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# Development of an Experience Transfer and Tacit Knowledge Management Platform for Major Overhauls, Outages, Shutdowns and Turnarounds (MoOSTs)

A thesis Submitted to the University of Manchester for
the Degree of Doctor of Philosophy (PhD)
in the Faculty of Science and Engineering, School of Engineering

2022

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   Journal Name:- Energies
   Status:- Published, Volume 13(7), 1721, 2020
   Indicators:- Cite score =4.7 Scopus, Impact factor = 3.004

2. Paper title:-Knowledge Criticality Assessment and Codification Framework for Major Maintenance Activities: A Case Study of Cement Rotary Kiln Plant
   Authors:- Iheukwumere-Esotu, L.O, Yunusa-Kaltungo, A.
   Journal Name:- Sustainability
   Status:- Published, Volume 13(9), 4619, 2021
   Indicators:- Cite score =3.9 Scopus, Impact factor = 3.251

3. Paper title:-Knowledge Management and Experience Transfer in Major Maintenance Activities: A Practitioner's Perspective
   Authors:- Iheukwumere-Esotu, L.O, Yunusa-Kaltungo, A.
   Journal Name:- Sustainability
   Status:- Published, Volume 14(1), 52, 2022
   Indicators:- Cite score =3.9 Scopus, Impact factor = 3.251

4. Paper title:-Development of an interactive Web-Based Knowledge Management Platform for Major Maintenance Activities: Case study of Cement Manufacturing Systems
   Authors:- Iheukwumere-Esotu, L.O, Yunusa-Kaltungo, A.
   Journal Name:- Production Planning and Control
   Status:- Submitted
   Indicators:- Cite score =8.2 Scopus, Impact factor = 7.044

## PEER-REVIEWED CONFERENCE PUBLICATIONS

1. Paper title:- A Systematic Analysis of Research Based Evidences of Major Overhauls, Outages, Shutdowns, Turnarounds (MoOSTs) Management
   Authors:-Iheukwumere-Esotu, L.O, Yunusa-Kaltungo, A.
   Conference Name:- International Conference on Maintenance Engineering IncoME-V 2020: Proceedings of IncoME-V & CEPE Net-2020, Mechanisms and Machine Science, Vol 105. Springer Cham, 2020
   Status:-Published

2. Paper title:- A Multi- Attribute Knowledge Criticality Framework for Ranking Major Maintenance Activities: Case Study of Cement Raw Mill Plant. ASME's International Mechanical Engineering Congress & Exposition held virtually on November 1-5, 2021
   Status:- Published

# ABSTRACT

The ability to cope within the age of industry 4.0 as well as manage new challenges facing industries that perform major maintenance activities due to the effects of COVID-19 pandemic have resulted into increased requirements to improve the predicted outcomes of major maintenance activities, and ensure that stakeholders expectations are met. Knowledge management (KM) strategies and effective knowledge management systems (KMS) have both been championed across industries involved with project-based activities as being vital for informed as well as improved decision-making. Ironically, within the body of knowledge, there are limited research-based studies and proposals that provide roadmaps on the design, implementation, evaluation as well as efficacies for KM strategies and KMS specifically for managing major overhauls, outages, shutdowns and turnarounds (MoOSTs). Hence, there is an urgent need to explore possible research that could potentially improve the accuracy of predicting and/or managing MoOSTs outcomes within the confines of stated challenges, by developing a MoOSTs specific KM strategy and KMS.

However, previous research based efforts on developing KM strategies and KMS proposals within MoOSTs have been fraught with many challenges. Perhaps, some of the challenges encountered, which have affected the viability of research efforts within MoOSTs, might be due to its inherent characteristics. The persisting problems within the discipline would seemingly advocate for the integration of a research approach that incorporates the strengths of both theoretical underpinnings as well as practical orientations. While the validity as well as the academic relevance of studies focused on only theoretical underpinnings is undeniably, their potential to simulate experiential learnings within practice is arguably lower than when case studies are applied. Since MoOSTs is an applied science, with huge practical and managerial implications, it is strongly advocated that a research approach for the design, implementation and evaluation of an effective KMS, be strongly linked to evidences from both research and practice.

