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Abstract:	

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Abstract

Purpose – This study investigates the integration of Industry 4.0 technologies with Condition-Based Maintenance (CBM) in upstream oil and gas operations, focusing on developing countries like Nigeria. The research identifies barriers to this integration and suggests solutions, intending to provide practical insights for improving operational efficiency in the oil and gas sector.

Design/methodology/approach – The study commenced with an exhaustive review of extant literature to identify existing barriers to I4.0 implementation and contextualize the study. Subsequent to this foundational step, primary data are gathered through the administration of carefully constructed questionnaires targeted at professionals specialised in maintenance within the upstream oil and gas sector. A semi-structured interview was also conducted to elicit more nuanced, contextual insights from these professionals. Analytically, the collected data were subjected to descriptive statistical methods for summarization and interpretation with a measurement model to define the relationships between observed variables and latent construct. Moreover, the Relative Importance Index (RII) was utilized to systematically prioritize and rank the key barriers to I4.0 integration to CBM within the upstream oil and gas upstream sector.

Findings – The most ranked obstacles in integrating industry 4.0 technologies to the CBM strategy in the O&G industry are lack of budget and finance, limited engineering and technological resources, lack of support from executives and leaders of the organisations, and lack of competence. Even though the journey of digitalisation has commenced in the oil and gas industry, there are limited studies in this area.

Originality/value – The study serves as both an academic cornerstone and a practical guide for the operational integration of Industry 4.0 technologies within Nigeria's Oil and gas (O&G) upstream sector. Specifically, it provides an exhaustive analysis of the obstacles impeding effective incorporation into Condition-Based Maintenance (CBM) practices. Additionally, the study contributes actionable insights for industry stakeholders to enhance overall performance and achieve key performance indices (KPIs).

Keywords industry: I4.0, condition-based maintenance, barriers, oil & gas industry

Paper type: A research paper (Case study and Literature review)

1 Introduction

Maintenance is a required activity in all facilities and describes the most efficient way to retain or restore the production equipment to a desired level of performance. It could be explained as technical and administrative actions taken during the usage period of an equipment or system to maintain or restore the required functionality of a plant, product or asse (Shin & Jun, 2015) t. It generally reduces production deferments and downtime, personnel safety, pollution prevention and associated safety hazards prevention, amongst others.

According to Westerkamp (2014), the critical aim of maintenance is to keep the facility in excellent Condition. This is achieved by safely providing the optimum level of quality maintenance services in due time, at the correct rate or frequency and at a reasonable cost. The inability to achieve this through ineffective or inadequate maintenance activities can impact the profitability and survival of the business (Patidar et al., 2017; Uche & Ogbonnaya, 2013).

The oil and gas industry is a competitive market requiring high performance in plants used for crude processing. This is achievable through high availability, reliability and maintainability of the process equipment in the plant and so remain vital drivers for the critical need to optimise maintenance activities (Chibu, 2018; Ahuja et al., 2008). The maintenance cost in oil and gas production is high, and an oil and gas plant could incur as much as 71% of running costs, especially the offshore oil and gas fields (GE, 2016). So there must be strategies for ensuring optimisation. It is noteworthy that the consequences of any failure within the plants cost even more, so there must be a balance between reliability and availability of equipment on one hand and maintenance cost reduction on the other for desired performance and safety in this industry.

There are various maintenance strategies applied in the industry, and Condition Based Maintenance (CBM) is of the most popular maintenance strategies that aim to address equipment downtime by monitoring the real-time Condition of an equipment asset to determine what maintenance activities need to be performed to restore equipment to a desired operating state. Contrary to other forms of maintenance like preventive maintenance, which uses time or calendar-based maintenance schedules (Maity et al., 2011) or other means to determine the schedule of maintenance to equipment, CBM requires that maintenance should only be executed when real-time indicators show anomalies or signs of decreasing performance. The CBM approach has gained further attention in recent times. The goal of CBM is to monitor a piece of equipment or plant continuously to spot impending failure so that required maintenance steps or actions are executed before a breakdown or failure of the equipment. Studies show that much value exists in the CBM approach. Much has been achieved, including improved system reliability, reduced downtime and maintenance cost, increased production performance, faster problem diagnosis and a reduction in the frequency of maintenance. CBM is a type of predictive maintenance approach employed in our modern day. Studies show significant benefits, which include reducing the uncertainty involved in maintenance activities, identification and prevention of potential failures, reduction in the failure consequences and ensuring a lower life-cycle cost for the plant or equipment (Rastegari, Archenti and Mobin, 2017; Rastegari & Mobin, 2016; J.H. Shin & Jun, 2015; Greenough & Grubic, 2011).

In general, studies show that CBM has many benefits, which range from reducing the cost of asset failures, chances of collateral damage to the system, unscheduled downtime due to catastrophic failure, time spent on maintenance, overtime costs, the requirement for emergency spare parts and, improving equipment reliability, safety and maintenance interval optimisation (Shin & Jun, 2015) cited in Bengtsson M., (2004); Prajapati, Bechtel and Ganesan, (2012). However, many organisations still struggle to implement CBM successfully due to challenges and pitfalls around upskilling staff to use the technologies efficiently, having the right operating conditions, high upfront costs, and the unpredictable volume of maintenance work and software requirements (Morrison (2019). Oil and gas plants are still tied down by frequent breakdowns and equipment failures, production losses, and cost overruns from poor maintenance systems, which can frequently be traced to lack of use or ineffective implementation of condition-based maintenance (Telford, Mazhar and Howard, 2011; Rastegari and Bengtsson, 2015; van de Kerkhof, Akkermans and Noorderhaven, 2016; Tiddens, 2018).

Parvizsedghy et al. (2015), in their study on implementing CBM in pipeline systems in the oil and gas industry, argued that a significant issue in CBM was planning. They revealed that the complexities and high cost of maintenance operations, the uncertainty of the maintenance operation costs, the economic indices, and the diversity of the maintenance operations make the maintenance planning of oil and gas pipelines a very challenging adventure.

Other possible reasons could range from the complexities of the production systems and equipment, competence and skills of employees, organisational culture, unavailability of spares, ageing equipment, and Supply Chain Management (SCM) issues (Uche & Ogbonnaya, 2013; Jain et al., 2014; Ingemarsdotter et al., 2021). Therefore, a successful CBM implementation demands an organisation's leadership commitment and appropriate structure, parameters, techniques, and technologies (Rastegari & Bengtsson, 2015; Shin & Jun, 2015)

Recent studies show how maintenance policies have evolved over history. The first recognised policy was corrective maintenance, next was the second generation of maintenance, known as preventive maintenance. The third generation is the generation of predictive maintenance and the 4th generation of maintenance, which is the current generation, is associated with the 4th Industrial Revolution and Industry 4.0 (Poór & Basl, 2019). The concept of industry 4.0 represents or describes a technological advancement or evolution in manufacturing and other industries and refers to the fourth industrial revolution related to the industry (Frank, Dalenogare and Ayala, 2019; Poór & Basl, 2019). It is seen as an era of manufacturing aimed at promoting the use of Cyber-Physical Systems (CPS) and artificial intelligence in manufacturing plants to reduce critical faults radically and improve the safe operation and equipment uptime, which translates into an improvement in production performance (Ramakrishnan et al., 2019). Oztemel and Gursev (2020) described Industry 4.0 as a manufacturing philosophy comprising modern automation systems with autonomy, flexibility and effectiveness in data exchanges for improved production and customisation of products. They identified the significant differences between industry 3.0 and Industry 4.0, which included: the Internet of Things (IoT) which allows the machines to communicate; systems autonomy, which, when combined with Cyber-physical systems (CPS), IoT, Machine-to-machine (M2M), brings about intelligent capabilities in the process and more consistent, robust, agile manufacturing systems; capability of machines to communicate with human operators. These technologies are present in all components associated with Industry 4.0 and leverage the industry 4.0 dimensions, making interconnectivity possible and intelligence of the new manufacturing systems (Frank et al., 2019). A summary of these fundamental technologies and some of their applications in the maintenance world are captured in Table 1.

A limited focus has been given to applying Industry 4.0 to oil and gas processing plants (Marhaug & Schjolberg, 2016), as well as the required comprehensive classification that would aid the optimal implementation of CBM is based on the principles of Industry 4.0 technologies. Marhaug & Schjolberg, (2016) investigated the application of Smart Maintenance (Industry 4.0) to condition-based maintenance to achieve safe operations and improved availability and profit in the operation and maintenance of subsea production systems. The focus was on Intelligent Predictive Maintenance, a sub-set of Industry 4.0. Their study reveals that significant oil and gas companies have invested in intelligent fields just as it is for the manufacturing industry. Hence, Industry 4.0 applies to manufacturing, oil and gas systems, and subsea production.

Integrating I4.0 technologies into CBM is expected to entail significant improvements in production efficiency, quality, production downtime and maintenance cost reduction (Spendla et al. (2017). Other key contributors to the study on the integration of the technologies are Mohammadpoor and Torabi (2020), who researched the utilisation of Big Data analytics, as an emerging trend in the upstream and downstream oil and gas industry; TOMA and POPA (2018), with a focus on IoT Security, Approaches in Oil & Gas Solution Industry 4.0; Wanasinghe et al., (2020) that researched the Internet of Things in the Oil and Gas Industry. Following this limitation and lack of empirical evidence on the link between industry 4.0 and Condition based maintenance in the oil and gas upstream, these research questions have become very important.

- RQ1. What are the barriers to integrating Industry 4.0 to condition-based maintenance within developing countries' oil and gas sectors such as Nigeria?
- RQ2. How do these barriers rank in terms of importance?

The integration between I4.0 and CBM in the oil and gas upstream is in its early stages, especially in developing nations like Nigeria. Progress is evidenced in the recent commencement of digitisation programs to overcome concerns about increased capital expenditure and the search for improved performance. Studies, however, show that challenges associated with the application of these industry 4.0 technologies range from budget unavailability to lack of awareness and support from stakeholders, limitations and lack of technological resources. The importance of this study is to make condition-based maintenance in the O&G industry meet the required performance through the integration of Industry 4.0 technologies. The study will examine the barriers to integrating Industry 4.0 to CBM so that required strategies can be adapted to allow for the right level of integration that will yield optimal benefits. The outcome will remain an essential resource for the oil and gas upstream sector, especially in developing nations faced with challenges of Industry 4.0 integration in its condition-based maintenance strategy and other related maintenance strategies.

TABLE 1

List of the primary industry 4.0 technologies and their applications/capabilities in the area of maintenance

Technology	Description	Application area in maintenance	Reference
Industrial Internet of Things	A system that integrates sensors and computing in an internet-based environment with wireless communication.	Condition monitoring, Opportunistic maintenance, Preventive maintenance, Predictive maintenance, Proactive maintenance, Predictive - Reliability based - Condition oriented - Reactive, condition-based maintenance, prescriptive maintenance, Autonomous maintenance, Maintenance management	(García & García, 2019); (Mourtzis & Vlachou, 2018a); (Boulouf et al., 2022); (O'Donovan et al., 2015); (Janak & Hadas, 2015); (Lalanda & Morand, 2017); (Chiu et al., 2017); (Holub & Hammer, 2017); (A. Kumar et al., 2019); (Zolotová et al., 2020); (Sénéchal, 2018); (Fusko et al., 2018); (Alonso et al., 2018); (Kiangala & Wang, 2018); (Tsai & Lai, 2018); (Dinardo et al., 2018); (Alqahtani et al., 2019); (Xia & Xi, 2019); (Ooijevaar et al., 2019); (Olaf & Hanser, 2019); (Roy et al., 2016); (Simon et al., 2018); (Silvestri et al., 2020a)
Big data	This refers to the strategy of analysing large volumes of data that are used when traditional data mining and handling techniques cannot uncover the insights and meaning of the underlying data	Predictive maintenance, reactive and proactive maintenance, Condition monitoring and selective maintenance, the perspective of maintenance, Ansari et al. (2018), preventive maintenance, predictive maintenance, Maintenance management	(García & García, 2019);(Bumblauskas et al., 2017); (Yan et al., 2017); (Boulouf et al., 2022); (Wan et al., 2017); (Chiu et al., 2017); (Yan et al., 2017); (Kiangala & Wang, 2018); (Frieß et al., 2018); (Subramaniyan et al., 2018); (Hesser & Markert, 2019); (Sahal et al., 2020); (Roy et al., 2016); (Peres et al., 2018); (Silvestri et al., 2020a)
Simulations	It refers to technologies that use the computer to imitate a real-world process or system.	Condition monitoring, reactive and proactive maintenance, predictive maintenance, Preventive maintenance, Maintenance management.	(García & García, 2019); (Kono & Haneda, 2021);(Fischer et al., 2020);(Terkaj et al., 2015); (Susto et al., 2018); (Frieß et al., 2018); (Subramaniyan et al., 2018); (Peres et al., 2018); (Silvestri et al., 2020a)
Cloud computing	The concept refers to IT services that are provisioned and accessed from a cloud computing provider	Opportunistic maintenance, Predictive maintenance, Condition-based maintenance, proactive maintenance, prescriptive maintenance, Preventive maintenance, Maintenance management. Digital Maintenance	(García & García, 2019);(Mourtzis & Vlachou, 2018a); (Schmidt & Wang, 2018); (Mourtzis et al., 2016); (Boulouf et al., 2022); (Upasani et al., 2017); (Wan et al., 2017); (Chiu et al., 2017); (A. Kumar et al., 2019); (Zolotová et al., 2020); (Fusko et al., 2018); (Mourtzis & Vlachou, 2018b); (Fernández-Caramés et al., 2018); (Hesser & Markert, 2019); (Xia & Xi, 2019); (Silvestri et al., 2020a)

