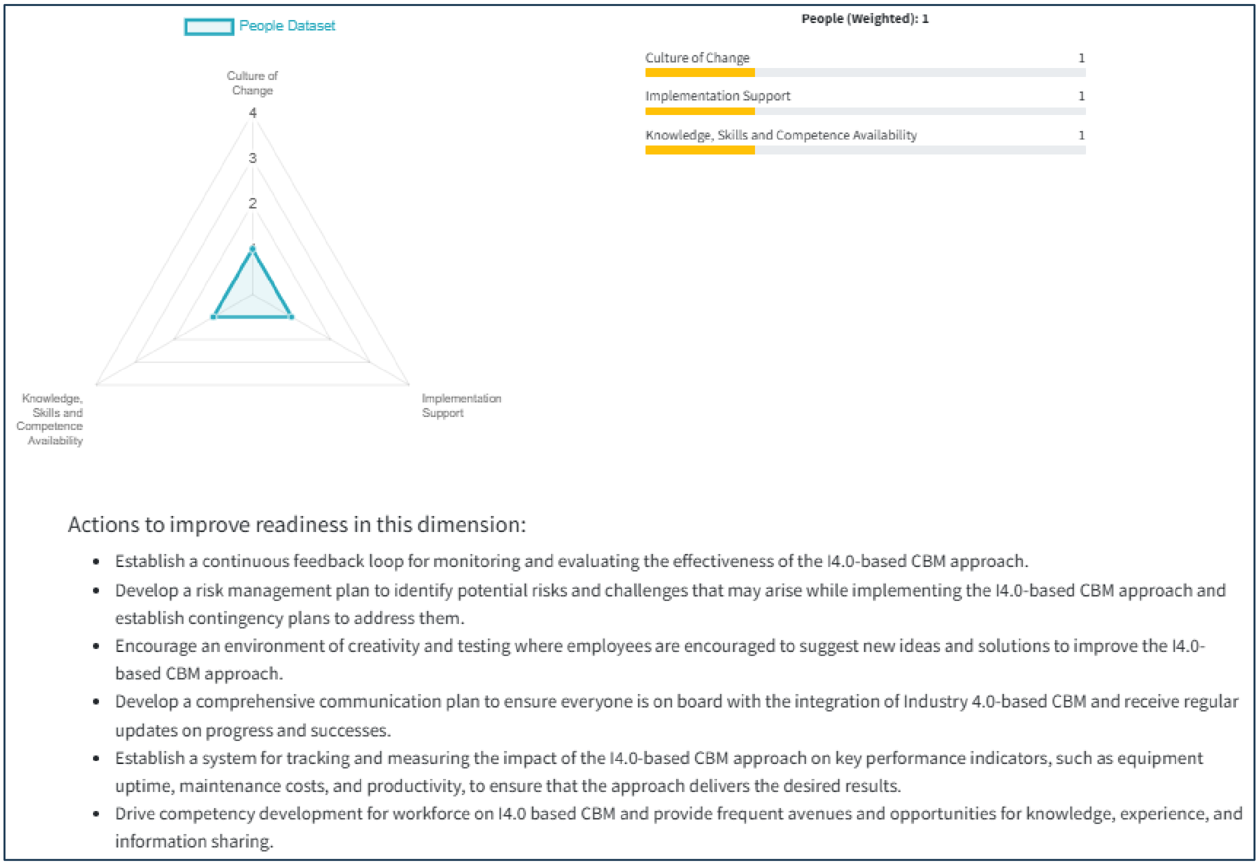

Figure 8. I4.0 Maturity Assessment Outcome for the dimension "People."

These efforts will enhance the effectiveness of I4.0 integration in CBM practices and contribute to the organisation's overall operational efficiency.