Therefore, this thesis strongly advocates for the adoption of a case study approach as an appropriate methodology for examining challenges and demonstrating possible solutions for developing an effective KMS within MoOSTs. Consequently, the proposal of the knowledge management and experience transfer platform developed within this thesis, present a unique opportunity for organizations within industries that perform MoOSTs to identify their most critical maintenance activities and improve on their ability to execute their core business functions as well as capture and retain specialist knowledge for reuse in subsequent MoOSTs cycle. MoOSTs organizations can achieve this by adopting electronic based knowledge management systems (KMS) that are easily integrated with their existing operational systems.

The interactive web-based knowledge platform for a MoOSTs intensive industry termed as a “MoOSTs knowledge platform” (MoOSTsKP) is designed to manage both tacit and explicit knowledge during MoOSTs. The MoOSTsKP has been developed with many objectives namely; to identify critical maintenance activities that support capture and retaining of specialist knowledge possessed by experienced professionals; and to overcome real-time knowledge capture limiters especially time restriction and temporary project environment, which is a main consideration within MoOSTs.

# DECLARATION

I declare that no portion of the work referred to in this report has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

# COPYRIGHT STATEMENT

# ACKNOWLEDGMENT

My colossal gratitude goes to the Almighty God for the strength and wisdom I received through His Grace during my PhD research.

I would like to express my sincere appreciation to the Petroleum Technology Development Fund (Federal Government of Nigeria) for wholly sponsoring each element of my Ph.D research at the University of Manchester (UK).

My sincere gratitude is extended to Dr. Akilu Yunusa-Kaltungo (my PhD supervisor) for providing guidance, support, motivation and encouragement through the entire length of this research. Through his efforts I was able to grow immensely as an early career researcher and appreciate the enormous responsibilities that comes with the pursuit of a lifetime of intellectual excellence. I am forever indebted to Dr. Akilu because he went over and beyond so many times to see me succeed and finish this work.

I would also like to extend my heartfelt gratitude to Nnamdi Esotu (my husband) for providing his unlimited support through the years it took to complete this PhD. He was my source of constant encouragement whenever I was weary. Thank you for all the nights you stayed waiting for me to get home. Thank you for all the hot meals you kept waiting for me. Thank you for being a good husband and father to the boys. Thank you for being a provider and my protector. Thank you my love!

I would like to thank my parents, Mr Iheukwumere and Mrs Hope Iheukwumere, sister (Ann Iheukwumere), brother (Okechukwu Iheukumere), inlaws, (the Esotus'). A big shout out goes out to my sons, Ogenna Esotu and Chimdi Esotu, I call them my PhD babies, I had them both during the degree and they bore the brunt of sacrifices that my degree mandated.

Finally, I would like to acknowledge the profound impact that my friends had on my research output. To my ever caring and steadfast friend Judith Ugbeh, a friend like no other. To Daniel Abara my worthy friend. Fikayo Adepoju my gist mate, our struggles were so relatable. To Luwei Kenisuomo and Edet Afangide, I will not forget all our political discussions on Pariser D floor at the University of Manchester, as well as the immense support you both rendered to me. I would also like to say thank you to my Tanzanian friend Neema Opiyo, for all her kind words during our time spent on this journey together.

# DEDICATION

This work is dedicated to my mother, Mrs Hope Ikechi Iheukwumere, for being the first person to believe in me. It is because you walked, that is why I can fly. Thank you for being my first teacher. Thank you for encouraging me to read as a child, for buying all my novels even when I would always misplace them. Thank you for all the nights you did my science projects with me. Thank you for watching my babies while I completed my PhD, thereby putting your life on hold. Thank you for all your fasting and prayers to see I succeed. I love you mum.

## QUOTE

For the revelation awaits an appointed time; it speaks of the end and will not prove false. Though it linger, wait for it. It will surely come and will not delay

NIV Habakkuk 2 vs 3.

