An Industry 4.0 Maturity and Readiness for Condition-Based Maintenance in O&G Companies: a Delphi Study-Based Approach for Development and Validation

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Abstract

Maintenance remains one of the major concerns of the oil and gas industry. Recently, there has been an increasing drive to realise high maintenance efficiency following the various challenges faced in equipment and plant management. Considering these, this study proposes an I4.0 maturity or readiness model specifically tailored to assist the Oil & Gas upstream companies in reaching a higher level of I4.0 maturity in their condition-based maintenance approach, thereby improving the efficiency and reliability of equipment and productivity at large. The study presents a proposed validated maturity and readiness model that focuses on condition-based maintenance in the oil and gas sector, integrating I4.0 and some key dimensions (Organisation; People; Process, Operations and Maintenance; IT/IT Solutions; and Environmental Sustainability) and assessment scales (from 0 to 4) to determine readiness and maturity level. The proposed model developed from the existing literature is validated through a Delphi study using experts from academia and the Oil & Gas industry to review its content and suitability for practical application. The results of the Delphi approach offer the model and a tool that provides an opportunity to self-evaluate readiness to implement or integrate I4.0 into the condition-based maintenance strategy (I4.0-based CBM). Experts found the maturity model robust in its content, relevant, clear, and helpful for the pathway to I4.0 integration to CBM and adoption in the overall maintenance strategy of the oil and gas plant. Business leaders, maintenance heads, and plant managers with experience in the oil and gas upstream sector will find the model very suitable for the onward journey to I4.0 integration in condition-based maintenance, especially in oil-rich developing nations where a facility was used as a case study. The proposed new I4.0 maturity model tailored to integrating I4.0 into CBM in the Oil & Gas (O&G) industry is essential to the body of knowledge and practice.

Keywords
Industry 4.0, Condition-based maintenance (CBM), O&G industry, Delphi study, Maturity Model

1. Introduction

This paper aims to present a finalised framework for implementing industry 4.0-based Condition-Based Maintenance (CBM) initiatives in the oil and gas sector. The framework results from extensive research, incorporating a theoretical foundation informed by literature and expert insights from a Delphi panel. Condition-based maintenance has proven to be an effective strategy encompassing repairs, inspections, and verifications. At present, there is a conspicuous absence of industry-specific frameworks and models for implementing Industry 4.0-based Condition-Based

Maintenance (CBM) initiatives. The oil and gas companies, in particular, lack the necessary knowledge to implement such initiatives, underscoring the requirement for a comprehensive guide to successfully operationalise these within their specific sectors. A critical limitation in the oil and gas industry regarding CBM is the lack of a clear roadmap for companies to follow. Therefore, there is an urgent need to design and establish a validated framework that can provide a roadmap to execute CBM within oil and gas companies, using the principles of Industry 4.0. Addressing this need, this paper proposes a validated framework tailored to suit the practical requirements of users in the oil and gas industry. This study focuses on the practical implementation aspects of CBM integrating Industry 4.0 technologies in the oil and gas sector using an Industry 4.0 maturity model, which has been shown to enhance equipment and plant performance in various industries.

1.1 Objectives

A Delphi study was conducted to verify and validate a proposed framework and model for I4.0 integration into condition-based maintenance in the Oil and Gas upstream sector.

The conceptual framework, which received verification and validation from an assortment of industry experts in the academia and practitioners from the oil and gas as well as the manufacturing industry through a Delphi, has a 6-step process (see Figure 1), while the revised I4.0 maturity model for the oil and gas sector is shown in Figure 2.

The 6-step process for the framework starts with identifying the organisation's maintenance priorities. Then, the Industry 4.0 maturity assessment tool is used to evaluate the readiness for Industry 4.0 integration with CBM. The results are analysed to identify gaps and recommendations. The next step that follows this is implementing Industry 4.0 policies and strategies to address these gaps and creating an action plan and a deployment roadmap. This goes on to measuring and monitoring the impact of these I4.0 strategies, which helps to control and adapt the approach for continual improvement. The process is cyclic, with constant reassessment and adaptation for achieving full maturity in Industry 4.0-based CBM.

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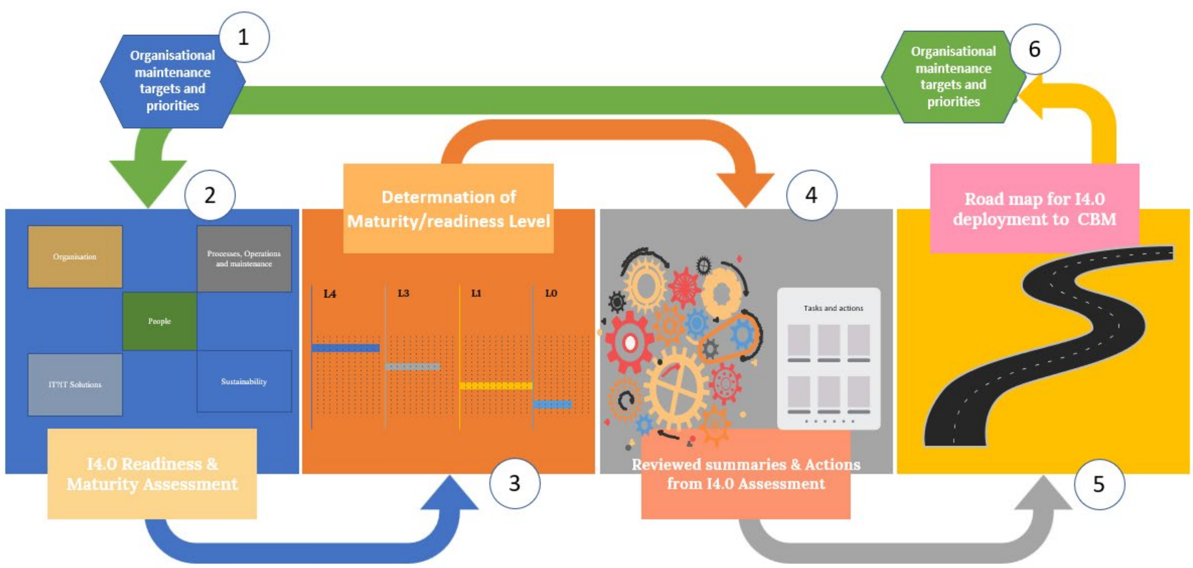