Augmented Reality	It is a type of interactive, reality-based display environment that takes the capabilities of the computer-generated display, sound and other effects to enhance the real-world experience;	Remote maintenance, collaborative maintenance, predictive maintenance, Preventive maintenance, Remote maintenance, Autonomous maintenance, condition-based maintenance, Maintenance management.	(García & García, 2019); (Scurati et al., 2018a); (Elia et al., 2016);(Fasuludeen Kunju et al., 2021); (Ceruti et al., 2019); (Boulouf et al., 2022); (Aschenbrenner et al., 2016); (Masoni et al., 2017); (Wan et al., 2017); (Fernández-Caramés et al., 2018); (Scurati et al., 2018b); (Gattullo et al., 2019); (Roy et al., 2016); (Silvestri et al., 2020a)
Autonomous Robots	These are robotic systems or robots that physically interacts with humans in a shared workspace.	Autonomous maintenance, remote maintenance, Inspection, planned maintenance, disturbance handling, Predictive maintenance, Maintenance management.	(García & García, 2019); (Friedrich et al., 2014); (Schiffer et al., 2010); (Parker & Draper, 2014); (Wong et al., 2018); (Boulouf et al., 2022); (Silvestri et al., 2020a)
Additive manufacturing	It is a manufacturing technology that creates three-dimensional (3D) solid objects using a series of additive or layered development frameworks.	Maintenance management: Maintenance time management, spare parts inventory and component assembly cost reduction, ease of replacement of discontinued parts; Self-maintenance and Remote maintenance, Maintenance management.	(García & García, 2019); (Fasuludeen Kunju et al., 2021); (Wessel et al., 2016); (Ceruti et al., 2019); (Boulouf et al., 2022); (Silvestri et al., 2020b)
Cyber Security	These are preventive methods to protect information from being stolen, compromised, or attacked.	Maintenance management	(García & García, 2019); (Zarreh et al., 2019); (Thaduri et al., 2019); (Ilhan & Karakose, 2019); (Nikhil et al., 2020); (Powell et al., 2019); (Boulouf et al., 2022); (Silvestri et al., 2020a)
Horizontal And Vertical Integration	Integration of data at all levels (from management to shop floor) of a company and between (from suppliers to customers) companies in the supply chain according to their data transfer patterns. They are usually connected through the Internet of Things application.	Maintenance management	(Ansari et al., 2019); (Thoben et al., 2017); (Boulouf et al., 2022); (Silvestri et al., 2020a)

2 Barriers to industry 4.0 implementation

A review of the barriers to Industry 4.0 implementation in the O&G industry by different researchers shows a list of essential actors that need to be managed for a safe transition into the use of the technologies and further application to maintenance strategies like condition-based maintenance in the industry. Wanasinghe et al. (2020), in their study, identified key challenges for implementing Digital twin in the O&G industry. In their opinion, scope and focus, lack of standardisation, cyber security, data ownership and sharing, accuracy and validity, functionality, unlocking experience, business model, people and policies, data storage and analytics, and maintenance are some of the critical barriers to Industry 4.0 technology implementation. Similarly, Cameron et al. (2018), on the same Digital Twin technology, identified eight challenges that need to be addressed for the fulfilment of the potential of the technology in the O&G industry, and they include challenges associated with business models, security and confidentiality; work practices; scope; usability; integration; maintenance; computational overload, edge and cloud; uncertainty and validation and data. In the same light, Mohammadpoor & Torabi (2020) researched Big Data (BD) analytics in the O&G industry, identified costs associated with managing the data recording, storage, and analysis; a lack of business support and awareness; the knowledge of personnel in oil companies and the data ownership issues; data transfer from the field to data processing facilities based on the type of data, amount of data, and data protocols; limitations associated with the data recording sensors as barriers to industry 4.0 implementation in the sector. Notably, the study identified the lack of business support and awareness as the biggest challenge in utilising Big Data in the industry.

In a systematic review by Nguyen et al. (2020), the identified barriers were categorised as technical and non-technical. These barriers included the challenges of how to deploy BD technologies effectively using available software tools and hardware computing platforms, issues of functionality, cybersecurity and maintenance, a collaboration between departments to deploy and operate the BD system effectively, standardisation, government-related issues, data privacy, data ownership and intellectual property rights. In another systematic review on the Internet of Things (IoT) in the O&G industry by Wanasinghe, Gosine et al. (2020), vulnerability to cyber-attacks, technological readiness for deploying in zone-0 and zone-1 hazardous environments, unavailability of communication infrastructure, Interoperability, Adaptability, and Standardisation, Data Storage and Analytics, labour concerns, Scope and Tool Selection, the mindset of the employees and maintenance and obsolescence were the key barriers identified as slowing down the pace of adoption of IoT technologies in both the upstream, midstream and downstream operations of the oil and gas sector.

Looking holistically at the deployment of the industry 4.0 concept to the oil and gas industry, Benayoune (2022) sees high investment cost and limited budget, lack of adequate skills, cyber security, resistance to change, and lack of standardisation as the key barriers Lu et al. (2019), in their systematic review and outlook on Oil and Gas 4.0, showcased challenges around the way of thinking, adapting to the new market and the time involved, insufficient funds, imperfections around supporting platforms and supporting facilities, limitations on technology interaction and integration, lack of interdisciplinary talent, lack of overall planning and standardisation as key barriers requiring attention in the oil and gas sector. Likewise, from a survey on Industry 4.0 for the upstream Oil and Gas Industry sector, Elijah et al. (2021) identified some barriers to industry 4.0 implementation. However, they categorised them as either technical, environmental or business barriers. A list of these barriers includes security of data and information during the use of the internet; interoperability challenges; scalability in terms of the number of sensors and actuators to be managed, the amount of data to be processed and stored, and the analytics needed; deployment issues; big data and its analytics; environmental challenges which are environmental pressures that can arise in the deployment and adoption of I4.0 technologies; skillset; transparency the lack of transparency and accountability regarding financial data and other information considered confidential among the O&G industry partners; business models unavailability; lack of funds for future investment.

Case studies of Bien Dong Poc (an oil and gas in Brazil) and the Russian Oil Refining and Petrochemical Industries carried out by Tran et al. (2020) and Zhdaneev et al. (2020) respectively itemised a myriad of barriers to industry 4.0 implementation in the oil and gas companies. The lack of training and retraining of personnel in the development of intelligent oilfield projects; the shortage of skilled labour in the oil and gas industry, and the lack of experience in similar projects are equally a challenge; the large number of traditional processes that need to be re-evaluated and digitised into digital processes that require vast amounts of time, manpower, and technological factors; the inertia or resistance to non-traditional change; Analysis and data management challenges; System safety; Geographical related issues; Macro policy; outdated business model; Limited automation; Budget limitation; Lack of knowledge; Unsuitable training programme; Inflexible structure; Security are the identified barriers common to BIEN DONG POC and of these, the human factor is identified as the the biggest challenge; The case study on the Russian Oil Refining and Petrochemical Industries identified the two key challenges to I4.0 implementation in the oil and gas were discussed as full integration of vertical production processes, which involves digital modelling, data integration and IoT sensor systems and; full integration of horizontal supply chain processes, which has to do with minimising human participation in repetitive production processes, integrating equipment, machines, computer and corporate IT systems.

A case study of the construction industry in Nigeria by Oke and Arowoiya, (2021), who researched the critical barriers to augmented reality technology adoption in developing countries, revealed a lack of technological awareness, difficulty in ease of Augmented Reality Technology (ART) system set up, the unwillingness of the government and private bodies to invest in augmented reality research, lack of repository database, lack of portability for ART equipment system. as the most important barriers of the 15 barriers identified. Others included the lack of solid internet connection, time recognition and tracking, accuracy for virtual element positioning, funds, GPS for ART tracking system and alignment problem, complexity in AR usage, long time recognition and tracking, limitation in generating a kinesthetic vision, defects in the detection and visual occlusion, technological limitation and acceptance, probable health issues due to long usage of augmented reality technology ART headgears.

3 Research method

This section discusses the categories of the applicable barriers, questionnaire development and collection of data through survey. Initially, the barriers applicable to the integration of Industry 4.0 within condition-based maintenance paradigms in the oil and gas sector were ascertained and systematically classified based on an exhaustive review of existing scholarly literature. Subsequently, an empirical inquiry was pursued through a survey-based approach. Subject-matter experts in the oil and gas industry were engaged to provide their insights via a designed questionnaire. The ratings are collected and further evaluated and analysed in the following sub-sections.

3.1 Identification and review of existing Barriers

An extensive literature review determined the primary challenges or barriers to integrating Industry 4.0 into condition-based maintenance in the oil and gas sector, using Nigeria as a case study. This literature reviewed barriers in the oil and gas industry and covered those encountered in other sectors, such as manufacturing, where there has been more research. The previous literature on barriers to I4.0 implementation and integration was primarily sourced from Scopus and Web of Science databases. Additional preliminary searches were conducted on Google Scholar to ensure comprehensiveness. The main keywords used included combinations of 'Industry 4.0', 'barriers', 'challenges', 'obstacles', 'problems' factors affecting', and terms related to specific sectors such as 'oil and gas', 'maintenance', 'manufacturing', and 'condition based maintenance'. Initial searches were conducted in the above databases to identify titles and articles matching the search keywords. For example, an initial search resulted in 130 titles with some overlaps. Duplicates and irrelevant articles were eliminated post-search, reducing 116 initial articles to 23 relevant papers. Table 2 shows the inclusion and exclusion criteria.

TABLE 2
Exclusion and Inclusion Criteria

Criteria	Inclusion	Exclusion
Literature type	Indexed journals, book chapters, conference proceedings, industry reports	Non-indexed journals, magazine articles
Language	English	Non-English
Timeline	Timeline Between years 2015 and 2022 (inclusive)	Before the year 2015
Access	Paper available in full-text	Access to the document is restricted
Research title	The paper provides research information on Industry 4.0 integration barriers or challenges.	The paper does not provide research information on Industry 4.0 integration barriers or challenges.
Key Research information	Contains and discusses barriers to Industry 4.0 integration in manufacturing or O&G industries	Does not contain and discuss barriers to Industry 4.0 integration in manufacturing or O&G industries
Article type	New barriers relating to Industry 4.0 integration to industries of interest are identified with information on the identified barriers.	A paper reviews existing or previously identified barriers and does not identify any new ones.

After the literature search, articles were reviewed to identify specific barriers or challenges. The identified barriers were further categorized into groups as they relate to maintenance for easier interpretation.

3.2 Identification of hindrances to Industry 4.0 integration into CBM

Regarding the integration of Industry 4.0 into condition-based maintenance for the oil and gas sector, the existing body of research is notably limited or sparse. However, the authors of the work believe that the identified barriers to the organisations (oil and gas) trickle down to the various teams, even if not all barriers, but a good number of the barriers. Also, the authors believe that similar barriers affecting implementation in the CBM systems within manufacturing may be applicable and, for the purpose of this study, have gone further to identify the barriers affecting the implementation of the CBM in developing nations like Nigeria. A total of 9 categories were identified using an iterative approach, which (Srivastava & Hopwood, 2009) see as essential for igniting understanding and fostering significant qualitative data analysis. The process essentially entails creating a set of themes based on an initial scan of barriers identified in the existing literature. Each identified barrier is then examined and either slotted into one of these pre-established themes or used to create a new theme if it does not fit into the existing categories. The barriers from the iteration include Budget/finance constraints, Limited engineering/ technological resources, Lack of competence, Lack of executive/leadership support, Poor maintenance plan execution, Wrong approach/methods, Lack of team integration, Environmental factors, and Lack of maintenance procedures. These are briefly described below, and Table 3 shows the categorisation and source literature.

Budget/Finance constraints

Funding a new project is a process in every organisation, and business leaders with stakeholders play a key role in this subject. Industry 4.0 implementation in an organisation will result in horizontal, vertical and end-to-end integration (Wang et al., 2016), and so to design and implement the architecture requires substantial initial investment costs, which are often significant (Lasi et al., 2014; Singer, 2015; Rojko, 2017; (Nimawat & Gidwani, 2021). Lu et al. (2019) cited that the cost of digital deployment is a significant challenge to the adoption of digital technologies, especially as the O&G industry requires the replacement and upgrades for a large number of equipment and systems. (Erol et al., 2016), (V. Kumar et al., 2021), and (Karadayi-Usta, 2020) all identify financial constraints as a significant barrier to adopting new technologies. Additional authors such as (Stentoft et al., 2019),(P. Kumar et al., 2021), (Govindan & Arampatzis, 2023b), and (Chauhan et al., 2021) corroborate this view. (Herceg et al., 2020) underline this point in a Serbian context, finding finance to be the primary obstacle to Industry 4.0 adoption, even eclipsing other challenges like strategic planning and organizational culture. Industries, especially SMEs, struggle to integrate Industry 4.0 principles due to limited financial resources. (Ghobakhloo & Fathi, 2020) note that most SMEs can only partially digitize their operations because of these constraints. While developed countries offer diverse financing options for Industry 4.0 adoption, developing nations primarily rely on the banking sector, which often provides insufficient financial support for such initiatives (León-García & Bermúdez-Segura, 2021). This is an investment challenge to developing nations like Nigeria. This high funding deters support from leadership and company owners, thus becoming a barrier to the integration of industry 4.0 technologies in the organisation.