# 1 INTRODUCTION

## 1.1. Introduction

The recent COVID-19 pandemic sweeping through the whole world, have changed human activities significantly. Maintenance organizations across various industries would need to adapt their operations to the conditions of the "new normal" [1]. This is in addition to existing considerations of a new industrial stage within industry 4.0, i.e. integration between maintenance operations systems and information communication technologies (ICT), which is changing competition rules and reframing adoption of Internet of Things (IoT) concepts and digitization [2]. The specific measurements of maintenance performance indices are now essential elements for strategic thinking in both service and manufacturing industries, with emerging research areas in major maintenance activities [3]. Major overhauls, outages, shutdown and turnarounds (MoOSTs) are essential maintenance activities, that contribute to maintaining the reliability of industrial plant's desired production capacity as well as, to ensure that the overall business goals are sustainable [4]. MoOSTs are important contributors to the appropriate management of plant assets and facilities by providing increased levels of availability. The reliability and integrity of equipment used in the process and continuous production industries deteriorates over time due to excessive wear and tear as such, MoOSTs activities are required to ensure the reliability and safety of such plants.

In the literature, there are several descriptions and shared perspectives of what MoOSTs are, [5] described the important role played by MoOSTs in sustaining the long term stability and continuous production of plant assets. Elwerfalli et.al, [6] described MoOSTs as an important maintenance management philosophy for the total periodic shutdown of plant facilities for a certain time to carry out maintenance activities which are associated with inspections, replacements, overhauls and repairs according to the scope of work in order to achieve total asset life cycle optimization.

The descriptions of some activities that are planned for in an individual MoOSTs event [7], [8] might include maintenance activities such as, inspections, testing, de-bottlenecking, revamps, repairs, overhauls and part replacements. While [9] described MoOSTs as large scale maintenance activities in major process and continuous production industries for the purpose of improving reliability and decreasing unscheduled breakdown of assets. Meanwhile, [10] described MoOSTs as crucial activities in process industries where the periodic plant shutdown is done to allow for inspections, repairs, replacements and overhauls so as to sustain the reliable process for the whole supply chain and cater to a wide range of customers.

## 1.2. Why MoOSTs is Important?

MoOSTs are governed by appropriate maintenance actions which are expected to ensure that the overall business objectives are achieved [8], [10]. For instance, [11] stated that to adapt to drastic changes in the global market organizations have to ensure that they have reliable production plants and high production efficiency which reduces costs, achieved through high maintenance productivity and the successful implementation of MoOSTs strategy. Pokharel and Jiao [12] emphasized on the seemingly importance of MoOSTs in the petrochemical industry in avoiding unscheduled breakdowns that can impact significantly on revenues. In the study by [12], it was stated that in many countries across the world, MoOSTs are mandatory in order to meet internal maintenance audit and statutory requirements. Although, MoOSTs have significant impact in continuous production and/or operations industry in increasing critical factors such as, reliability, productivity and reducing maintenance costs, but it can also result in loss of revenue running up to millions of dollars if not properly managed. According to [13], on average MoOSTs can last up to 20-60 days, and could utilise about 1500-2,000 extra skilled contractor workers performing various tasks, with likelihood of costs that can reach up to 35-52% of the maintenance budget in an individual or whole plant shutdowns event across different industries.

In the literature, there are three identified strategy for determining which assets and plant facilities are selected for MoOSTs [8], [14]. Firstly, assets that are critical to the operation of the plant and cannot be taken down without shutting the plant. Secondly, assets with defects which were identified through routine maintenance checks, and/ or a condition monitoring system but cannot be taken down whilst in operation. Thirdly, assets which do not require the plant to be taken down, but are performed based on the opportunity provided during MoOSTs. However, the uniqueness of assets comprised in the bulk of activities performed during MoOSTs may lead to delays that are most evident in systems where failures are not self-revealed, especially in production critical systems, whereby running inspections are impractical [15]. Consequently, MoOSTs management is particularly burdened with overt reliance on specific inspections of equipment during execution phase, as well as constraints, such as separation of asset owners and complex accountability for asset management, which makes the measurement of asset maintenance performance and its continuous control and evaluation critical [5].