Figure 1. The proposed framework for Industry 4.) based CBM in the oil and gas sector

The maturity model consists of five key dimensions with 27 sub-dimensions and comes with an online self-assessment tool that organizations and maintenance teams can use to evaluate their readiness level and receive recommendations on the next steps. Key aspects of condition-based maintenance, such as data collection, data transmission, data storage, data analysis, prognosis, diagnosis, and decision support, are key focus areas for the dimensions.

Figure 2 . The Proposed I4.0 Maturity Model for CBM in the Oil and Gas Industry

2. Literature Review

Maintenance is a critical factor in production industries, and research has shown the effectiveness of adopting Condition-Based Maintenance (CBM) as a strategy (Swanson 2001). CBM has been widely employed in modern industries due to its manifold benefits (Rastegari et al. 2017; Rastegari & Mobin 2016; Shin & Jun 2015; Greenough & Grubic 2011) and can be characterised as a maintenance strategy that utilises real-time conditions of the system, gathered and analysed from real-time data, to make informed maintenance decisions (Alaswad & Xiang 2017). Observing equipment during operation can obtain precise and timely information about its condition, facilitating informed decision-making (Shi et al. 2020). CBM proves to be advantageous for managing high-value assets by identifying and rectifying issues before equipment damage occurs (Fathy 2017). Research has highlighted the varying degrees of CBM adoption across companies, with challenges such as appropriate tool selection, competency management, and data analysis persisting. Despite the gains and prevalent use of CBM, low maturity levels in complex technical CBM systems continue to be an issue (Bengtsson et al. 2004).

Studies have proposed models and methods aimed at enhancing CBM management, including the development of a CBM framework for cost-benefit analysis and the consideration of enabling factors for successful CBM implementation (Scarf 2007; Rastegari & Bengtsson 2015). In the oil and gas sector, CBM is being applied and has yielded production benefits (Mitchell 2011). However, challenges exist in CBM implementation for pipeline systems, such as planning complexities and high maintenance costs (Parvizsedghy et al. 2015). The implementation of CBM in the manufacturing and oil and gas sectors has revealed comparable results, although standards may differ.

Industry 4.0, representing an evolution in manufacturing, integrates existing standards with technological trends, including artificial intelligence, to optimise production performance (Ramakrishnan et al. 2019). While limited application of Industry 4.0 principles has been observed in the oil and gas industry, investigations into applying smart maintenance to CBM have shown promise in enhancing safe operations and increasing availability (Marhaug & Schjolberg 2016). Industry 4.0 has the potential to significantly improve CBM, leading to enhanced production efficiency and reduced downtime (Spendla et al. 2017; Krupitzer et al. 2020). Research emphasizes the crucial role of CBM in the era of big data, suggesting its incorporation into large manufacturing companies to improve product quality and practices (Spendla et al. 2017; Ramakrishnan et al. 2019). Overall, research has provided frameworks, models, and insights to enhance CBM management and implementation, showcasing its importance in various industries.

2.1 Delphi Approach

The Delphi method is an interactive forecasting technique that hinges on the collective insights of an expert panel. This approach begins with a series of questionnaires distributed over multiple rounds. After each round, the facilitator summarises the experts' judgments and rationale, maintaining anonymity (Flanagan et al. 2016; Spranger et al. 2022; Linstone & Turoff 2002). Encouraged by the others' responses, experts revise their answers to narrow down the range of responses and align on a consensus. This iterative process continues until a defined criterion is met, such as a specific number of rounds, consensus attainment, or result stability. The consensus result is usually decided by the median, mean, or Standard Deviation (SD) scores of the final round (Chuenjitwongsa 2017)(Hasson et al. 2000) (Hsu & Sandford 2007)

This technique is ideal for structuring group communication to address complex issues, as it helps harmonize expert opinions or stimulates ideas for further investigation. Unlike traditional focus groups, the Delphi approach creates a remote focus group where experts contribute independently, uninfluenced by the group dynamics or personalities (McLean et al. 2023; Iñaki et al. 2006). This independence promotes honest, open inputs, leading to a statistical response for a comprehensive opinion analysis (Hsu & Sandford, 2007); (Campos-Climent et al. 2012). Successful execution of the Delphi approach rests on the expert panel's apt selection, and expertise and experience take precedence over panel size (Wakefield & Tom 2014). Ensuring a balanced mix of roles and experiences in maintenance, digitalization, and I4.0 across academia and industry for a study like this is crucial for robust outcomes. Generally, the Delphi method begins with an open-ended phase, gradually narrowing down to quantitative results in subsequent rounds. A facilitator defines criteria to evaluate survey feedback, often via a Likert scale, and decides if further rounds are needed based on the consensus level.

3. Methods

This study primarily targets the integration of Industry 4.0 (I4.0) technologies into Condition-Based Maintenance (CBM) within the oil and gas sector, examining also, existing I4.0 maturity models. The observed gaps within these maturity models necessitated the development of a new I4.0-influenced model explicitly designed for CBM, followed by the model's validation. The study unfolded in three stages. First, a systematic literature review initially provided a foundational understanding of Industry 4.0, Condition-Based Maintenance (CBM) and I4.0 maturity models. Next was an online survey and interviews with industry professionals which added practical perspectives to these theoretical findings. Then, a critical review of existing maturity models identified gaps and areas for improvement. These steps informed the Delphi study, where the proposed model was refined by a panel of experts, ensuring its validity and applicability in the industry. Further details are provided in Sections 3.1 to 3.3.