5.3 Summary of Action Research Outcome

Table 3 showcases a carefully selected list of initiatives stemming from the Industry 4.0 (I4.0) Maturity and Readiness Assessment, specifically tailored to enhance operational efficiency through I4.0-based Condition-Based Maintenance (CBM). The asset leadership has refined these initiatives into a focused action plan, prioritising the elevation of I4.0 maturity within the CBM framework. Utilising a well-established prioritisation tool, the team will systematically sequence these actions to ensure alignment with the primary objective of enhancing operational efficiency. The creation of a detailed roadmap is essential, outlining a structured approach to attain the desired I4.0 maturity in CBM progressively. This methodical strategy is pivotal in driving continuous improvement and laying a robust foundation for the seamless integration of I4.0 technologies, ultimately leading to superior operational performance.

Table 3. Formulated I4.0 Integration to CBM Action Plan

Dimension	Actions
Organisation	1. Establish a structured framework for continuous Improvement that regularly evaluates maintenance policies, strategies, and technologies. This framework should be supported by clear objectives, mission, vision, policies, and governance structures at every level of the organisation. 2. Prioritise investment in the necessary resources, training, and authority for the workforce to effectively integrate Industry 4.0 into CBM. This includes providing budget and financial strategies for implementing Industry 4.0-based CBM across all facilities.

	3. Foster a culture of collaboration and knowledge-sharing across all levels of the organisation and with external stakeholders to drive innovation and continuous improvement in its maintenance operations. 4. Integrate the I4.0-based CBM strategy with other business processes and systems to maximise the benefits of the technology. This includes integrating with enterprise resource planning (ERP) systems, supply chain management systems, and other critical business applications.
People	1. Establish a continuous feedback loop for monitoring and evaluating the effectiveness of the I4.0-based CBM approach. 2. Develop a risk management plan to identify potential risks and challenges that may arise while implementing the I4.0-based CBM approach and establish contingency plans to address them. 3. Encourage an environment of creativity and testing where employees are encouraged to suggest new ideas and solutions to improve the I4.0-based CBM approach. 4. Develop a comprehensive communication plan to ensure everyone is on board with the integration of Industry 4.0-based CBM and receive regular updates on progress and successes. 5. Establish a system for tracking and measuring the impact of the I4.0-based CBM approach on key performance indicators, such as equipment uptime, maintenance costs, and productivity, to ensure that the approach delivers the desired results. 6. Drive competency development for the workforce on I4.0-based CBM and provide frequent avenues and opportunities for knowledge, experience, and information sharing.
Industry 4.0 Solutions	1. Continuously monitor and improve the performance of the I4.0-based CBM system through the review of the key performance indicators (KPIs), training and providing resources to employees responsible for implementing and maintaining the facilities, and updating the system to keep up with technological advancements. 2. Promote a culture of continuous improvement and innovation to drive the success of the I4.0-based CBM system. 3. Establish a team or department dedicated to the goals and objectives of the I4.0-based CBM strategy to manage and oversee the implementation process. 4. Establish a clear communication plan to ensure that all stakeholders in the organisation are aware of I4.0 and its application to CBM. 5. Invest in training and development programs to equip employees with the necessary skills and knowledge in data analysis, cloud computing, IoT, and cybersecurity training. 6. Continuously monitor and evaluate the effectiveness of the CBM strategy and make adjustments as needed. 7. Establish a system for continuous feedback from employees, stakeholders, and customers to ensure that their needs and concerns are being addressed. 8. Implement a robust data management and governance framework to ensure the accuracy, reliability, and security of maintenance data and analytics.
Processes, Operations and Maintenance	1. Establish a system for continuous improvement that includes regular audits and evaluations, stakeholder feedback, and a process for implementing changes. 2. Foster a culture of innovation and collaboration by establishing cross-functional teams that include employees from different departments and teams. 3. Develop a long-term strategy that outlines the system's goals, objectives, and milestones. The strategy should also include a plan for monitoring and evaluating progress. 4. Embrace emerging technologies in I4.0 that can improve their I4.0-based CBM system to stay ahead of the curve by staying up-to-date on industry trends and investing in research and development. 5. Leverage data analytics: I4.0-based CBM systems tools to analyse the data, identify trends and patterns and support data-driven decisions. 6. Assign competent personnel to manage maintenance improvement initiatives in line with I4.0-based CBM objectives. Track, review, and regularly audit the I4.0-based CBM activity planning, implementation, completion, and results. 7. Formulate and implement a structure and scheme to drive and promote I4.0-based CBM and develop processes to implement Improvement in the level of integration of Industry 4.0 to