Furthermore, during MoOSTs there is an overt reliance of skilled workforce with greater dependencies on external multidisciplinary workforce due to large amount of activities to be performed at a predetermined short time frame, which could comprise of arrays of interrelated activities, executed at the same time, in the same place and at different levels of the plant [16][17]. This leads to increased possibilities of uncertainties via emergent jobs, accidents, errors, and scope changes that makes planning, preparation and execution complex, and these are far more than normal compared to what is obtainable in engineering procurement and construction (EPCs) projects or even routine maintenance activities. Hence, these differences are even more conspicuous during MoOSTs activities execution phase, determined to be the phase with the most inherent risk, this is because it is characterised by discovery of large numbers of unplanned and/or emergent work as well as strict activities regimes that are often associated with reduced margins of error [7]. However, the execution phase, as well as other phases within MoOSTs provides immense opportunity for the maintenance organizations to capture knowledge and foster expertise transfer within the organization due to the large number of staff and contract workers performing large-scale as well as complex maintenance activities at an instance [13].

## 1.3. Why Current Research Approach within MoOSTs Needs to Change

Recently, MoOSTs management have attracted the interest of many researchers and practitioners mostly due to its significant impact on plant performance [11], [18]–[20], but the inability of decision makers to achieve predicted outcome is a major challenge. This might be because despite the many advances made in techniques for predicting corrosion and deterioration, the associated risks of discovering additional work exists. Such additional work associated with MoOSTs might come from a number of sources and actions such as; oversight in determining project work scope, equipment deteriorating faster than predictions made from predictive tools analysis, and/or damages associated with opening up the equipment for inspections etc [21], [22]. The many challenges associated with planning and management of MoOSTs, are not limited to but also include management of uncertainty, resource constraints, unavailability of spares, complex activity relationships, and organizational behaviours [23]. Traditional project management techniques such as critical path method (CPM), and programme evaluation review technique (PERT) have been used to manage MoOSTs [5]. Unfortunately, delays, cost overrun and uncompleted activities in MoOSTs are commonly observed, thus limiting the effectiveness of applying traditional project management methods alone [18], [24].

Prior research efforts within MoOSTs were aimed at identifying elements perceived to be critical performance indicators that could overcome such challenges and make useful predictions, such as general information gathering, increased participation in supply chain effectiveness, improving lessons learned and sharing best practices [25]. The culmination of such research efforts have been reflected in numerous ways that are not limited to the adoption of strategies in practice that emphasises large-scale data gathering and information processing (inspection records, designs, drawings, historical data and lessons learned etc) [26]. However, because big data does not feature only large data volumes and high speed data collection but also data with complicated issues, which imposes challenges in analysis, the efficacy of current strategies for managing large data within MoOSTs for effective prognosis is limited [26]. The increasing importance of MoOSTs, as an effective action for improving predictive and prescriptive maintenance of production systems including equipment and physical assets which will be the most important application areas of industrial analytics within the next three years [27].

Therefore, a significant change in current research direction is required. In addition, industry 4.0 has revolutionised industrial processes integration of information and communication technologies (ICT) across major industries and has also been a major factor in encouraging new perspectives on how crucial data management is to MoOSTs [28]. Where industry 4.0 implies a revolution where industrial processes integrate computer tools to facilitate the handling of large amounts of data and related information, as well as their transfer and interpretation, because previous means for storing information are restrictive for handling large data that are generated due to, the interconnectivity of most organizations global systems [29]. Hence, with the rapid advancement and development of information and communication technologies (ICT) and integration of maintenance process within these frameworks, it might imply that most organizations are facing challenges and at the same time competency needs [30], [31]. In practice, competency challenges are dire because human operators are key resources within MoOSTs organizations, since such workers are aware of specific technological processes [32], [33].