TABLE 3
Barriers to Industry 4.0 integration into CBM in the O&G industry

Categorization themes	Reference (Source)	Barriers
Financial	(Raj et al., 2020); (Kamble et al., 2018a); (Jasiulewicz-Kaczmarek et al., 2022a); (Erol et al., 2016b); (Kiel et al., 2017); (Müller, 2017); (Pech & Vaněček, 2022);(Schröder, 2016); (Orzes et al., 2019); (Blessing & Amoah, 2023); (Jena & Patel, 2022a); (Horváth & Szabó, 2019); (Digital, 2016); (Ghadge et al.,	Budget/finance constraints
Leadership and Management		Lack of executive/leadership support
Technical Resource		Limited engineering/ technological resources
Procedures		Lack of maintenance procedures

Integration/Collaboration	2020); (Pavan et al., 2022); (Pech & Vaněček, 2022); (Oke & Arowoiya, 2021b); (Moktadir et al., 2019); (P. Kumar et al., 2021); (Tortorella et al., 2021); (Raj et al., 2019); (Kiss et al., 2023); (Yilmaz et al., 2022); (Chauhan et al., 2021); (Bakhtari et al., 2021); (Kiel et al., 2017); (Pavan et al., 2022);(Bashar Bhuiyan et al., 2020); (Jena & Patel, 2022a); (Lu, Huang, et al., 2019); (Raj et al., 2019); (Oke & Arowoiya, 2021b); (Kamble et al., 2018a); (Jasiulewicz-Kaczmarek et al., 2022a); (Gökalp et al., 2017); (Orzes et al., 2019)	Lack of team integration
Planning and work execution		Poor maintenance plan execution
Competency		Lack of competence
Environment		Environmental factors
Methods/Methodology		Wrong approach/methods

Limited engineering/ technological resources

Most people, especially those in the O&G industry, are not so knowledgeable about Industry 4.0 and much so those in the developing nations. This lack of awareness among stakeholders, lack of information technology infrastructure, lack of training and technological exposure are part of the major restraints to the integration of the technologies into the organisations talk-less of their maintenance systems. Indeed, achieving success would be a challenge without adequate resources to help integrate the technologies into existing strategies. Several studies, including those by (Raj et al., 2020)(Kamble et al., 2018a), (Senna et al., 2022), (P. Kumar et al., 2021), and (V. Kumar et al., 2021) identify multiple barriers to Industry 4.0 adoption. including immature technology, poor infrastructure, and fragmented digital strategies, exacerbated by limited resources. (Müller et al., 2017) highlight the absence of technical standards and architectural frameworks. Additional obstacles include insufficient broadband and connectivity, scalability and interoperability issues, an incomplete IT foundation for data-driven services. Related research by (Chauhan et al., 2021) and(Nimawat & Gidwani, 2021) points to engineering and technical resource deficiencies such as inefficient IT and poor broadband. (Jena & Patel, 2022) and (Sayem et al., 2022) further specify technological barriers such as market unavailability, compatibility issues, and integration difficulties. Intriguingly, (Pech & Vaněček, 2022) in their research notes that both SMEs and large enterprises encounter similar obstacles in adopting Industry 4.0.

Engineering and technical resources, infrastructure, and skills, amongst others, are resources required to make integration a success and studies show that the O&G still lags in the area of technology compared to manufacturing and much so it is for developing nations when compared to developed nations. Indeed for this to be a success, more resources will be required in the O&G sector owing to the demand that will come from more interconnectivity if equipment, processes, data interpretations, security, skills, specialist and much more. Studies by Petrol MI (2018) show a kind of increase in technical resources like analytics specialists, software engineers, data management and instrumentation technologists to measure operations in real-time and for CBM, required data for better decision making.

Lack of competence

Recent studies on barriers to adoption and implementation of Industry 4.0 revealed a lack of digital talent and knowledge gap (Zhifeng, 2019; Lu et al., 2019; Mogos, Eleftheriadis and Myklebust, 2019; Tran et al., 2020); Benayoune et al., 2022) were found to be amongst the main barriers. According to Tran et al., 2020, a lack of technological knowledge and expertise to conduct industry 4.0 implementation projects in the O&G industry is a challenging one. The little knowledge about implementation risks and consequences, according to Mogos, Eleftheriadis and Myklebust, 2019, is also a barrier. (Jena & Patel, 2022)identify a lack of empirical research and unfamiliarity with smart devices as significant barriers to the adoption of Industry 4.0 (I4.0). This is compounded by industrial reluctance to understand the impact of digitization and data on existing systems. (Türkeş et al., 2019) and others note that SMEs cite a "lack of knowledge about Industry 4.0" as a primary hindrance, highlighting a common thread in research by (Stentoft et al., 2019) and (Nimawat & Gidwani, 2021). (Kamble et al., 2018b), (Raj et al., 2020),(Breunig et al., 2017) emphasize the role of digital proficiency, arguing that a digitally unskilled workforce hampers collaboration with software providers. (P. Kumar et al., 2021), (Machado et al., 2019a), (Govindan & Arampatzis, 2023b), and (Chauhan et al., 2021) extend this to include workforce skill gaps and the complexities of integrating new business models. (Jena & Patel, 2022) and (Herceg et al., 2020) and (Chiarini et al., 2020) further underline these challenges, emphasizing that competency issues remain significant barriers to effective I4.0 implementation. Adopting and integrating Industry 4.0 into CBM, like every other process in any organisation, would involve a change of skills required for sustainability in the O&G sector and, according to Benayoune et al., (2022), would impact the skills and resources of new employees in the system thus implying some change in the employment patterns for smooth running operations and maintenance of the plant. These skills are not readily available in developing nations, making this a challenge for the industry.

Lack of executive/leadership support

Studies show that there is a lack of understanding by company executives and owners on the benefits from Industry 4.0, which places some setbacks on the support required from this executive for integrating these new technologies into the existing strategies like the CBM strategy. Their lack of knowledge, and awareness stalls the adoption and integration of Industry 4.0 (Herceg et al., 2020). (Govindan & Arampatzis, 2023b) highlight leadership as the primary constraint in adopting Industry 4.0, noting its crucial role in shaping organizational trajectory and employee alignment. (Müller, 2019) and (Chauhan et al., 2021) observe that while top management extols Industry 4.0 adoption importance, it often fails to implement it operationally, highlighting this as an organization-specific, intrinsic barrier. (Majumdar et al., 2021) and (Jasiulewicz-Kaczmarek et al., 2022a) also emphasize the necessity of executive support for successful Industry 4.0 integration. (Sayem et al., 2022), (Nimawat & Das Gidwani, 2022) and (V. Kumar et al., 2021) concur, arguing for the unequivocal commitment of top management as essential. (Shamim et al., 2016) add that the absence of such commitment can impede organizational learning, capability enhancement, and innovation, thereby obstructing Industry 4.0 alignment. Again, considering the fact that some organisations may be attracted to projects with short-term results, it can be difficult getting into projects like industry 4.0, which require high costs at the start with long-term results. Company executives who are not knowledgeable, who lack understanding of the benefits from Industry 4.0 and are unable to quantify the financial benefits, especially with high-cost investment proposals, may find it difficult to support the investment or perhaps see no need.

Poor maintenance plan execution

In line with trying to integrate the industry 4.0 technologies into CBM of the O&G industry, poor maintenance plan execution may become a concern. Maintenance plans are known to be very clear and describe goals and road maps that show how to attain these goals. Following the introduction of technologies (Industry 4.0) that require automation would imply that the maintenance planning also would have to be automated. Not having this in place certainly would bring some bottlenecks to integration into CBM. It would impact work practices and execution. Maintenance plans must be robust yet flexible in asset management, particularly as organizations move toward Industry 4.0 to enhance operational efficiency ((Sahli et al., 2021). (Cheng et al., 2020)) suggest that proactive resource allocation by maintenance managers is critical for asset longevity, aligning with Industry 4.0 goals. However, (Herceg et al., 2020) note that complex maintenance planning can slow this transition. Suboptimal maintenance undermines Industry 4.0's reliance on innovative technologies and data analytics. Effective use of I4.0 technologies requires reliable tools and data; inaccuracies compromise maintenance decisions. (Tijani et al., 2016) argue that an ineffective maintenance culture, often due to leadership or policy constraints, can impede technological progress and thereby hinder the successful implementation of Industry 4.0. Again, the effectiveness of maintenance execution depends on the quality of human management and skills, considering the fact that machines and equipment would depend on human operators for control. Unavailability of these required skills would certainly yield wrong controls and plans, leading to poor execution.

Wrong approach/methods.

Maintenance strategies play a crucial role in improving progressively technical performances and economic savings. The integration of Industry 4.0 technologies to CBM would result in relevant innovations able to cause some changes and bring improvement to condition-based maintenance; however, there would be a risk of wrong approaches, which can be a factor of failure. This factor is a barrier to the complete integration of these technologies. Still, from a technology standpoint, (León-García & Bermúdez-Segura, 2021) and (Raj et al., 2020) discuss the complexity of integrating legacy systems with new Industry 4.0 technologies. This sentiment is reinforced by (Moeuf et al., 2018), who note that integration is a recurring challenge. (Senna et al., 2022)further emphasize the difficulties in achieving compatibility and interoperability between existing equipment and new machinery, including extracting and integrating data from IoT devices. This view finds further empirical support from like (Raj et al., 2020), (Senna et al., 2022) and (Machado et al., 2019b), who illuminate the hindrance posed by an absent or misguided digital strategy. Such a deficit precludes effective collaboration with software specialists, thereby exacerbating the complexity of Industry 4.0 integration. (Raj et al., 2020) elaborate that this misalignment contributes to challenges in technological adaptation, further complicating the Industry 4.0 adoption process. In a similar vein, (Majumdar et al., 2021), (Orzes et al., 2019) highlight the absence of a methodical approach as an impediment to Industry 4.0 integration. They contend that the nascent state of Industry 4.0 results in a dearth of established standards and reference architectures, elements critical for streamlined implementation.

Lack of team integration

According to Baiden and Price (2003), team integration is s an alignment of various teams to conformity with each other. It is design development by bringing all multidisciplinary teams to work in a structured, consistent and simultaneous manner to achieve efficiency and higher performance. Organisations trying to integrate CBM into existing strategies like CBM might face integration challenges in their journey towards achieving this goal, and Sivanuja and Sandanayake, (2022), in their study, revealed that facility to a smart system is not a complex one, however, but goes with a challenge in identifying the integration requirements of the systems. This sort of integration usually requires different teams and could be a barrier to achieving the integration of new technologies like Industry 4.0 into existing strategies like CBM in the O&G industry. (Yilmaz et al., 2022) investigated the managerial obstacles in the initiation of new systems, emphasizing that incongruent objectives across different teams obstruct the effective integration of Industry 4.0 principles. This misalignment, they argue, particularly hampers the successful implementation of Condition-Based Maintenance (CBM). A corroborative stance is presented by (Jasiulewicz-Kaczmarek et al., 2022b), who identify the lack of interdepartmental collaboration, notably between maintenance and other units, as a significant barrier. (V. Kumar et al., 2021) highlight the absence of academia-industry collaboration as a significant "strategic barrier" to innovation and advanced developments. This view is supported by scholars such as (Karadayi-Usta, 2020) (Karadayi-Usta, 2020), (Ghobakhloo et al., 2022), (Müller, 2019), (Jasiulewicz-Kaczmarek et al., 2022a), and (Govindan & Arampatzis, 2023a) who also mention challenges like poor supplier cooperation and lack of departmental synergy during the transition to Industry 4.0.

Environmental factors

According to Ben-Daya, Kumar and Murthy, (2016), the environment in which maintenance activities are carried out is of prime importance and must be adjusted to aid maintenance actions. Environmental factors differ from one country to another and even from one organisation to another, and in the maintenance context, they refer to the conditions under which maintenance is carried out. There are technological concepts that may not function well, or organisations may find it very difficult to maintain under harsh environmental conditions such as excess heat or cold, poor lighting, excess humidity, and more. This could be a barrier to the integration of the industry 4.0 technologies, especially in Nigerian and African countries where there is continuous high and extreme weather conditions that could impede access to services in complex ways. According to Khan, Sadiq and Haddara, 2004, during pipeline inspection used in the O&G industry, the physical condition evaluation often exposed to different environmental conditions and the probability of failure for pipelines is the key factors that influence the decision-making process for effective maintenance of pipeline systems. According to (Kiss et al., 2023), the implementation of Industry 4.0 is notably influenced by a company's geographical location, along with the surrounding social and economic conditions, and the prevailing institutional framework—factors collectively referred to as location-based influences. These influences are sure to prevent full integration of I4.0, especially when facilitating to obstructing the intended outcome. Changes in circumstances, such as weather, environmental conditions and constraints, or emerging changes in legislation regarding supportive regulatory landscape can transform these once-positive influencers into barriers.