The Delphi method, known for its systematic forecasting process, involves a panel of experts who answer questionnaires in multiple rounds. This was employed for this study however, an online variant of the Delphi method was used, providing an efficient and anonymous platform for expert collaboration and consensus-building. The validation process through the Delphi method helped ensure that our I4.0-based CBM framework and maturity model is well-grounded in expert knowledge and can address the identified gaps in existing models. Upon the successful validation of our maturity model, this study proceeds to introduce a novel framework that serves as a guideline for implementing CBM in the oil and gas sector, grounded on the technologies of I4.0. This proposed framework addresses the requirements for a successful transition to I4.0-based CBM in the oil and gas industry, providing a practical guide for companies looking to integrate these advanced technologies into their maintenance practices.

3.1 Research Phase 1: Systematic Literature Review

This study commenced with an extensive literature review, carefully evaluating the upstream oil and gas (O&G) sector's unique requirements for Industry 4.0 implementation. Existing Industry 4.0 maturity models (MMs) were critically assessed to determine their suitability to the upstream O&G sector, identifying significant research gaps. The models, as they currently stand, do not entirely meet the specialized needs of the O&G sector. The study utilized a systematic literature review approach, a well-regarded method for assessing and interpreting all available research information pertaining to a particular subject. This approach was intended to discern evident gaps in existing models, which could inform the adaptation or creation of an Industry 4.0 MM tailored for the upstream O&G industry.

The review scope was confined to literature published between 2015 and 2021 inclusive. The systematic review methodology employed in this study adhered to the steps laid out in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement to ensure a comprehensive, reproducible, and high-quality review.

The PRISMA statement, introduced by Moher et al. (2009), offers a standardized procedure for conducting and reporting systematic reviews and has been universally recognized for its robustness and effectiveness.
The main discoveries of the literature review revolved around the lack of robustness of the current MMs concerning O&G sector requirements, the absence of readiness assessments or O&G-specific MMs, discrepancies in the dimensions and levels across various MMs, and a deficiency in model validation.

3.2 Research Phase 2: Online Survey and Interview

The study involved an empirical investigation into the integration of Industry 4.0 technologies into Condition-Based Maintenance (CBM) practices in a multinational upstream oil and gas company in Nigeria. It utilized a combination of a survey and virtual interviews to gather data. A questionnaire survey was conducted via Google Forms, with a standardised set of both closed and open-ended questions. These were grouped under key themes, including Facility Operation/Maintenance Philosophy, Condition-Based Maintenance, and Industry 4.0 Application. The survey targeted maintenance staff and their support teams in Oil and Gas companies in Nigeria, particularly those that had implemented CBM for over a decade and had begun their journey towards digitalization. From this, a total of 167 complete responses were received and analyzed.

The interviewees occupied various roles within the maintenance department, providing a rounded perspective on the issues around I4.0 implementation. Like the survey, the interviews were grouped into themes and lasted between 30 and 45 minutes each. The research included an in-depth examination of the organization's current CBM strategy and its initial steps towards I4.0 Implementation. This analysis identified major barriers to the integration of Industry 4.0 technology were identified, including high costs, limited technological resources, and a lack of competence in Industry 4.0 technology.

This allowed the research to prioritize these obstacles and devise strategies to overcome the most pressing ones, thereby improving the prospects for the successful integration of Industry 4.0 technologies into the CBM strategy.
Based on the findings, the study proposed several strategies, including the adoption of an Industry 4.0 maturity model to guide implementation, upgrading facilities and equipment to be compatible with Industry 4.0 technologies, and initiating educational programs to upskill the organization's staff.

3.3 Research Phase 3: Critical Literature Review

In this stage of the study, an in-depth assessment of current implementation frameworks and models was conducted, identifying their respective advantages and drawbacks. Using these strengths along with the themes and variables verified in the initial two research phases, the foundation for a new CBM framework and maturity model was created. A shared characteristic observed in existing frameworks was the utilization of a common structure for maturity models having key scopes or dimensions, sub-dimension and maturity levels with the incorporation of an assessment tool into the model.

The existing Industry 4.0 maturity models fell short of this research's objectives, which included the following:

1. A model tailored specifically to the oil and gas industry;
2. A model that responded to the key requirements of the oil and gas industry, as determined from the systematic literature review conducted in the first phase of the research; and
3. A model aimed at facilitating the integration of Industry 4.0 into condition-based maintenance in the oil and gas sector rather than a generic model.

The outcome of this research phase was the creation of a new Industry 4.0 maturity model and conceptual framework specifically tailored for condition-based maintenance within the oil and gas industry. The proposed framework comprises six steps, as illustrated in Figure 1 and Section 1.1. To ensure academic rigor and practical applicability, this model and framework underwent a review by a panel of industry and academic experts via a Delphi study. This combined approach of the initial literature review and subsequent Delphi study mirrors the methodology employed by Hinckeldeyn et al. (2015), asserting that it provides a more harmonized understanding and comprehensive overview.
The use of a Delphi study supplements the existing research, adding an extra layer of validation and triangulation to the results, which aligns with the methodological approach of previous research (Iñaki et al.2006).

4. The Delphi Study

In this study, 29 participated and completed the survey, establishing an impressive response rate consistent with Delphi studies (Ab Latif et al. 2016; Veugelers et al. 2020). Selection and willingness of panelists are crucial for Delphi studies (Green et al. 1999); (Nasa et al. 2021); (Colton & Hatcher 2004), hence experts from different industries, academic backgrounds, and regions were invited to gather rich data. The selection of potential panel members was grounded in well-defined criteria, including a minimum of five years of experience in plant operations and maintenance in the industry and active engagement in research with contributions to high-impact journals in the fields of Industry 4.0, digitalisation, and maintenance management. The panel members held various roles in the industry, ranging from Oil and gas plant managers to academic researchers specialising in digitalisation, Industry 4.0, and maintenance.