## 1.4. Knowledge Management and Experience Transfer during MoOSTs as Potential Solutions

In today's knowledge-based economy, maintenance organizations can not underestimate the importance of effective Knowledge management (KM), because the two fields of knowledge and maintenance are key to obtaining competitive advantage [32], [34]. According to Ambani et al.,[18] knowledge is the most valuable asset of an organization because it enable it to differentiate itself from its competitors as well as compete efficiently and effectively to the best of its ability. KM facilitates the systematic identification, acquisition, storage/retention, transfer and utilization of knowledge by individuals, teams and entire organizations to reach their strategic and operational goals [35]**.** KM is not an end in itself, but fundamentally entails capture and reuse which in turn help organizations to prevent failures as well as identify new solutions to problems already faced by the organization [36]. KM is particularly important for project-based learning, because the systematic identification of knowledge and retention of project experiences enables an organization to compare the performance of its various projects, then document its most effective problem-solving mechanisms for future use to gain competitive advantage [36], [37].

A major challenge facing MoOSTs organization is an inability to harness the knowledge possessed by both internal employees and outsourced labour resources acquired from the awareness of performing MoOSTs over long periods of time alongside effective conversion into corporate knowledge, which can be shared and properly managed throughout the organization [38]. The harnessing of knowledge often proves challenging because personal knowledge possessed by employees are mostly tacit knowledge and employers as well as outsourced experts who leave during any of these reasons including but not limited to; project closure, mergers, reorganization, downsizing or culture change etc., take away such valuable knowledge, skills and experiences [38], [39]. Notwithstanding the above, the KM aspect of MoOSTs as it relates to capture and transfer of tacit knowledge is a narrowly understood and explored area in MoOSTs discipline, one of such reason being the difficulty in capturing engineering knowledge from people based on temporary activities [40]. As such, very limited studies are available on tacit knowledge capture and experience transfer platforms within MoOSTs.

## 1.5. Gaps in MoOSTs Knowledge Management Research

There are several important research gaps that need to be addressed to improve and expand knowledge management and experience transfer's research as well as it applications in MoOSTs. The first gap is that there have been limited research that have undertaken systematic literature reviews (SLRs) to determine the knowledge management challenges specifically related to MoOSTs management. One of the few review studies within MoOSTs which have identified the knowledge gap within this discipline, was by [41], here the issue of adoption of benchmarking 'best practices' in order to improve organizational capabilities based on a literature review covering practices from various companies operating in the power industry was presented. Another, recent publication [25] synthesized available findings on turnaround maintenance (TAM) studies from investigating trends in turnaround maintenance planning and identifying systems gaps in current systems approach, this study identified the potentials of knowledge management as a key gap in existing research. However, as useful as the information triangulation performed in the study were [22] a detailed action driven research for effectively intra and inter sectoral learning framework was missing. The practical implications of the limited availability of review studies might have contributed to the under development of MoOSTs as compared to other industrial maintenance elements such as; Condition monitoring [42]–[44]. Maintenance planning [45]. Maintenance optimization [46]–[48]. General maintenance management [49] that have several literatures review studies which capture significant systematic knowledge trends that can facilitate knowledge capture and transfer.

Furthermore, in the literature, other complex elements which further constrains decision-makers in MoOSTs from satisfactorily achieving predetermined objectives have been identified, one of which is the lack of a formalized approach for capturing tacit knowledge from experienced practitioners [22], [50]. Consequently, because MoOSTs is an applied discipline, significant human endeavors are required in the planning and management, which makes it pertinent to examine and obtain the perspectives of experienced MoOSTs practitioners [51].

Therefore, it is imperative to conduct an empirical study across diverse industries involved in MoOSTs activities to obtain the perspectives of practitioners, in order to validate the findings generated from the SLR. This should help determine the extent of alignment between research and practice, as well as probe underlying causes of any alignments or misalignments.

Another research gap, identified from this study, was concerned with developing an approach for assessing barriers to knowledge management with emphasis on capture and transfer of expertise specifically developed for managing MoOSTs. Consequently, there are evidences supporting arguments that favours unique approaches to sharing knowledge and facilitating experience transfer within projects, which depend heavily on social practices and patterns in organizational activities [52].