Lack of maintenance procedures

Maintenance procedures are available to provide directions as may be required for the performance of work and to ensure that maintenance is performed safely and efficiently. The lack of guides or directions may be a barrier to the integration of new technologies into existing CBM practices. Well-written procedures for most tasks and especially for tasks seemingly requiring integration or synchronisation with new technologies, are very important as the detailed list of steps that describe how to perform the desired maintenance task are made available. Unavailability of the steps that involve the synchronisation of these new digital technologies with the existing strategies causes represent a challenge that needs to be addressed for successful integration (Lu et al., 2019; Mogos, Eleftheriadis and Myklebust, 2019; Nguyen et al., 2020; Tran et al., 2020). In a study by (Jasiulewicz-Kaczmarek et al., 2022b) on Assessing the Barriers to Industry 4.0 Implementation From a Maintenance Management Perspective, several barriers associated with maintenance were delineated. A salient barrier underscored was the absence of structured maintenance processes and activities, which is intrinsically connected to procedural guidelines governing work execution within industrial settings. The genesis of structured maintenance activities is deeply rooted in the establishment of rigorous procedures. Both concepts are related to the organization and predictability of operations, especially in fields that require regular maintenance to ensure efficiency, safety, and reliability. The absence of one almost always affects the effectiveness of the other, leading to inefficiencies, inconsistencies, and increased operational risks.

3.3 Questionnaire design

Questionnaires serve as a pivotal instrument in survey research, facilitating the systematic acquisition of data uniformly. Historically, surveys, with a particular emphasis on questionnaires, have been instrumental in delivering an illustrative "snapshot" reflecting the status quo of a given phenomenon at a distinct juncture (Manstein et al., 2023). This study employed meticulously crafted questionnaires to garner insights from diverse maintenance professionals and other pertinent Nigerian oil and gas stakeholders. These instruments were tailored to encapsulate critical data on integrating Industry 4.0 paradigms and condition-based maintenance protocols endemic to the sector.

The questionnaire aimed to investigate how well the principles of Industry 4.0 have been integrated into maintenance procedures, particularly in emerging oil and gas sectors like Nigeria. The survey comprised 24 carefully selected questions, including closed and open-ended types. These were organized under Facility Operation/Maintenance Philosophy, Condition-Based Maintenance, and Industry 4.0 Implementation. A preliminary version was distributed to a select group for a pilot study to ensure the questionnaire's reliability and validity. This step aimed to identify and rectify any potential issues (Fowler Jr, 2013). Upon accruing 10% of the anticipated responses, a rigorous analysis was undertaken to ascertain the questionnaire's alignment with the research objectives with the insights offered by participants into its clarity, relevance, and ease of understanding. Post this validation, the refined instrument was subsequently extended to a broader spectrum of professionals within the oil and gas sector.

Questionnaire reliability assessment

When designing or evaluating a questionnaire, achieving good internal consistency is crucial. If the items in a scale are not internally consistent, this could suggest that they are not collectively measuring the intended construct effectively, and the results could be misleading or difficult to interpret. Hair et al., (2019) described internal consistency as the assessment of how closely the items in a scale align with the same fundamental concept and Cronbach's Alpha coefficient is frequently employed to gauge this form of reliability. Taber, (2017) and (DeVellis, 2017) noted that Cronbach's Alpha is computed to ascertain the level of correlation between the items in a scale with a coefficient value of 0.7 or above typically deemed acceptable. Using Cronbach's alpha, the reliability of the coefficient of the variables of this study was determined as 0.871, reflecting the adequacy and validity of the questionnaire.

3.4 Data gathering and sampling size

This study focused on Nigeria's oil and gas industry, an emerging nation. A questionnaire survey was conducted to gain information and comprehend individuals' perceptions and feelings on a larger scale and in line with the research objectives. This step aimed to gather complementary information on the case study and compare them with interview outcomes. The data collection involved creating an online survey using Google Forms to achieve responses from Oil and gas company participants. As the subject area involved maintenance, the data collection was limited to participants to maintenance staff and their support team members of the organisation; a minimum of 150 participants was the target considering the limitation to the maintenance team and its related functions; however, a total of 167 complete responses were received used for the study. The basic data were gathered using convenience sampling as there was insufficient knowledge of the population and sample sizes. While the findings of this study may not exhibit universal generalizability, they could resonate with a significant proportion of the target population. This notion is underpinned by the Central Limit Theorem (CLT). The CLT posits that as the sample size increases, the distribution of the sample mean asymptotically approximates a normal distribution (Lateef Olanrewaju & Idrus, 2020). A minimum sample size threshold of 30 observations is conventionally endorsed to employ the CLT validly. In this context, the obtained completed responses of 150 exceed this stipulated threshold, aligning with the CLT's criteria and validating its applicability for the ensuing statistical analysis (Chan & Adabre, 2019); (Olanrewaju et al., 2022). Again, consideration was given to organisations in Nigeria's oil and gas industry that have been implementing CBM for more than ten years and may have also commenced the journey to digitalisation as findings from studies reveal that the manufacturing industries birthed I4.0, not the oil gas.

With regard to the interviewees' selection, complementary criteria were selected. Participants should have been working for at least seven years in their organisations. The target was to interview at least two persons each from the leadership, supervisors and technicians categories of the company's maintenance discipline. This gave a more robust picture and a well-rounded study. In all, six personnel participated in the interviews. The profile of the interview participants is captured in Table 4. Semi-structured open-ended virtual interviews were planned considering the COVID-19 pandemic. The questions were grouped in similar themes to the questionnaire survey: Facility Operation/Maintenance Philosophy, Condition-Based Maintenance and Industry 4.0 Application. All interviews were audio-recorded and followed a similar sequence of questions, lasting from 30 to 45 minutes each. The audio-recorded information was transcribed and subsequently analysed qualitatively and concurrently with the quantitative data.

TABLE 4
Profile of the selected interview participants

Interviewee	Maintenance experience	Role	Experience in the company
A1	20 years	Manager	16 years
A2	11 years	Manager	11 years
A3	22 years	Maintenance Supervisor	21 years
A4	18 years	Maintenance Supervisor	18 years
A5	17 years	Team leader	14 years
A6	11 years	Team leader	11 years

3.5 Data analysis and techniques

The triangulation approach, which involves collecting both quantitative and qualitative data concurrently with consideration of the pragmatic philosophical view, was adopted. The data and information from one method complement the underlying weaknesses of one method with the strengths of the other. Generally, descriptive statistics were used for analysis and the Relative Importance Index (RII) was used to determine further the significance of the barriers to I4.0 integration into CBM improvement in the O&G industry following respondents' ratings. The Statistical

Package for the Social Sciences (Version 26) was used for the analysis. In the questionnaire, the identified barriers were added for evaluation by respondents. A five-point Likert scale was provided to indicate the numerical value, which describes the level of importance of each barrier. The respondents were asked to rate the level of importance of the barriers on a scale of 1–5, where 1 is 'least important', 2 'fairly important', 3 'important', 4 'very important', and 5 'extremely important'.

The Relative Importance Index (RII) formula is.

Relative Importance Index (RII) = $\frac{\sum W}{AN}$ $(0 \leq RII \leq 1)$ (1)

Where: W is the weighting given to each factor ranging from 1 to 5.
A is the highest weight which is 5 in this case, and N is the total number of respondents (Chan & Kumaraswamy, 1997) in the research.

Findings are discussed in the next section, with general propositions to support the integration of I4.0 technologies into the CBM in the oil and gas upstream industry.

3.6 Measurement Model

In the structural equation modelling (SEM) framework presented in Figure 1, three latent constructs have been delineated—namely, Financial, Leadership, and Strategic Barriers (FLSB); Technical Resources and Operational Execution Barriers (TROEB); and Competence, Team Integration, and External Factors Barriers (CTEB)—each reflecting distinct thematic barriers within an organizational context as it pertains to the implementation of Industry 4.0 technologies in CBM. The grouping arises from the observation that these measured barriers, herein referred to as indicators, are associated with various aspects of organizational dynamics. Some indicators relate to high-level strategic factors within the organization, others are rooted in operational execution and resource allocation, while the others focus on the human and external environmental elements of organizational change. Utilizing AMOS for the specification and estimation of the model, the analysis affords an empirical foundation to hypothesize the interrelations (McDonald & Ho, 2002) among these barrier classifications. The SEM diagram posits that:

Group 1: Financial, Leadership, and Strategic Barriers (FLSB) encapsulates the macro-level obstructions, predominantly arising from executive decision-making levels, affecting financial flexibility, leadership endorsement, and strategic deployment in relation to Industry 4.0 integration.
Group 2: Technical Resources and Operational Execution Barriers (TROEB) encapsulates the micro-level impediments directly influencing the tangible application of Industry 4.0 technologies. This includes the infrastructural and procedural capabilities necessary for seamless integration and the execution efficacy of maintenance frameworks.
Group 3: Competence, Team Integration, and External Factors Barriers (CTEB) encapsulates the human capital and environmental impediments that impact the assimilation of Industry 4.0. This realm underscores the pivotal role of workforce proficiency, cohesive team dynamics, and external environmental influences.

Each latent variable is inextricably linked through covariance associations, suggesting interdependencies(Mccoach, 2003) wherein the presence or magnitude of one barrier category may inform the extent of another. Additionally, each latent construct is operationally defined by its observable indicators—measurable variables that apparently serve as manifestations of the latent barriers. These encompass Budget/Finance Constraints (BFC), Lack of Competence (LC), Lack of Maintenance Procedures (LMP), Lack of Executive/Leadership Support (LELS), Poor Maintenance Plan Execution (PMPE), Wrong Approach/Methods (WAM), Limited Engineering/Technological Resources (LETR), Environmental Factors (EF), and Lack of Team Integration (LTI). Accompanying these indicators are error terms (e), representing measurement error or variance unaccounted for by the model. The covariance between errors—particularly between BFC and LELS—suggests a recognition of potential unmeasured variables that may concurrently influence these observed indicators. This correlation imply an underlying dimension such as organizational culture or industry-specific economic conditions affecting both

Executive/Leadership Support and Budget/financial decision-making. The empirical evidence of a consistent covariation between these elements warrants the correlation of their error terms, thus enhancing the model's fit.

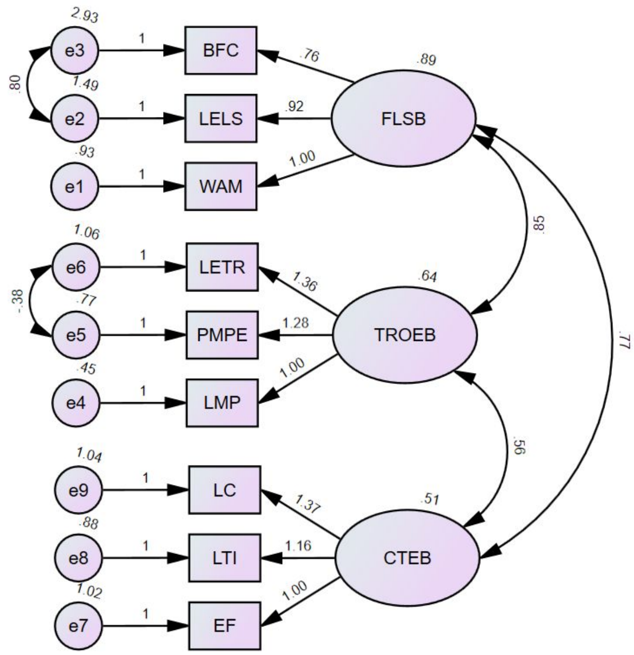

FIGURE 1. Measurement Model for the barriers to I4.0 integration

4 Findings and discussions

4.1 Characteristics of the Sample: Workforce Roles and Experience

Figure 2 summarises the roles of respondents; 39.52% of the respondents are Maintenance Technicians, which rank highest in the number of respondents, followed by the Maintenance/Operations Supervisors, which represent 15.57% of the total respondents. The Team Lead/Discipline/Maintenance Support Leads represent 13.17% of the population, and 8.98% of the respondents are Maintenance/Reliability Engineers. A further classification of the respondents in terms of their leadership roles is displayed in Figure 3.