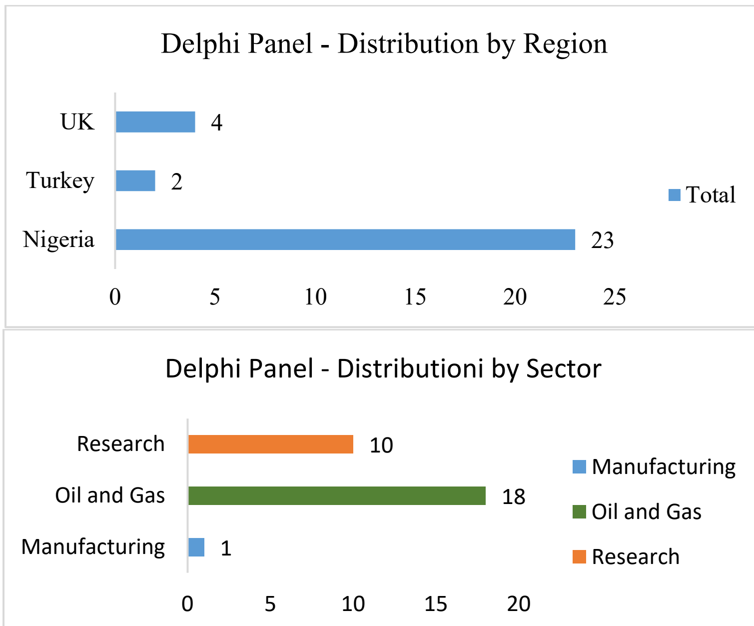

Figure 3. Descriptive statistics of expert Delphi panel engaged in the study

Panelists were contacted via email and represented a variety of oil and gas plants and academic institutions primarily located in Africa, Europe, and Asia. See Figure 3 for the panel distribution by region. The key points and activities in this Delphi study are graphically summarized in Figure 4.

Using a convergent parallel mixed-method design, the study employed both quantitative measures (Likert scale for consensus analysis) and qualitative measures (open-ended questioning for thematic synthesis). This dual approach was used to numerically assess the levels of expert agreement on various aspects of the conceptual framework and to allow experts to freely share their views and improvement suggestions. The combination of these methods was noted to take advantage of the strengths of both approaches and enrich the data collected, leading to more balanced perspectives on the phenomenon under investigation (Leech & Onwuegbuzie 2009), (Tranfield et al. 2003). The survey was created on SmartSurvey, a user-friendly platform with robust data collection capabilities (Nair & Adams 2009).

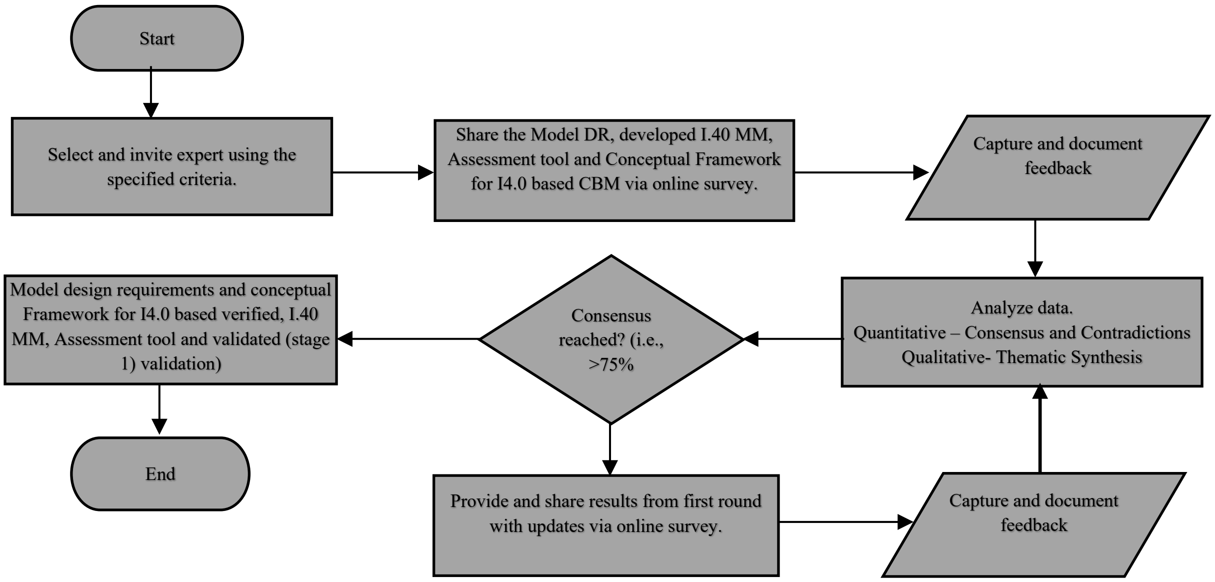

Figure 4. Delphi study verification, validation and analysis process

A pilot test was conducted to refine the survey according to the research objectives before the commencement of the Delphi study. The Likert scale, four categories without a neutral option (Strongly Disagree, Disagree, Agree, Strongly Agree), was used to ensure clear responses (Allen & Seaman 2007). However, in certain instances, for instance, during the determination of the relative importance of the model dimensions, a more granulated 10-level Likert scale was employed. The evaluation criteria for the proposed conceptual framework and model assessment tools included Correctness, Completeness, Clarity, and Conciseness (Al-Debei & Fitzgerald 2009); (Petter et al.2008).

Reaching a consensus among experts, achieved through verification and validation, is a fundamental aspect of Delphi studies. Different studies have various ways of defining this, including quantifying uncertainty levels, achieving above a certain percentage of agreement, and assessing the extent of expert feedback (Hsu & Sandford 2007; Diamond et al. 2014; Barrios et al. 2021; Niederberger & Köberich 2021). This study opted for the per cent agreement approach, widely used in Delphi studies, as it provides an objective definition of consensus (Diamond et al. 2014). For this study, A consensus was considered achieved when over 75% of expert participants indicated agreement (score of 3 or above). Expert feedback with reference to the practicality, feasibility and content of the Maturity assessment tool was also captured to validate the maturity assessment tool developed as part of a key step of the implementation procedure for the frame work.