Existing project management based studies [53]–[55] have focused on identifying and reviewing potential knowledge sharing barriers within project management organizations and environments, which although useful in order to provide a comprehensive and structured starting point for effective audit systems, do not present a holistic approach for identifying and prioritizing barriers to knowledge management and MoOSTs. Moreover, in the literature, it was observed that the use of hybrid engineering failure analysis approaches alongside multi-criteria decision-making analysis (MCDA) for identifying and prioritizing barriers to knowledge management and experience transfer within MoOSTs to encourage deep learning acquired through experience rather than information gathering activities is scant [20], [25], [56].

Moreover, the continued reliance on utilizing information embedded within maintenance management system (MMS) as the most important decision-making tool for providing technical support when performing maintenance related tasks is over stated [57], [58]. This is because, as useful as these existing databases and information management systems are in identifying lagging indicators (generating audit and/or post mortem reports, as well as, suggestions for measuring and storing such captured information), their ability to support prognosis and sustainable tacit knowledge management for enhanced decision-making are quite limited [59]. Therefore, research based studies within maintenance, can leverage on different techniques such as, expert opinion data (based on years of knowledge acquisition), developing engineering as well as, applying mathematical relationships from prior information and past experiences on similar datasets to discern learning effects, reducing the steepness of learning curves and provide insights into maintenance activities [26].

Consequently, it is imperative to intensify research efforts towards attainment of a KM criticality analysis strategy that aim to provide complementary solutions for prognosis and enhanced decision-making from critically assessing maintenance tasks. The purpose of such KM criticality analysis strategy is to identify elements of maintenance activities during MoOSTs and prioritize them, in a bid to establish the most critical maintenance activities. This is of immense use to the maintenance organization because such criticality analysis can provide information leading to continuous improvement and learning from experience.

The last gap argues that there is limited research in MoOSTs to develop a KMS that can facilitate organizational learning, competency building with lessons learned from previous projects and organizational historical information [60], [61]. According to [62] the failures of KM solutions within industries involved in projects could be due to lack of the mechanisms, processes, more specifically databases that provide formal structure and/or strategic systems for knowledge transfer i.e. presenting the huge data and information in such a way to be used in ways specific to the organization processes. Furthermore, most of the KMS in literature were developed to manage mostly explicit knowledge, known to be less complex to manage compared to tacit knowledge. Therefore, because there are limited research investigating knowledge capture and transfer as a possible mechanism for managing MoOSTs, there is need for a proposal for capturing tacit knowledge and facilitating experience transfer within this discipline.

In summary, the thesis is encompassing showing the rigour in research leading up to the effective demonstration of the implantation of a knowledge management system for a MoOSTs intensive industry termed as a "MoOSTs knowledge platform" (MoOSTsKP). A systematic literature review to determine the current state of research within MoOSTs was undertaken. In addition, trends and limitations of existing knowledge activities and technology utilised in project-based activities are investigated to reinforce the need for the thesis direction. The research philosophy on which the knowledge platform is built on i.e integration of MoOSTs criticality assessed parameters for identification of critical MoOSTs activities as well as the steps to building the knowledge platform aimed at overcoming the identified barriers to KMS are shown. Validation of this early stage development of the MoOSTsKP is achieved by means of expert opinion, with provision for comments and recommendations for improving the knowledge platform.

## 1.6. Research Aim and Objectives

The aim of this research is to develop and comprehensively evaluate approaches for, identifying and prioritising barriers to knowledge management and experience transfer in major maintenance activities, as well as identifying and prioritising critical maintenance activities during MoOSTs, to enable the design and evaluation of a research-based generic approach that can be adapted to different case-based models within practice in the form of an interactive web-based knowledge platform for knowledge capture and experience transfer during MoOSTs, so that the loss of knowledge and expertise in this discipline can be significantly minimised.