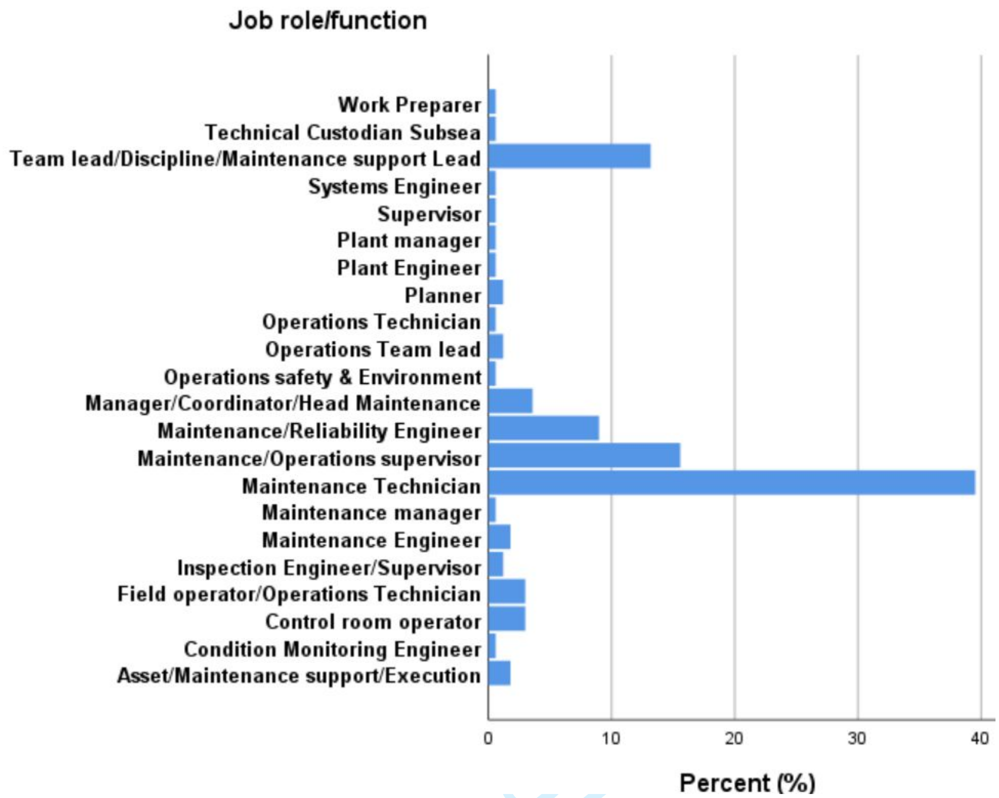

FIGURE 2. Job role/function in the maintenance team of the organisation

Following the classification, 18.56% belong to the leadership category comprising all team leaders, managers, and heads of maintenance departments, 32.34% of the respondents play the role of supervisors, which includes maintenance and reliability engineers and 49.1%, which the largest group, are the technicians comprising of all including the schedulers and planners. The Technicians are more represented in this survey and occupy roles in electrical, mechanical, instrumentation and support functions. The survey was prepared to encourage broad participation from different roles in the maintenance discipline, including the leadership occupying maintenance-related roles.

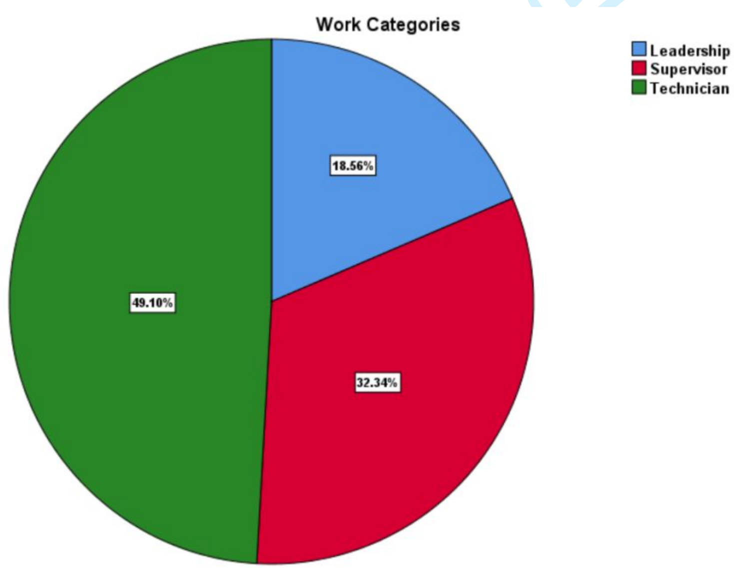

FIGURE 3. Work categories in the organisation

The geographic coverage of the survey was limited to Nigeria, a rich oil-producing nation and developing country. The respondents were from the same multinational oil company with some reasonable level of academic qualification. Figure 4 shows the details of the education of the respondents. The distribution of college education is highest and much more familiar among field technicians. About 50% of respondents are university or polytechnic graduates, and 22% are respondents with master's degrees. The respondents with PhD are the minor percentage in number and fall under the leadership category. There is an uneven distribution in the level of education amongst all categories, but generally, A more significant percentage are university or polytechnic graduates.

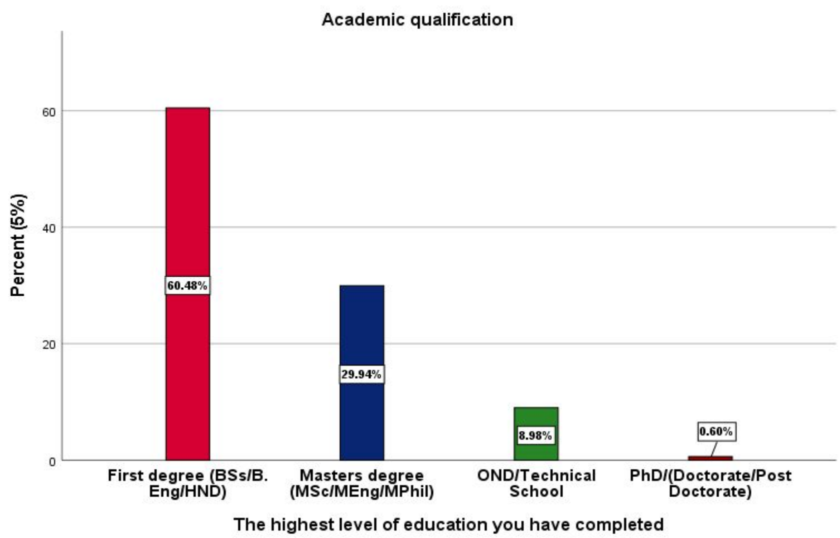

FIGURE 4. Academic qualification of respondents.

With respect to working experience in maintenance, Table 5 showcases years of working experience; data shows that the minimum number of years of experience in maintenance is two years, and a good number of respondents had previously worked in other organisations as maintenance staff, bringing their total combined maintenance experience to be well over 200 years.

TABLE 5
Years of experience

Years	Frequency	(%)
2 to 5 years	19	11.377246
6 to 10 years	32	19.161677
11 to 15 years	28	16.766467
16 to 20 years	46	27.54491
21 to 25 years	19	11.377246

Above 26 years	25	14.97006

Viewing the staff categories, respondents with the highest work experience in maintenance are the technicians, followed closely by the supervisors and the leadership (Figure 5). This trend is similar to intermediate maintenance experience However, the trend defers with respondents having low experience in maintenance. Supervisors take the lead in this category, while Technicians are the least under this category. In all, a more significant number of respondents fall under the category of staff with high experience in maintenance.

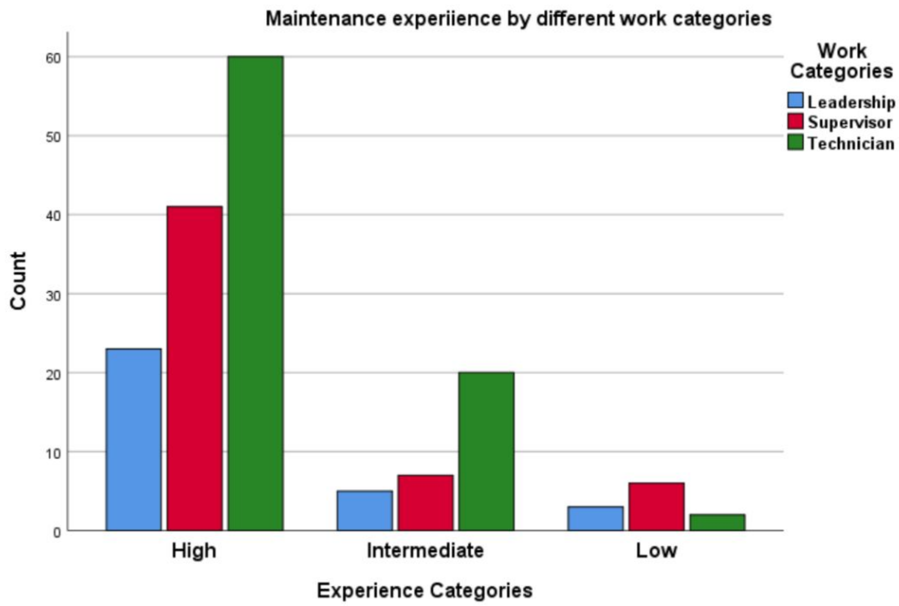

FIGURE 5. Maintenance experience of respondents from different work categories

This good level of maintenance experience is key for effectiveness in maintenance; however, with the high level of maintenance experience, there is limited awareness of the concept of Industry 4.0. Figure 6 shows that only 5% of the respondents are aware of IoT required for incorporating I4.0 into the organisation's CBM practices. The interview session with the two respondents from the leadership categories revealed some limitations in staff knowledge, and awareness level as the company's digitalisation journey was only recent. Application of Industry 4.0 concepts is still at an infant stage and limited. Workers are yet to be trained, and maintenance management systems are yet to be fully synchronised with industry 4.0 technologies.

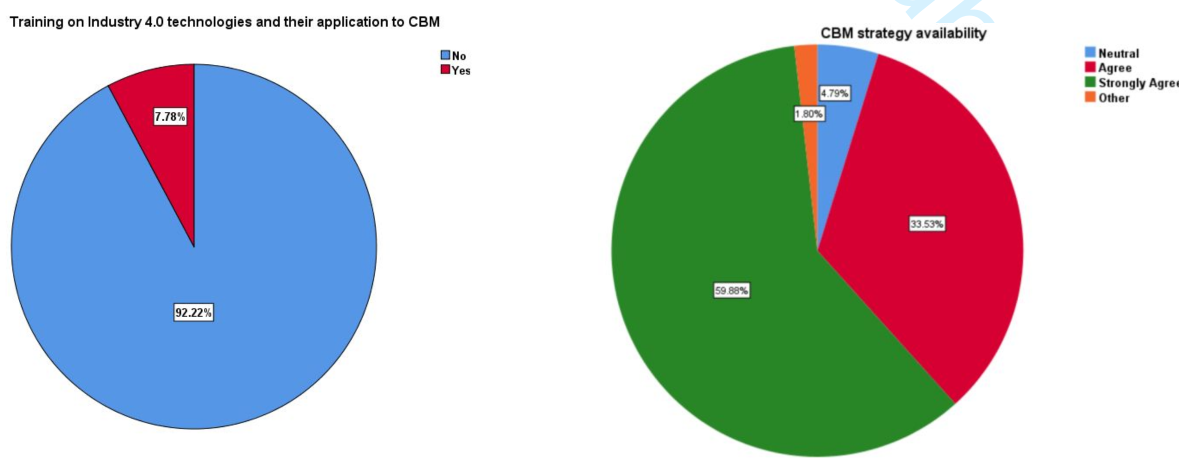

FIGURE 6. Training on Industry 4.0

FIGURE 7. CBM strategy availability

Data gathered points out that the Condition-based maintenance (CBM) strategy is well established, documented, and aligned with the company's overall maintenance strategy (Figure 7). 58.88% of respondents strongly agree, and 33.53 % agree, but just a few are neutral on the effectiveness of the CBM strategy adopted. Despite the acclaimed effectiveness, some barriers exist to achieving complete success in embedding industry 4.0 technologies. The key barriers identified are lack of budget and finance, limited technological resources, lack of executive leadership, lack of competence, poor maintenance plan execution, wrong approach/methods, lack of team integration, environmental factors, and lack of maintenance procedures.

4.2 Measurement Model Analysis

4.2.1 Goodness-of-Fit Indices

Model variables from Figure 1 were estimated with maximum likelihood estimation (MLE), a prevalent method in Structural Equation Modelling (SEM) known for providing reliable estimates in small samples(Fruet-Cardozo et al., 2019). The robustness of MLE is such that it can produce unbiased estimates even when normal distribution conditions are not strictly met.

The model's fit was evaluated using several indices (CMIN/df, GFI, CFI, TLI, SRMR, and RMSEA), with all values falling within acceptable ranges (Bentler, 1990; Hu & Bentler, 1999; Wheaton et al., 1977)). The results in Table 6 indicate that the model adequately captures the challenges of integrating Industry 4.0 into Condition-Based Maintenance in the oil and gas industry.

TABLE 6
Goodness-of-Fit

Fit Indices	Recommended Value	Reference	Obtained values
P-value	Insignificant	Bagozzi & Yi, (1988)	0.460
CMIN/df	3 - 5	Less than 2 ((Wheaton et al., 1977)) to 5 (Schumacker & Lomax, 2010)	1
GFI	> 0.9	Hair Jr et al., (2010)	0.972
CFI	> 0.9	Bentler, (1990)	1
TLI	> 0.9	Bentler, (1990))	1
SRMR	<0.08	Hu & Bentler, (1999)	0.0293
RMSEA	<0.08	Hu & Bentler, (1999)	0.001

CMIN (Chi-square Test): The P-value is not statistically significant (p = .460). This suggests that the model does not significantly deviate from the observed data. The CMIN/DF ratio is 1.000, indicating a perfect fit per the common heuristic that values close to or less than 2 indicate a good fit.

GFI (Goodness of Fit Index): GFI: A value of .972 is consistent with the criteria, suggesting the model accounts for a high proportion of the variance in the observed variables.