5. Results and Discussion

Expert feedback was solicited on the different sections, as they are integral to formulating an effective management solution for I4.0 integration. All conceptual aspects of the framework for integration of Industry 4.0 to CBM in the oil and gas industry achieved expert consensus (above 75% agreement) in the first round. However, some model improvement areas were identified through qualitative thematic feedback analysis on areas with lower consensus. These were addressed and recirculated to the Delphi panel for additional feedback and confirmation.

5.1 Verification and Validation Outcomes (Quantitative)

As part of the plan to validate fundamental aspects of the study, the Delphi panellists were asked to indicate their level of agreement or disagreement with the design requirements that formed the bedrock of the model design and the subdimensions as relevant and instrumental for I4.0 integration to CBM for equipment reliability improvement. The levels of agreement captured from the Delphi panel specialists are presented in Figures 5 and 6.

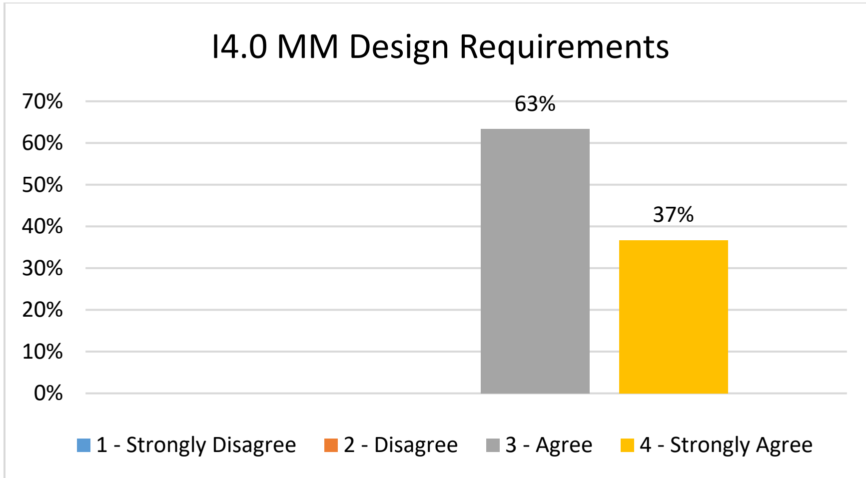

Figure 5. Expert agreement levels regarding the design requirement of the Industry 4.0 maturity model

The consensus rate by the Delphi panellist was 100% (sum of % Agree and Strongly Agree) on the design requirements (Figure 5). This high consensus rate suggests a high level of agreement among the experts on the design requirements implying a robust or reliable result.

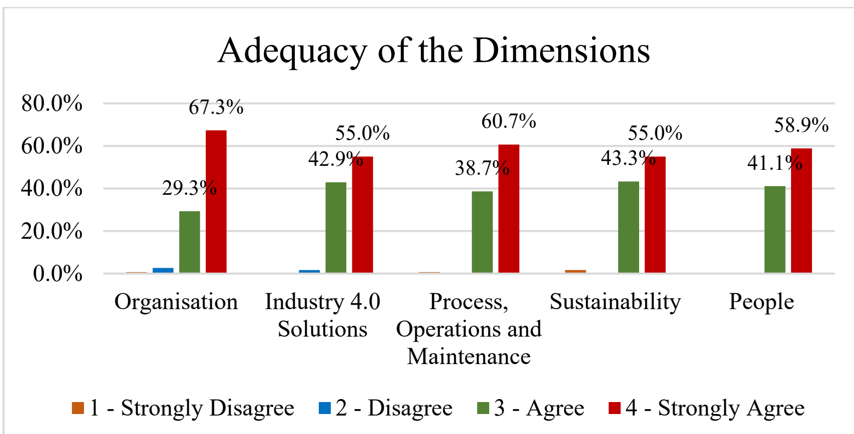

Figure 6. Expert agreement levels regarding the Dimensions of the I4.0 MM for CBM

Figure 6 shows the agreement level of the Delphi participants on each of the five dimensions. Each sub-dimension was considered significantly important for integrating I4.0 into CBM for equipment and reliability improvement in the oil and gas sector, as indicated by the level of agreement by the Delphi panellists. The consensus was greater than 96% for all five dimensions, with the dimensions 'People' having a consensus of 100% and 'Organisation' having the least consensus value of 96.7%.

The Delphi panel of experts further evaluated the sub-dimensions, ranking their relative importance for the integration of Industry 4.0 with Condition-Based Maintenance in the oil and gas industry. Using a scale from 1 (not important) to 10 (extremely important), the experts identified all dimensions as important, with rankings greater than 7.5 indicating a ranking above 'moderate importance'. Table 1 showcases these relative importance ratings, affirming the relevance of all dimensions as per the panel's assessment. Least rating is 7.67 for the dimension 'Sustainability', which falls on the upper end of the 'moderately important' category of the scale, with 'Organisation' (8.270) and 'Process, Operations and Maintenance' (8.26) having the highest ratings falling under the 'extremely important' category of the scale.

Table 1. Relative importance ranking for the dimensions.

S/No	Dimensions	Rating
1	Organisation	8.27
2	People	8.16
3	Industry 4.0 Solutions	7.98
4	Process, Operations and Maintenance	8.26
5	Sustainability	7.67

These findings corroborate the propositions of the conceptual framework, suggesting the potential for achieving I4.0-based CBM in the oil and gas sector using the I4.0 maturity model, which incorporates an embedded assessment tool and recommendations based on identified maturity levels. The results align with similar studies for other industries, reinforcing the importance of maturity models in I4.0 implementation and the ensuing enhancement of equipment reliability and performance where they are utilised.