Its objectives are:

i. **Research Objective 1:** To conduct a SLR which comprehensively identifies trends, gaps and limitations in MoOSTs research on the basis of its complexities, to establish an overall picture of research methods, demographic information and selections of appropriate principles governing its successful management; and to identify the challenges in MoOSTs that are specific to knowledge management.

ii. **Research Objective 2:** To conduct a comparative study across diverse industries involved in MoOSTs activities to obtain the perspectives of practitioners on the knowledge management challenges which are identified in real-world practices during MoOSTs, to validate the findings generated from the prior SLR;

iii. **Research Objective 3:** To develop a generic approach by combining engineering failure analysis tools and multi-criteria decision-making (MCDM) techniques that can be adapted to different case-based models within practice capable of identifying and ranking barriers to knowledge management and experience transfer based on the perceptions of experts who have significant involvements in MoOSTs, to enable the selection of appropriate solutions specific to the individually identified and ranked knowledge barrier;

iv. **Research Objective 4:** To develop a generic approach by utilising qualitative criticality analysis approach and fuzzy logic, that can be adapted to different case-based models within practice capable of identifying crucial attributes of maintenance activities during MoOSTs in order to prioritise them with the aim being to establish maintenance task criticality;

v. **Research Objective 5:** To design and evaluate the implantation of a generic approach that can be adapted to different case-based models within practice in the form of an interactive web-based knowledge management platform developed specifically for MoOSTs, to foster knowledge management as well as minimise loss of expertise.

## 1.7. Contribution to Knowledge

The original contributions to knowledge provided by this study is outlined below;

1. Empirical evidence of the extent of alignment between findings obtained from literature (SLR) based on the identified knowledge management challenges in MoOSTs as well as underlying causes- Chapter 4;

2. Development of a generic framework by combining engineering failure analysis tools and multi-criteria decision-making (MCDM) techniques that can be adapted to different case-based models within practice capable of identifying and ranking barriers to knowledge management and experience transfer based on the perceptions of experts who have significant involvements in MoOSTs, to enable the selection of appropriate solutions specific to the individually identified and ranked knowledge barrier for prioritising barriers to knowledge and experience transfer in MoOSTs by adopting reliability engineering tools and multi criteria decision making techniques – Chapter 5;
3. A research-based generic approach, that can be adapted to different case-based models within practice capable of identifying critical attributes of MoOSTs activities and developing a hybrid MoOSTs activity criticality assessment framework that combines quantitative criticality analysis as well as a technique for representing uncertain information generated from qualitative analysis to establish the most critical MoOSTs activities that would benefit from the knowledge management and experience transfer platform –Chapter 6; and

vi. A research-based generic approach that can be adapted to different case-based models within practice for designing and evaluating an interactive web-based knowledge platform for knowledge capture and experience transfer during MoOSTs, to foster knowledge management as well as minimise loss of expertise.

4. – Chapter 7.

## 1.8. Outline of Thesis

This thesis is not presented in the traditional PhD thesis format, but rather presented in the journal format thesis (JFT) where the core context is provided in the form of published/submitted research and peer-reviewed conference papers in line with The University of Manchester 'Presentation of Theses Policy Guidelines'.

However, as in the traditional PhD thesis format, the JFT requires that all cited references are compiled and grouped under "Bibliography" at the end of the thesis.
The rationale for submitting this as a JFT is as follows:

i. JFT avoids duplication of research work. Each accepted, published, and submitted peer reviewed journal papers has become a chapter in the thesis;

ii. The peer-review process in journals improves the quality of research; and

iii. Presenting in journal format should also improve research impact of this study, since peer-reviewed journal papers are immediately available online and can be more broadly disseminated to larger audiences compared to PhD monographs.

Three chapters in this thesis (Chapters 4, 5, 6) are already published in peer-reviewed journals. One other chapter (Chapter 7) has been submitted to a journal and is still under review. There are two more papers which have been published as peer-reviewed conference papers. These conference papers are not stand-alone thesis chapters but some of their findings are referenced in the thesis along with the journal papers where they were generated from where possible. A complete list of the author's published and submitted papers is provided in the "List of publication". An authorised permission to submit the thesis as a JFT is provided in the general Appendix. Figure 1.1 shows a graphical abstract of the various chapters and their associated contents, which is further elaborated in the subsequent paragraphs.