CFI (Comparative Fit Index): The model has a CFI of 1, which signifies a perfect fit in SEM, indicating the model fits the data perfectly.

The SRMR (Standardized Root Mean Square Residual): A value of 0.0293 indicates a good fit for the SEM model, as values below 0.05 are typically considered indicative of a well-fitting model.

RMSEA (Root Mean Square Error of Approximation): An RMSEA of .001 is outstanding, far below the .05 threshold for a good fit since lower RMSEA values indicate a closer fit to the data.

The measurement model appears to have a very good fit across all indices. The high baseline comparison values, low RMSEA, non-significant chi-square, and reasonable measures all suggest that the model represents the data very well.

4.2.2 Weights and Coefficients of Regressions, Variances, and Covariances

The regressions (Table 7) indicate that the barriers identified and grouped under Financial, Leadership, and Strategic Barriers (FLSB); Technical Resources and Operational Execution Barriers (TROEB); and Competence, Team Integration, and External Factors Barriers (CTEB) are significant and are strong predictors of their indicators (Observed variables). The model emphasizes the interconnectivity between different types of barriers and specific organizational challenges to the integration of I4.0 to CBM in the oil and gas.

TABLE 7
Regressions

			Estimate	S.E.	C.R.	P	Label
WAM	<---	FLSB	1.000				
LELS	<---	FLSB	.916	.116	7.911	***	par_1
BFC	<---	FLSB	.763	.143	5.352	***	par_2
LMP	<---	TROEB	1.000				
PMPE	<---	TROEB	1.280	.130	9.864	***	par_3
LETR	<---	TROEB	1.360	.145	9.366	***	par_4
EF	<---	CTEB	1.000				
LTI	<---	CTEB	1.162	.172	6.742	***	par_5
LC	<---	CTEB	1.374	.198	6.947	***	par_6

Table 8 summarises the covariances and indicates that all parameters presented are statistically significant and contribute to the model. FLSB, TROEB, and CTEB have substantial estimated effects. The error variances (e1 - e9) are also significant, indicating that while the model accounts for a significant portion of the variances, substantial unexplained parts remain captured by these error terms. The high significance levels across all parameters suggest a robust model with well-estimated paths and error variances.

TABLE 8
Variances

	Estimate	S.E.	C.R.	P	Label
FLSB	.892	.193	4.624	***	par_12
TROEB	.643	.113	5.674	***	par_13
CTEB	.509	.133	3.839	***	par_14
e1	.928	.134	6.905	***	par_15
e2	1.492	.179	8.334	***	par_16
e3	2.935	.321	9.148	***	par_17
e4	.449	.058	7.787	***	par_18
e5	.771	.108	7.125	***	par_19
e6	1.061	.142	7.458	***	par_20
e7	1.019	.120	8.471	***	par_21
e8	.879	.111	7.948	***	par_22
e9	1.042	.136	7.652	***	par_23

The covariances from Table 9 indicate that there are significant relationships between the different groups of barriers within the model, as well as notable associations between the errors of certain observed variables. These covariances indicate that the latent constructs and the measurement errors are not independent, which could be due to various reasons, including potential overlap in the concepts they represent or shared method variance.

TABLE 9
Covariances

			Estimate	S.E.	C.R.	P	Label
FLSB	<-->	TROEB	.853	.124	6.884	***	par_7
TROEB	<-->	CTEB	.562	.099	5.690	***	par_8
FLSB	<-->	CTEB	.769	.132	5.813	***	par_9
e2	<-->	e3	.799	.182	4.393	***	par_10
e5	<-->	e6	-.375	.092	-4.068	***	par_11

The Measurement Model analysis suggests that the corresponding latent variables significantly influence the observed variables representing barriers. The strength of these relationships varies, with some barrier groups being more strongly predicted by their latent factors than others. The significant covariances between the latent variables indicate interrelatedness among different types of barriers within the organizational context. The overall fit indices of the model (e.g., RMSEA, CFI, NFI) are consistent with the criteria, showing that the model is well-specified and effectively captures the relationships between the barriers.

4.3 The Relative Importance (RII) of the Barriers

Further evaluation of the identified barriers ranks them in the order of importance using the Relative Importance Index (RII). Table 10 showcases the values obtained for RII for each barrier type from analysing the responses received from the questionnaire survey. Focusing on the four most significant barriers, the respondents identified budget and financial constraints as the most significant barriers following the rankings. The Relative Importance Index (RII) for budget constraints in adopting Industry 4.0 is 0.618, highlighting its significance within the oil and gas industry in Nigeria. This is similar to findings from similar studies conducted by (Sayem et al., 2022), which showcased high capital investment (finance) as a significant barrier to I4.0 adoption in manufacturing industries for emerging nations like Nigeria. From a maintenance perspective, (Jasiulewicz-Kaczmarek et al., 2022b) also identified Finance/Budget related barriers tagged as 'high investment required' as one of the most significant barriers to I4.0 implementation. Financial barriers are multifaceted, impacting design changes, workforce training, and ongoing operations. These changes are costly and time-consuming, with expenses varying between organizations. Transitioning from a Condition-Based Maintenance (CBM) approach to full Industry 4.0 integration involves upfront costs for R&D, re-skilling, and up-skilling employees. These investments are essential for leveraging the full potential of new technologies. Additional costs may include maintenance, data management, and transitional downtime. In short, the RII value underscores the financial hurdles organizations face in embracing Industry 4.0. A range of expenses must be factored into strategic planning, from design changes to workforce training.

Next to this barrier is Limited engineering/ technological resources, which ranks as the second most important barrier with an RII value of 0.503. Many studies, including this, have shown that technology is an important requirement or aspect for achieving maturity in Industry 4.0 Implementation. According to (Hajirahimova, 2015), the O&G still lags in technology implementation compared to manufacturing, making this an area requiring more attention for Industry 4.0 integration. One reason for this technological lag is the specialized nature of O&G operations compared to manufacturing. Technologies in manufacturing have seen broader applications and thus have evolved rapidly. The barrier is not just about having adequate technology but also about the challenges of implementing it in a specialized and highly regulated environment. Moreover, the transition to a data-centric model is crucial for effective condition-based maintenance, which also presents a technological challenge. Limited engineering and technological resources are a significant hurdle to Industry 4.0 adoption, requiring attention across multiple fronts, including financial investment, skills development, and regulatory compliance.

TABLE 10
Ranking of barriers affecting integration of I4.0 into CBM in oil and gas sector.

S/No	Barriers	RII	Rank
1	Budget/finance constraints	**0.618**	1
2	Lack of executive/leadership support	**0.479**	3

3	Limited engineering/ technological resources	**0.503**	2
4	Lack of maintenance procedures	**0.328**	9
5	Lack of team integration	**0.400**	6
6	Poor maintenance plan execution	**0.411**	5
7	Lack of competence	**0.427**	4
8	Environmental factors	**0.382**	8
9	Wrong approach/methods	**0.396**	7

So, having all the technological resources available to realise this integration is an important area uncovered from the evaluation.

The RII score of 0.479 for lack of executive/leadership support highlights its role as a notable barrier to Industry 4.0 adoption in Nigeria's Oil and Gas sector. Achieving Industry 4.0's complex technical goals requires substantial resources, both physical and software-based, as well as skilled personnel. Without financial backing and strategic direction from leadership, these critical elements cannot be secured, hindering the successful implementation of Industry 4.0. Therefore, executive support is crucial for navigating this transformation's financial and technical complexities. A study by (Govindan & Arampatzis, 2023a) considers support by leadership as a significant barrier that emerged as the greatest influencer of all other barriers from analysis, especially because leadership is the factor that decides the policy of an organisation towards Industry 4.0 implementation. And in an emerging country like Nigeria, this is no different, as seen from the data gathered. This shows the importance of the leaders and executives in making the integration successful.

Some studies by authors such as (Jasiulewicz-Kaczmarek et al., 2022b), (Horváth & Szabó, 2019) see competence as one of the most significant barriers for Industrial leaders. As seen in this study, most respondents do not possess the required knowledge of I4.0 to maintain a facility with full integration of industry 4.0 technologies. This brings competency to another critical area that must be considered in the oil and gas sector. This study showcases RII of 0.427 for lack of competence as a barrier to I4.0 integration to Condition-based maintenance in the oil and gas companies in Nigeria. This figure quantifies the obstacle, making it easier for industry stakeholders to prioritize it alongside other challenges, such as financial constraints, technological limitations, and leadership support and commitment. Lack of competence in this context does not merely refer to the absence of basic skills; it underscores a critical gap in specialized knowledge and expertise necessary to implement and manage Industry 4.0 solutions effectively.

While the barriers mentioned above with higher RII remain significant barriers to integrating Industry 4.0 technologies into condition-based maintenance (CBM) in the oil and gas sector in Nigeria, other factors such as lack of maintenance procedures, environmental factors, and poor maintenance plan execution also pose challenges. These issues, although not as pronounced in ranking, still warrant attention from organizational leadership. For instance, the absence of robust maintenance procedures can result in the underutilization or misuse of advanced systems, environmental constraints can limit the effectiveness of Industry 4.0 tools, and poor execution of maintenance plans can negate any potential efficiency gains. Collectively, these barriers compound the difficulties faced by the industry in fully adopting and benefiting from Industry 4.0 technologies in their CBM strategies.

5 Conclusion and recommendation

In this paper, we investigated integrating I4.0 technologies into CBM practices in a multinational company. An empirical investigation based on one case study in an oil and gas upstream industry located in Nigeria.

The good level of maintenance experience, limited awareness of the concept of Industry 4.0, recent company's digitalisation journey and barriers to integration of industry 4.0 to CBM are some of key findings of this study. These suggest a need to explore industry 4.0 technologies in Nigeria's oil and gas facilities to take advantage of opportunities associated with integrating I4.0 technologies in their maintenance strategies and, in this case, the condition-based maintenance strategy. Though there have been limited studies in this area requiring industry 4.0 into CBM for the oil and gas industry, this case study analysis provides more insights into the level of integration and barriers to the success of the integration.

The findings further indicate that the organisation has a CBM strategy in place and has generally commenced the journey to digitalisation, which is currently at an infant stage but would need to manage the various barriers such as high cost (budget/finance), limited technological resources and access to the right technology which includes hardware, software, adequate internet availability and professionals in I4.0, lack of competence in I4.0 technology among others to progress. This requires support from the organisation's leadership to develop policies geared toward addressing these barriers and promoting the integration of I4.0 in the CBM strategy.

The measurement model provides an invaluable insights into the interplay of various barriers to Industry 4.0 integration. It presents a compelling case for a nuanced understanding of the intricacies involved in operationalizing such advanced technological paradigms within an established industrial framework. The substantial alignment of the model with empirical data through the SEM approach highlights its potential as a foundational tool for strategizing barrier mitigation in the pursuit of I4.0 integration to CBM in the oil and gas sector.

Employing the Relative Importance Index (RII) theory allowed further evaluation of the significance of the identified barriers to the integration of Industry 4.0 to CBM, increasing the likelihood of succeeding through a focus on eliminating the most significant barriers. The level of importance of these barriers may differ from one organisation to another; however, they are most likely common to all oil and gas upstream industries in developing nations.

Given these, the use of an Industry 4.0 maturity model to guide the implementation of the technologies in the condition-based maintenance strategy is proposed for these oil and gas organisations in developing nations, especially Nigeria. To succeed, a condition-based maintenance framework based on industry 4.0 technologies should be developed to support the maintenance teams' practical work execution and decision-making. There would be a need to upgrade facilities and equipment to function with these Industry 4.0 technologies, which remains an area for consideration by the leadership of the organisations as this could be capital-intensive (high costs). Again, creating educational programs and awareness initiatives to upskill staff as the journey towards integration commences is another critical area. There is a need for sensitization and training programs to make professionals aware of and understand their benefits. Leadership and key stakeholders need to be cognizant of the concept and the benefits of using these technologies in CBM execution as well. So, overcoming these significant barriers remains key to the successful integration of Industry 4.0 into the condition-based maintenance strategy for the oil and gas industry. In line with this study, an ongoing Industry 4.0 readiness model is being developed by the authors to support the integration of Industry 4.0 into the CBM strategy of the oil and gas upstream sector.

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5.1 Contributions

This research constitutes a seminal contribution to scholarly discourse on the operational integration of Industry 4.0 technologies within the framework of Condition-Based Maintenance (CBM) in the Oil and Gas (O&G) Upstream sector within Nigeria. One of the study's foremost contributions would be an exhaustive list of barriers to integrating Industry 4.0 into condition-based maintenance, specifically within the context of developing countries like Nigeria. This would help stakeholders identify issues they may not have previously considered and provides a structured approach to resource allocation and strategy development. To further aid decision-makers, the study ranked these barriers in terms of their importance, enabling a focused effort on overcoming the most critical obstacles first. Although the research is localized to Nigeria's oil and gas sector, the identified barriers could have global relevance. This amplifies the study's value by contributing to the collective understanding of challenges in adopting Industry 4.0 in condition-based maintenance across the oil and gas sectors worldwide. Doing so lays the foundation for the effective implementation of Industry 4.0 technologies into CBM practices, thereby paving the way for enhanced operational performance and the attainment of key performance indices (KPIs). The research serves as an academic milestone and a practical guide for industry practitioners and policymakers in Nigeria's O&G sector.