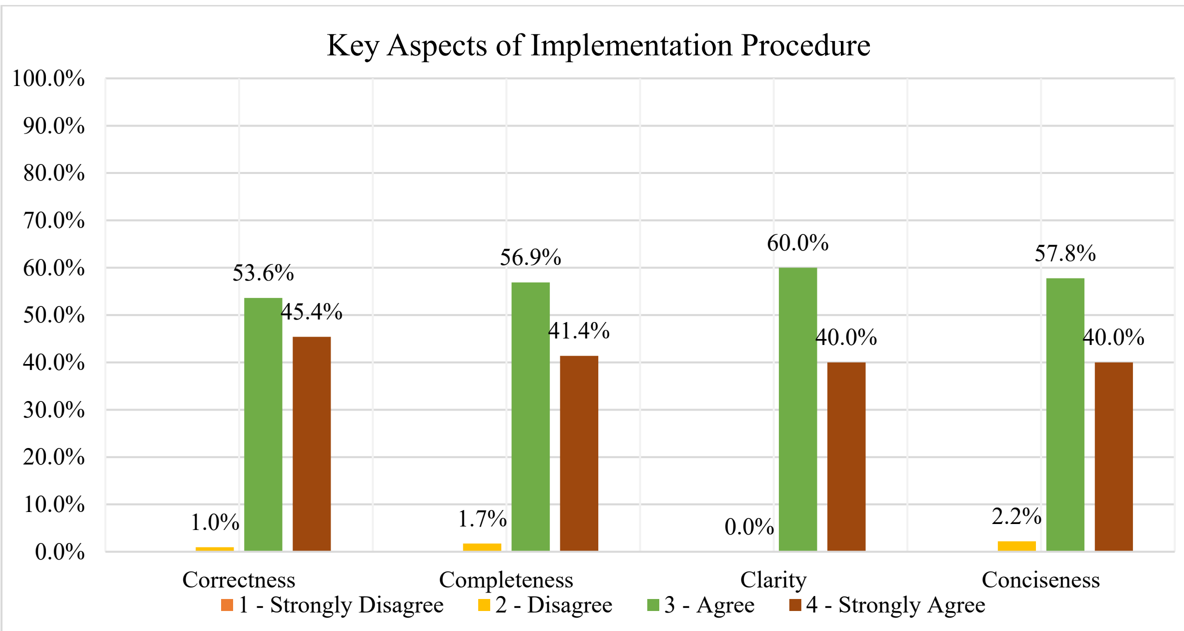

Figure 7. Expert agreement levels on key aspects of the proposed framework implementation procedure

As part of the study, the Delphi panellists were asked to indicate their level of agreement or disagreement with the various essential aspects of the proposed conceptual framework. Figure 7 portrays the degree of consensus obtained from the Delphi panel experts. The distinctive elements that make up the essential validation categories—correctness, completeness, clarity, conciseness, and supply chain deployment—are amalgamated to present an encompassing perspective of each category. Table 2 below outlines the various features that constitute the key validation categories of correctness, completeness, clarity and conciseness, along with high consensus levels established for each.

Table 2. Expert consensus analysis on the correctness, completeness, clarity, and conciseness aspects of the proposed framework implementation procedure

Correctness	Rating
The integration of Industry 4.0 to condition-based maintenance in the oil and gas upstream sector is much needed to ensure improvement in equipment reliability and production performance.	100%
The components of the framework are aligned with established theories and methodologies.	100%

The I4.0 technologies adopted in this framework are compatible with integration into CBM of facilities for oil and gas production.	97%
The step-by-step structure utilised is feasible for this type of framework for driving continual I4.0 embedment to CBM, full maturity and ultimate performance improvement in the facilities.	100%
The framework facilitates the measurement and improvement of organisational equipment reliability and equipment performance.	97%
The framework facilitates managerial decision-making and action deployment with reference to I4.0. integration to CBM and facility reliability improvement	100%
The framework contributes to the body of knowledge through a novel concept integrating Industry 4.0 with Condition-based maintenance	100%
Completeness	
The framework is complete to drive integration of Industry 4.0 into condition-based maintenance in the oil and gas facility	100%
The framework covers all essential steps necessary to drive continual improvement in equipment reliability	97%
Clarity	
The description of the components aligns with the framework	100%
The description of the framework is explicit and clear	100%
The application of the framework is feasible	100%
Conciseness	
The framework is neither complex nor oversimplified	93%
The interconnections between the components of the framework are clear	100%
The framework is of practical use to the oil and gas industry	100%

Further to this was the authentication of the questions and indicators formulated for the maturity evaluation on the five dimensions and verification of the practical aspects of the developed maturity assessment tool. The expert Delphi panellists initially indicated their views on whether the evaluation questions and indicators, within their area of expertise, precisely and comprehensively depicted the relevant dimensions under consideration for assessing maturity levels by choosing among "yes", "no", or "I am not an expert" options. The results of this quantitative assessment are exhibited in Figure 8, and the corresponding consensus outcomes are itemized in Table 3.

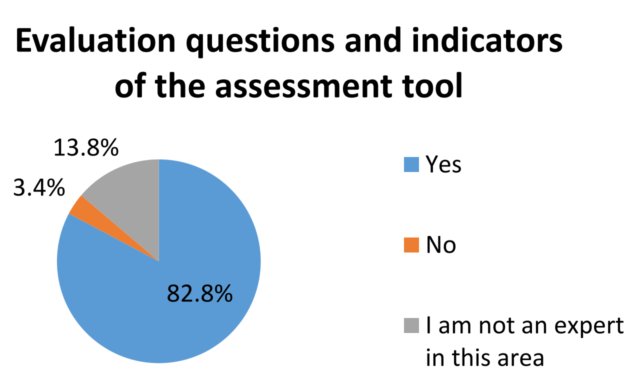

Figure 8. Expert agreement levels regarding the questions and indicators defined for I4.0 MM dimensions.