	CBM throughout the organisation and establish a communication protocol for information sharing with chain members.
Sustainability (Environment)	1. Establish sustainability as a shared value across the organisation and maintenance discipline by identifying the sustainability direction and goals in line with I4.0 objectives. 2. Provide the necessary I4.0-based CBM-related resources, training, and authority to the workforce to drive sustainability improvement activities. This includes developing and establishing systems for monitoring energy consumption, resource use, fugitive emissions, and gas flare. 3. Develop sustainability performance KPIs with defined measurements and reliability improvement of maintenance systems using I4.0. 4. Develop and declare a sustainability statement capturing carbon footprint reduction using I4.0-based CBM. 5. Integrate environmental sustainability into the business and I4.0 CBM plans. This includes considering GHG impact from operations and maintenance activities from and within the facilities. 6. Establish and promote an association among sustainability team members and the CBM team and assign sustainability responsibility to a unit or team linked to CBM. 7. Align environmental sustainability and I4.0 CBM efforts, drive evaluation and control processes to focus on coordinated, continuous measuring of key parameters influenced by I4.0 CBM. 8. Standardise I4.0 and sustainability-linked processes and focus on structured processes for the individual I4.0 activities.

A series of thematic observations were made during the action research with the Production Asset. These were analysed using a structured approach involving compiling, disassembling, reassembling, interpreting, and concluding. The observations revealed the organisation's current capabilities and the complex challenges and opportunities of integrating I4.0 with CBM. Notable opportunities include workforce upskilling, reallocating resources for better I4.0 support, proactive leadership engagement, upgrading facilities, cultivating an innovative culture, embedding CBM processes deeply within operations, investing in necessary tools and technology, and shifting to sophisticated data management systems. These insights provide a comprehensive view of the current state and will be instrumental in developing a targeted roadmap for advancing I4.0 integration within the CBM framework at Production Unit A, ultimately aiming to boost operational efficiency.

6. Conclusion

This study synthesises the findings from action research in the oil and gas upstream sector, specifically focusing on enhancing operational efficiency through Industry 4.0 (I4.0) based Condition-Based Maintenance (CBM) within Organisation A in the Niger Delta region of Nigeria. The research highlighted the critical contextual elements, facilitating factors, acknowledging presence of obstacles in applying the I4.0 maturity model and CBM framework. It demonstrated the CBM framework's applicability on improving operational efficiency and equipment reliability.

The maturity assessment revealed the Prroduction Unit A's initial readiness for I4.0, particularly noting a Level 1 maturity in 'People.' This underscores the need for structured development in knowledge, skills, and cultural adaptation to maximise I4.0 benefits. The research suggests a pathway for integrating I4.0 into CBM processes, emphasising the importance of workforce upskilling, infrastructure enhancement, active leadership, and fostering an innovative culture. However, the study acknowledges the limitations inherent in action research, including the context-specific nature of findings and the challenges in generalising results. Despite these, the insights and thematic observations provide a valuable foundation for Organisation A to advance its digital transformation and for the broader oil and gas industry to consider when adopting I4.0 technologies.

The study offers a detailed account and a strategic roadmap for enhancing operational efficiency through I4.0-based CBM (which can be referred to as CBM 4.0). It contributes to the discourse on digital transformation in the oil and gas sector, offering actionable insights and a framework adaptable by other industry players for their I4.0 initiatives.

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