5.2 Practical implication

This study offers multiple contributions to research, policy, and management practices concerning the integration of Industry 4.0 into Condition-Based Maintenance (CBM) in the oil and gas sector. It comprehensively identifies and ranks key barriers to such integration, offering managers a valuable guide for action. The results highlight the pivotal role of leadership in driving successful implementation, emphasizing the need for strategic roadmaps and targeted investments in Industry 4.0 resources. Furthermore, the study suggests that developing nations, particularly Nigeria, should establish programs to address common barriers like budget constraints, leadership gaps, and limited technological resources. These findings not only deepen the academic discourse on the challenges of adopting Industry 4.0 in Condiiton-based maintenance within the oil and gas sectors but also offer practical insights for industry leaders and policymakers in developing nations, directing their focus towards effective strategies for technology adoption and operational improvement. The study would likely offer actionable recommendations for companies in these sectors, enabling them to plan and execute their Industry 4.0 adoption strategies in maintenance more effectively.

5.3 Limitations and Future Research

This study presents several notable contributions and limitations, which offer directions for future research in the integration of Industry 4.0 into Condition-Based Maintenance (CBM) within the oil and gas sector. First, the study's validity is tempered by a limited sample size and a specific focus on Nigeria, a developing oil-rich nation. The Cronbach's alpha of 0.871 suggests good internal consistency, but the generalization of findings could benefit from expanded sampling across multiple organizations in both developing and developed countries. Future research could employ multiple case studies and use different ranking and prioritizing tools, including Multiple Criteria Decision Making (MCDM) techniques, for comparative analysis. Second, the study concentrates solely on CBM in the oil and gas sector, leaving room for future research to investigate how other maintenance strategies like Total Productive Maintenance (TPM) and Reliability-Centered Maintenance (RCM) could similarly benefit from Industry 4.0 integration. Third, given that this study focuses on upstream operations in a developing nation, extending the research to other economic contexts could yield broader insights. Industry 4.0 is still a relatively new concept, particularly in the oil and gas sector, indicating a need to explore its potential benefits and challenges further. Lastly, future research could explore how the integration of Industry 4.0 technologies with various components of CBM impacts key performance indicators such as equipment availability and overall productivity in the oil and gas sector. This would offer more comprehensive insights into the utility and efficacy of Industry 4.0 technologies for diagnostic, prognostic, and decision-support roles in maintenance within the oil and gas sector.

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TABLE 1
List of the primary industry 4.0 technologies and their applications/capabilities in the area of maintenance

Technology	Description	Application area in maintenance	Reference
Industrial Internet of Things	A system that integrates sensors and computing in an internet-based environment with wireless communication.	Condition monitoring, Opportunistic maintenance, Preventive maintenance, Predictive maintenance, Proactive maintenance, Predictive - Reliability based - Condition oriented - Reactive, condition-based maintenance, prescriptive maintenance, Autonomous maintenance, Maintenance management	(García & García, 2019; Mourtzis & Vlachou, 2018a; Boulouf et al., 2022; O'Donovan et al., 2015; Janak & Hadas, 2015; Lalanda & Morand, 2017; Chiu et al., 2017; Holub & Hammer, 2017; A. Kumar et al., 2019; Zolotová et al., 2020; Sénéchal, 2018; Fusko et al., 2018; Alonso et al., 2018; Kiangala & Wang, 2018; Tsai & Lai, 2018; Dinardo et al., 2018; Alqahtani et al., 2019; Xia & Xi, 2019; Ooijevaar et al., 2019; Olaf & Hanser, 2019; Roy et al., 2016; Simon et al., 2018; Silvestri et al., 2020)
Big data	This refers to the strategy of analysing large volumes of data that are used when traditional data mining and handling techniques cannot uncover the insights and meaning of the underlying data	Predictive maintenance, reactive and proactive maintenance, Condition monitoring and selective maintenance, the perspective of maintenance, Ansari et al. (2018), preventive maintenance, predictive maintenance, Maintenance management	(García & García, 2019; Bumblauskas et al., 2017; Yan et al., 2017; Boulouf et al., 2022; Wan et al., 2017; Chiu et al., 2017; Yan et al., 2017; Kiangala & Wang, 2018; Frieß et al., 2018; Subramaniyan et al., 2018; Hesser & Markert, 2019; Sahal et al., 2020; Roy et al., 2016; Peres et al., 2018; Silvestri et al., 2020)
Simulations	It refers to technologies that use the computer to imitate a real-world process or system.	Condition monitoring, reactive and proactive maintenance, predictive maintenance, Preventive maintenance, Maintenance management.	(García & García, 2019; Kono & Haneda, 2021; Fischer et al., 2020; Terkaj et al., 2015; Susto et al., 2018; Frieß et al., 2018; Subramaniyan et al., 2018; Peres et al., 2018; Silvestri et al., 2020)
Cloud computing	The concept refers to IT services that are provisioned and accessed from a cloud computing provider	Opportunistic maintenance, Predictive maintenance, Condition-based maintenance, proactive maintenance, prescriptive maintenance, Preventive maintenance, Maintenance management. Digital Maintenance	(García & García, 2019; Mourtzis & Vlachou, 2018a; Schmidt & Wang, 2018; Mourtzis et al., 2016; Boulouf et al., 2022; Upasani et al., 2017; Wan et al., 2017; Chiu et al., 2017; A. Kumar et al., 2019; Zolotová et al., 2020; Fusko et al., 2018; Mourtzis & Vlachou, 2018b; Fernández-Caramés et al., 2018; Hesser & Markert, 2019; Xia & Xi, 2019; Silvestri et al., 2020)
Augmented Reality	It is a type of interactive, reality-based display environment that takes the capabilities of the computer-generated display, sound and other effects to enhance the real-world experience;	Remote maintenance, collaborative maintenance, predictive maintenance, Preventive maintenance, Remote maintenance, Autonomous maintenance, condition-based maintenance, Maintenance management.	(García & García, 2019; Scurati et al., 2018a; Elia et al., 2016; Fasuludeen Kunju et al., 2021; Ceruti et al., 2019; Boulouf et al., 2022; Aschenbrenner et al., 2016; Masoni et al., 2017; Wan et al., 2017; Fernández-Caramés et al., 2018; Scurati et al., 2018b; Gattullo et al., 2019; Roy et al., 2016; Silvestri et al., 2020)
Autonomous Robots	These are robotic systems or robots that physically interacts with humans in a shared workspace.	Autonomous maintenance, remote maintenance, Inspection, planned maintenance, disturbance handling, Predictive maintenance, Maintenance management.	(García & García, 2019; Friedrich et al., 2014; Schiffer et al., 2010; Parker & Draper, 2014; Wong et al., 2018; Boulouf et al., 2022; Silvestri et al., 2020)

Additive manufacturing	It is a manufacturing technology that creates three-dimensional (3D) solid objects using a series of additive or layered development frameworks.	Maintenance management: Maintenance time management, spare parts inventory and component assembly cost reduction, ease of replacement of discontinued parts; Self-maintenance and Remote maintenance, Maintenance management.	(García & García, 2019; Fasuludeen Kunju et al., 2021; Wessel et al., 2016; Ceruti et al., 2019; Boulouf et al., 2022; Silvestri et al., 2020)
Cyber Security	These are preventive methods to protect information from being stolen, compromised, or attacked.	Maintenance management	(García & García, 2019; Zarreh et al., 2019; Thaduri et al., 2019; Ilhan & Karakose, 2019; Nikhil et al., 2020; Powell et al., 2019; Boulouf et al., 2022; Silvestri et al., 2020)
Horizontal And Vertical Integration	Integration of data at all levels (from management to shop floor) of a company and between (from suppliers to customers) companies in the supply chain according to their data transfer patterns. They are usually connected through the Internet of Things application.	Maintenance management	(Ansari et al., 2019; Thoben et al., 2017; Boulouf et al., 2022; Silvestri et al., 2020)

TABLE 2
Exclusion and Inclusion Criteria

Criteria	Inclusion	Exclusion
Literature type	Indexed journals, book chapters, conference proceedings, industry reports	Non-indexed journals, magazine articles
Language	English	Non-English
Timeline	Timeline Between years 2015 and 2022 (inclusive)	Before the year 2015
Access	Paper available in full-text	Access to the document is restricted
Research title	The paper provides research information on Industry 4.0 integration barriers or challenges.	The paper does not provide research information on Industry 4.0 integration barriers or challenges.
Key Research information	Contains and discusses barriers to Industry 4.0 integration in manufacturing or O&G industries	Does not contain and discuss barriers to Industry 4.0 integration in manufacturing or O&G industries
Article type	New barriers relating to Industry 4.0 integration to industries of interest are identified with information on the identified barriers.	A paper reviews existing or previously identified barriers and does not identify any new ones.

TABLE 3

Barriers to Industry 4.0 integration into CBM in the O&G industry

Categorization themes	**Reference (Source)**	**Barriers**
Financial	(Raj et al., 2020; Kamble et al., 2018b; Jasiulewicz-Kaczmarek et al., 2022a; Erol et al., 2016; Kiel et al., 2017; Müller, 2017; Pech & Vaněček, 2022; Schröder, 2016; Orzes et al., 2019; Blessing & Amoah, 2023; Jena & Patel, 2022; Horváth & Szabó, 2019; Digital, 2016; Ghadge et al., 2020; Pavan et al., 2022; Pech & Vaněček, 2022; Oke & Arowoiya, 2021; Moktadir et al., 2019; P. Kumar et al., 2021; Tortorella et al., 2021; Raj et al., 2019; Kiss et al., 2023; Yilmaz et al., 2022; Chauhan et al., 2021; Bakhtari et al., 2021; Kiel et al., 2017; Pavan et al., 2022; Bashar Bhuiyan et al., 2020); Jena & Patel, 2022; Lu et al., 2019; Raj et al., 2019; Oke & Arowoiya, 2021; Kamble et al., 2018b; Jasiulewicz-Kaczmarek et al., 2022a; Gökalp et al., 2017; Orzes et al., 2019)	Budget/finance constraints
Leadership and Management		Lack of executive/leadership support
Technical Resource		Limited engineering/ technological resources
Procedures		Lack of maintenance procedures
Integration/Collaboration		Lack of team integration
Planning and work execution		Poor maintenance plan execution
Competency		Lack of competence
Environment		Environmental factors
Methods/Methodology		Wrong approach/methods

TABLE 4
Profile of the selected interview participants

Interviewee	Maintenance experience	Role	Experience in the company
A1	20 years	Manager	16 years
A2	11 years	Manager	11 years
A3	22 years	Maintenance Supervisor	21 years
A4	18 years	Maintenance Supervisor	18 years
A5	17 years	Team leader	14 years
A6	11 years	Team leader	11 years