Following this, experts were requested to express their levels of agreement on various critical attributes of the developed assessment tool, such as enabling evaluation of the prospective integration of Industry 4.0 to condition-based maintenance facilities in the oil and gas upstream facilities, enabling alignment of the various aspect of CBM modules (CBM modules) with industry 4.0 technologies for integration, feasibility and practical utility in the O&G industry). The results from this inquiry are illustrated in Figure 9.

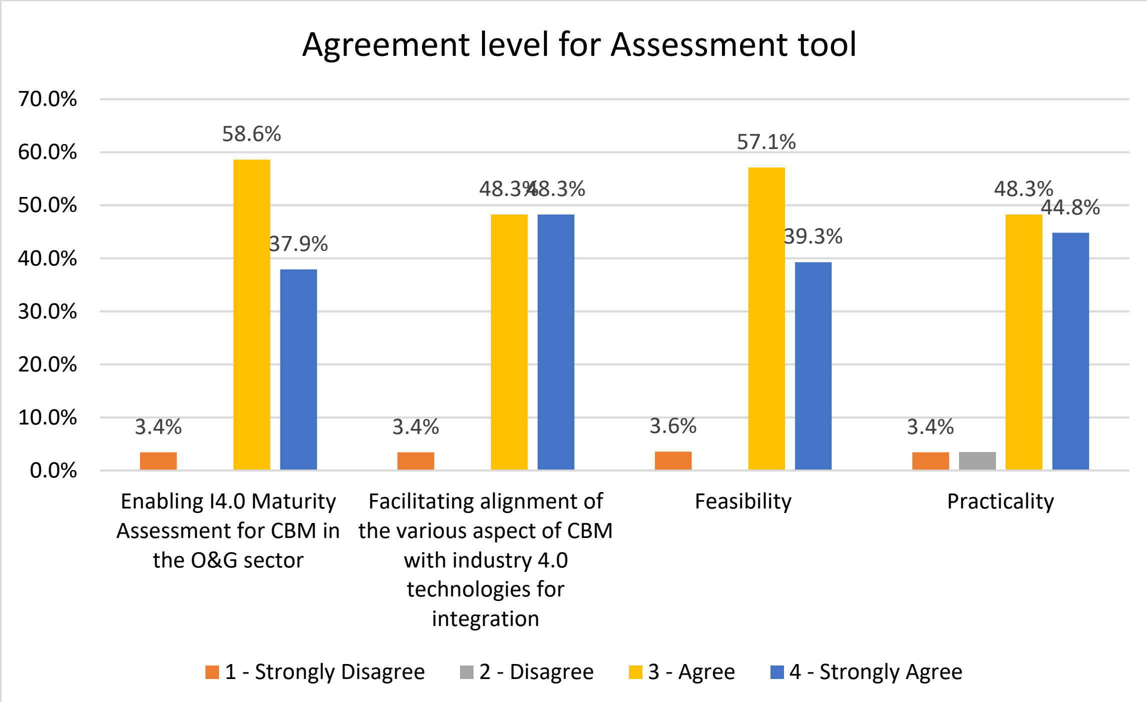

Figure 9. Expert agreement levels on the various validation aspects of the Maturity Assessment tool developed.

A high consensus rate, as shown in Table 3, among panelists, were outcomes for the evaluation questions and indicators used for the assessment tool and the various aspects of the assessment of the tool. The high consensus among panelists underscores the maturity assessment tool's value for evaluating the readiness and capability of facilities to adopt and benefit from Industry 4.0 technologies. It validates the tool's ability to examine the maturity level of Industry 4.0 in CBM, which is crucial for successful integration. The consensus highlights the tool's practicality and real-world applicability, suggesting its potential to significantly aid the planning, implementation, and evaluation of Industry 4.0 integration efforts in the Oil and Gas upstream sector.

Table 3. Expert consensus analysis on the practical relevance of the Maturity Assessment tool developed.

Aspect	**Rate**
The maturity and readiness model enables maturity assessment of the prospective integration of Industry 4.0 to condition-based maintenance facilities in the oil and gas upstream facilities	96.6%
The maturity and readiness model enables gauging alignment of the various aspect of CBM (CBM modules) with industry 4.0 technologies for integration	96.6%
The application of the maturity model and readiness assessment tool is feasible.	96.4%
The assessment tool is of practical use to the oil and gas upstream industry	93.1%

5.2 Verification and Validation Outcomes (Qualitative)

The experts freely articulated their thoughts, recommendations, and critiques via open-ended questions, offering explanations for any disagreements with specific aspects of the implementation procedure for the framework and

suggesting potential improvements. The qualitative data was subsequently methodically analysed using the five key stages—compiling, disassembling, reassembling, interpreting, and concluding—for thematic coding and synthesis, as proposed by Castleberry & Nolen (2018).
Similarly, qualitative feedback regarding the assessment tool and its evaluation questions and indicators was collected from the Delphi panel. This feedback provided potential enhancement suggestions and additional sub-dimensions deemed vital for defining and assessing the industry 4.0 maturity model synthesised under the conceptual framework. We adhered to the systematic thematic synthesis process previously mentioned to ensure a structured and thorough analysis, interpretation, and conclusion of the qualitative feedback gathered for the developed maturity assessment tool, which is not only designed to enable the maturity assessment in I4.0 dimensions but also to provide a platform for formulating improvement actions for the integration of I4.0 to CBM. Table 4 details the qualitative feedback derived from various segments of this study, encompassing additional sub-dimension suggestions, themes, and executed actions.

Table 4. Key suggestion themes and actions from the study implemented.