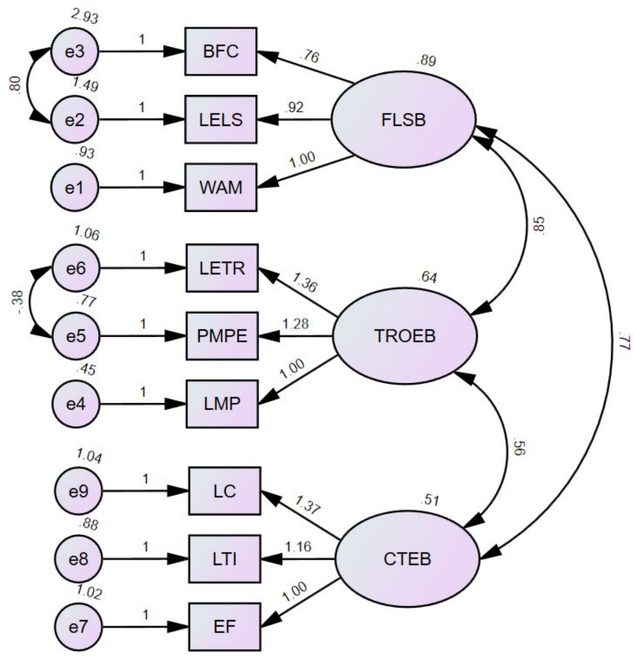

FIGURE 1. Measurement Model for the barriers to I4.0 integration

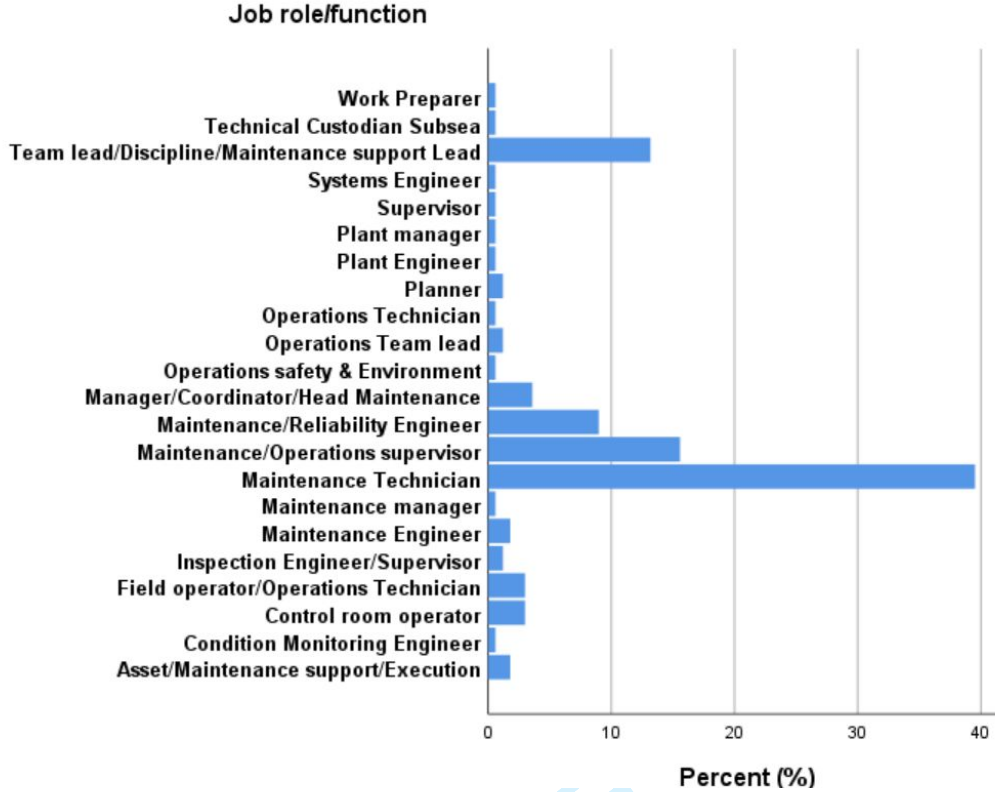

FIGURE 2. Job role/function in the maintenance team of the organisation

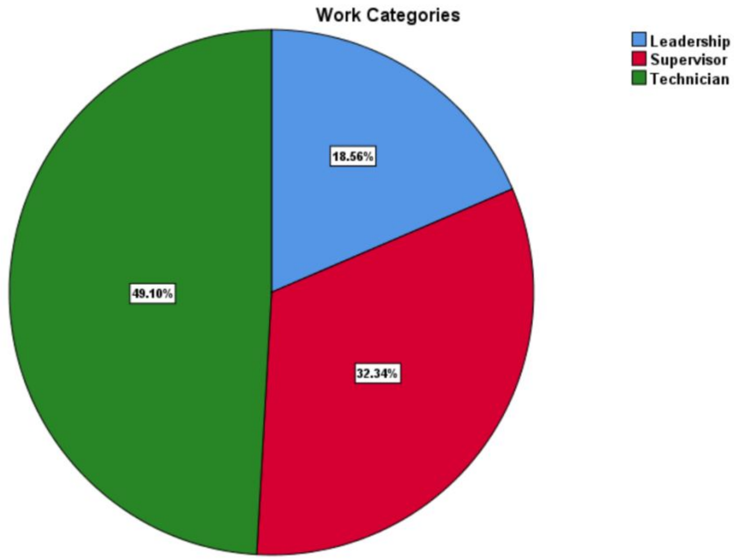

FIGURE 3. Work categories in the organisation

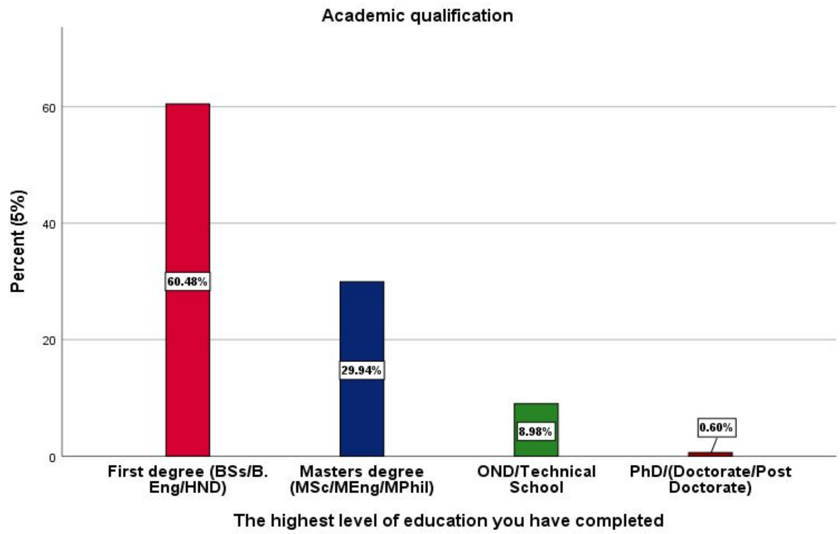

FIGURE 4. Academic qualification of respondents

TABLE 5
Years of experience

Years	Frequency	(%)
2 to 5 years	19	11.377246
6 to 10 years	32	19.161677
11 to 15 years	28	16.766467
16 to 20 years	46	27.54491
21 to 25 years	19	11.377246
Above 26 years	25	14.97006

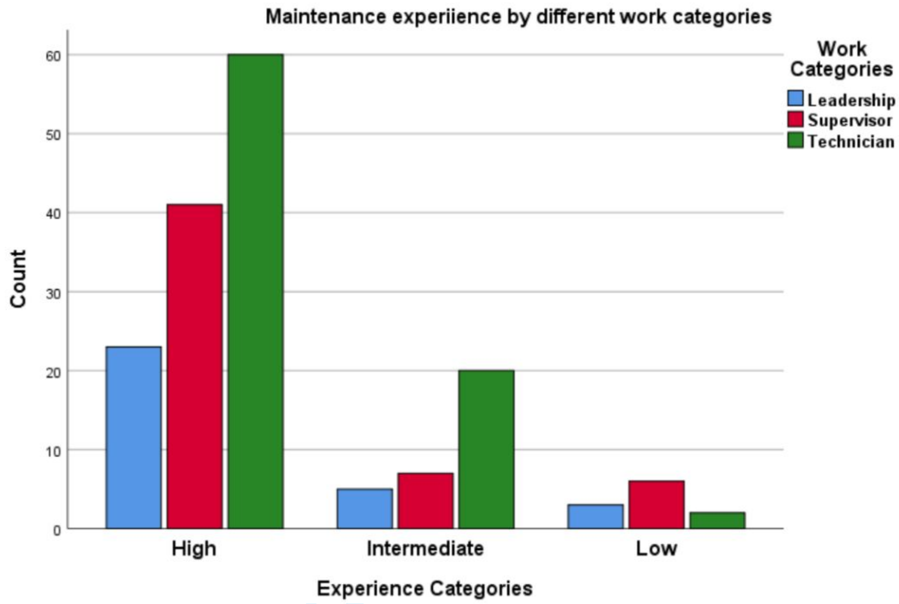

FIGURE 5. Maintenance experience of respondents from different work categories

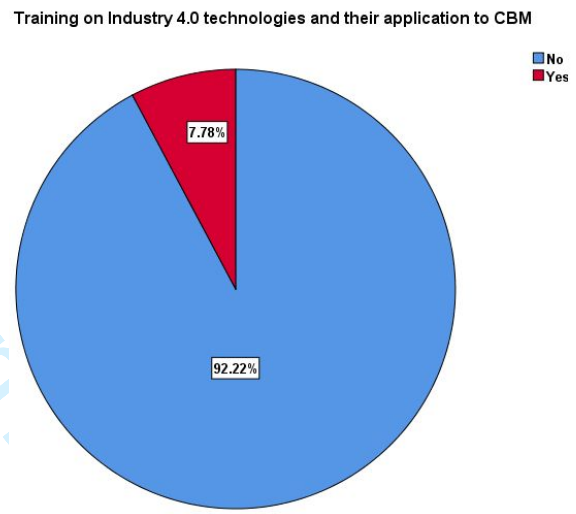

FIGURE 6. Training on Industry 4.0

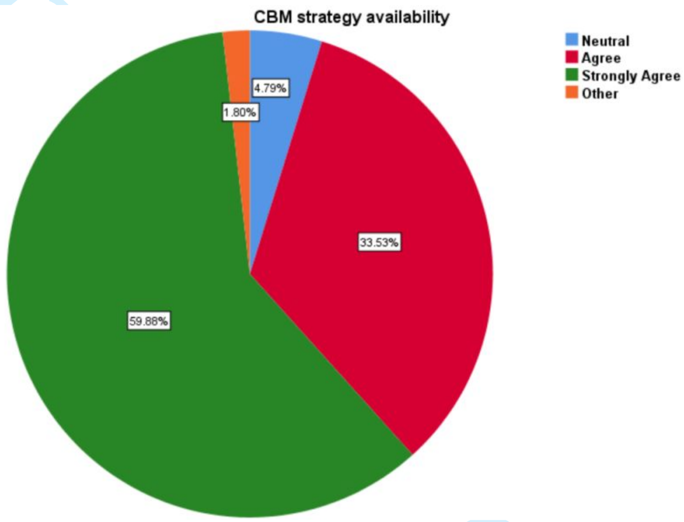

FIGURE 7. CBM strategy availability

TABLE 6
Goodness-of-Fit

Fit Indices	Recommended Value	Reference	Obtained values
P-value	Insignificant	Bagozzi & Yi, (1988)	0.460
CMIN/df	3 - 5	Less than 2 ((Wheaton et al., 1977)) to 5 (Schumacker & Lomax, 2010)	1
GFI	> 0.9	Hair Jr et al., (2010)	0.972
CFI	> 0.9	Bentler, (1990)	1
TLI	> 0.9	Bentler, (1990))	1
SRMR	<0.08	Hu & Bentler, (1999)	0.0293
RMSEA	<0.08	Hu & Bentler, (1999)	0.001

TABLE 7
Regressions

			Estimate	S.E.	C.R.	P	Label
WAM	<---	FLSB	1.000				
LELS	<---	FLSB	.916	.116	7.911	***	par_1
BFC	<---	FLSB	.763	.143	5.352	***	par_2
LMP	<---	TROEB	1.000				
PMPE	<---	TROEB	1.280	.130	9.864	***	par_3
LETR	<---	TROEB	1.360	.145	9.366	***	par_4
EF	<---	CTEB	1.000				
LTI	<---	CTEB	1.162	.172	6.742	***	par_5
LC	<---	CTEB	1.374	.198	6.947	***	par_6

TABLE 8
Variances

	Estimate	S.E.	C.R.	P	Label
FLSB	.892	.193	4.624	***	par_12
TROEB	.643	.113	5.674	***	par_13
CTEB	.509	.133	3.839	***	par_14
e1	.928	.134	6.905	***	par_15
e2	1.492	.179	8.334	***	par_16
e3	2.935	.321	9.148	***	par_17
e4	.449	.058	7.787	***	par_18
e5	.771	.108	7.125	***	par_19
e6	1.061	.142	7.458	***	par_20
e7	1.019	.120	8.471	***	par_21
e8	.879	.111	7.948	***	par_22
e9	1.042	.136	7.652	***	par_23

TABLE 9
Covariances

			Estimate	S.E.	C.R.	P	Label
FLSB	<-->	TROEB	.853	.124	6.884	***	par_7
TROEB	<-->	CTEB	.562	.099	5.690	***	par_8
FLSB	<-->	CTEB	.769	.132	5.813	***	par_9
e2	<-->	e3	.799	.182	4.393	***	par_10
e5	<-->	e6	-.375	.092	-4.068	***	par_11

TABLE 10

Ranking of barriers affecting integration of I4.0 into CBM in oil and gas sector.

S/No	**Barriers**	**RII**	**Rank**
1	Budget/finance constraints	**0.618**	1
2	Lack of executive/leadership support	**0.479**	3
3	Limited engineering/ technological resources	**0.503**	2
4	Lack of maintenance procedures	**0.328**	9
5	Lack of team integration	**0.400**	6
6	Poor maintenance plan execution	**0.411**	5
7	Lack of competence	**0.427**	4
8	Environmental factors	**0.382**	8
9	Wrong approach/methods	**0.396**	7

Reviewer Suggestion and Revision Log - Integration of Industry 4.0 to the CBM Practices of the O&G Upstream Sector in Nigeria

The authors sincerely acknowledge the valuable contributions of the two anonymous reviewers for their insightful and constructive input during the review process. After careful consideration of the recommendation item, revisions below were duly implemented.

Item	Reviewer No	Review Comment / Suggestion / Question	Author Comments	Revision Action
1	1	I went through this revised version R1 and I have to say that it has been much improved. In my opinion there is no need for further changes. Great job!	Acknowledged.	No further actioni taken
8	1	I want to suggest to the author not to use the graphs. Instead, I recommend the author use different approaches to highlight its results and outcomes. Instead, if the author can use the SEM approach for better understanding or develop the conceptual framework, it would add more value to the study and make it look professional.	Acknowledged	1.Utilizing the Structural Equation Modeling (SEM) approach, I constructed a measurement model that elucidates the relationship between nine barrier indicators, identified through the survey, and the overarching latent variable conceptualized as "Barrier." Recognizing the multifaceted nature of these barriers, I segmented them into three distinct groups, thus creating a tripartite measurement model comprising three latent constructs. 2. I included a sentence at the abstract to update the methodolgy which now includes an SEM apporach - use of a measurement model 3. At the conclusion, I included a paragraph that concludes about the Measurement Model included as part of the study. 4. All new inputs including the change to the Figure & Table numbers as a result of the inclusion of more Figures and Tables are in blue fonts.