Aspect	Feedback	Suggestion theme	Response / Action
Conceptual Framework - Correctness	"I think you need to validate this framework in a real environment before some of the above assertions can be accepted."	A pilot study is necessary to showcase the practical implementation facets.	In the following phase of the research, a real-world action research study was conducted to showcase the utilisation of the diagnostic tool and implementation procedure, highlighting the significant practical implementation aspects.
Conceptual Framework - Completeness	"I think there are other essential steps and features that would benefit the framework."	A pilot study is necessary to showcase the practical implementation facets.	
Conceptual Framework - Clarity	"I think at a first glance it may seem a bit complicated (mainly for SMEs), but the description is helpful, and there are very good elements in there."	A pilot study is necessary to showcase the practical implementation facets.	
Dimension - industry 4.0 solutions	"I think you should explore the benefit of other emerging technologies, such as AI and Blockchain technologies, for CBM."	Additional sub-dimensions required	In response to the feedback, two additional sub-dimensions have been incorporated into the Maturity Model and Assessment Tool under the "Industry 4.0 Solutions" dimension.
Dimension - industry 4.0 solutions	"I strongly agree with the criteria, but I think AI would play a very important role in this category."	Additional sub-dimensions required	
Dimension - Sustainability	"Agree with those dimensions and would include additional capabilities. One thing that I4.0 tools could do is helping with the measurement of Carbon, Water, Electricity, Gas, etc. Also, it could help in the decision-making process and create automatic reports."	The subdimensions are required to be more specific / less subjective, or generic.	
Dimension - Sustainability	"Environment is too general. Waste reduction, energy consumption etc., are all specific and individual sub-dimensions, the applicability of which need to be considered and implemented specifically into your framework."	Review and further breakdown of the subdimension "Environment" as it relates to the study	Updated the subdimensions under Environment (sustainability). Now having a total of 3 as against two subdimensions. The maturity Model and Assessment Tool were updated in response to the feedback.
Dimension - Organisation	"Communication and collaboration is a highly significant factor, no	More emphasis required	One additional sub-dimensions have been

	doubt about that. However, in its current form, having both the internal and external stakeholders under one line feels too high level. Workforce engagement may need to be dealt with separately, as it would be critical for I4.0 implementation."	on the clear separation of internal and external stakeholders under communication and collaboration	incorporated into the Maturity Model and Assessment Tool under the dimension "Organisation", differentiating communication and collaboration with internal and external stakeholders.
I4.0 Maturity Assessment tool	"The use of artificial intelligence for maintenance valuation in condition-based maintenance"	Additional sub-dimensions required	Implemented under the dimension "Industry 4.0 Solutions" as mentioned in this table

While high consensus was reached on diverse facets and indicators of the original tool design, the findings from the thematic synthesis prompted further refinement of the tool, incorporating valuable insights and recommendations from the expert panelists.

Table 3 illustrates the qualitative analysis that unveiled several salient themes for further development. These insights prompted a revision of an aspect of the Industry 4.0 maturity model marked with asterisks (**) in Figure 2 and updating of the assessment tool, which included additional evaluation questions and indicators in line with the suggestions by the Delphi panellists. All updates were then recirculated to the Delphi panel for validation. A total of nine valid suggestions emerged and were incorporated, providing potential avenues to enhance the proposed framework and model. This incorporation significantly enhanced the tool's objectivity and applicability, transforming it into a robust maturity assessment instrument for seamless integration of Industry 4.0 with CBM in the oil and gas sector.

The recommendation for practical demonstration purposes was also highlighted as significant. This suggestion emphasises the value of seeing the tool in action, giving users a tangible sense of its functionality and effectiveness. Implementing this feedback would help validate the tool's efficacy in real-world scenarios and provide an opportunity to identify and address any potential usability issues before broader deployment. This hands-on approach is fundamental in bridging the gap between theoretical design and practical application, reinforcing user confidence and facilitating broader acceptance of the tool in its intended context.

Ultimately, it was of significant note that the Delphi experts reached a unanimous consensus on several aspects of the proposed framework. They agreed that integrating Industry 4.0 with condition-based maintenance in the oil and gas upstream sector is vital for enhancing equipment reliability and production performance. The experts found the framework to be aligned with established theories, feasibly structured, and comprehensive. They recognized its contribution to knowledge by innovatively integrating Industry 4.0 with condition-based maintenance and found its application feasible. Its explicit and clear descriptions, interconnections, and practical utility for the oil and gas industry were also unanimously acknowledged.

6. Conclusion

This study presented the verification and preliminary validation processes executed for an I4.0 maturity model and the corresponding assessment tool, a conceptual framework of Industry 4.0 based Condition Based Maintenance (CBM) having a six-step process, each step leading to a specific outcome that moves an organisation further towards implementing Industry 4.0 in condition-based maintenance (CBM). These processes were carried out via feedback from an international Delphi panel of subject matter experts boasting a broad range of industrial, technical, and regional expertise. Consequently, a substantial degree of consensus was achieved concerning the conceptual framework, its implementation elements (correctness, completeness, clarity, conciseness), and the Industry 4.0 maturity model proposed for CBM in the oil and gas industry.

All identified dimensions within the model received high importance ratings from the expert Delphi panel, with average scores ranging from 7.67 to 8.27 (on a scale where 10 signifies extreme importance). The dimensions and subdimensions under "Process, Operations and Maintenance", "People", and "Organization" were recognized as the three most important dimensions for integrating Industry 4.0 into CBM, echoing the viewpoints of numerous scholars in the existing literature.

While consensus was reached regarding all facets of the implementation procedure for the framework, Industry 4.0 Maturity Model and assessment tool, several opportunities for improvement were identified through the qualitative feedback. Consequently, these enhancements were integrated into the Maturity Model and Framework, leading to a more robust Industry 4.0 maturity assessment for CBM and fostering more effective integration of Industry 4.0 into CBM for optimal improvement in plant equipment performance and reliability.

A summary of the Delphi study findings and the executed improvements was shared with the Delphi panel participants. All participants acknowledged these modifications, affirmed the study's outcomes, and enabled the conceptual framework's verification and initial validation.

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