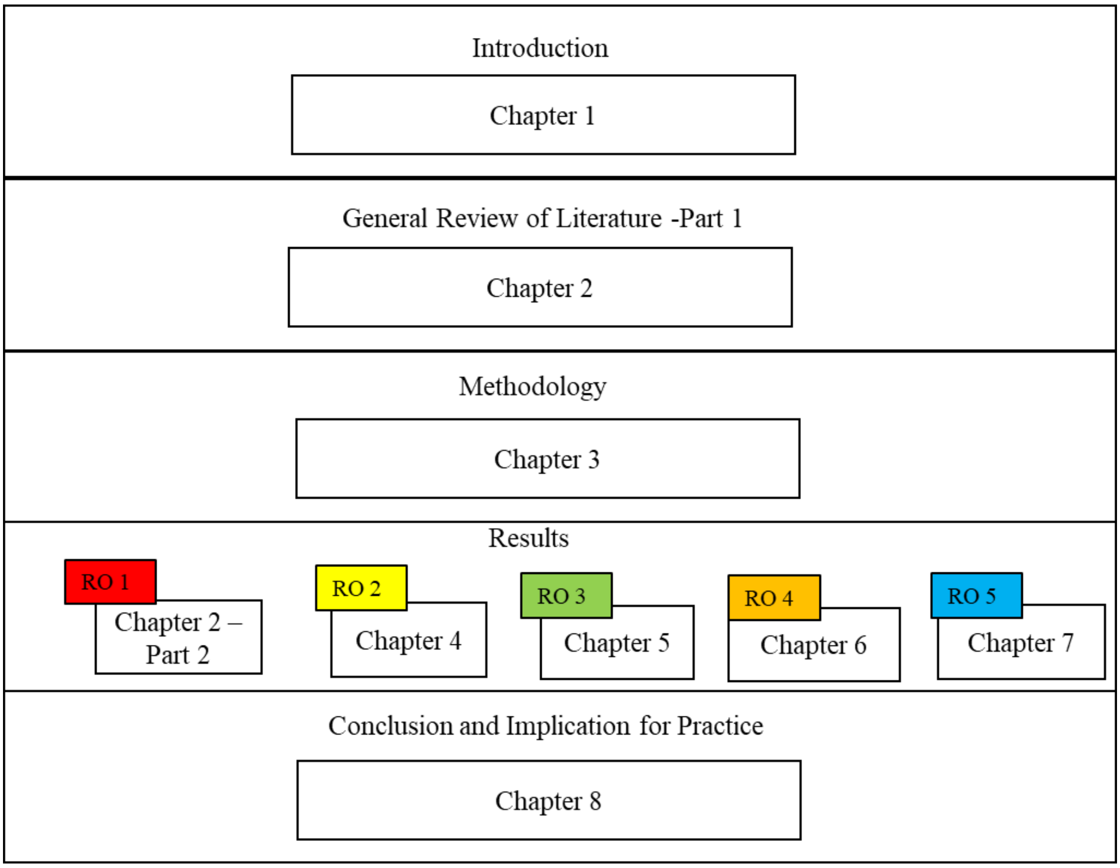


Figure 1. 1 Thesis Content

This JFT thesis comprises of 7 subsequent chapters: Chapter 2 is a systematic literature review (SLR) and overall theoretical framework on which the thesis is based on, Chapter 3 explains the research methodology, Chapters 5,6,7 present and discuss the results, and Chapter 8 concludes the thesis. A brief summary of these chapters is provided below.

**Chapter 2- General Overview and A Systematic literature review identifying knowledge management trends in Major Overhauls, Outages, Shutdowns, and Turnarounds (MoOSTs) Activities.**

This chapter is divided into two parts- Part 1 and Part 2. Part 1 presents a general background of maintenance, which includes definitions of maintenance terminologies, the evolution of maintenance and in-depth explanation of what MoOSTs entails. Part 2, is a SLR based on identifying knowledge trends in MoOSTs. The SLR protocol, inclusion and exclusion criteria, classification framework and results are presented in the later sections of this chapter along with its significant findings. A portion of SLR has been published by *Springer, Cham* in International Conference on Maintenance Engineering IncoME-V 2020 and the extended version presented in the thesis. Owning to the JFT, the general overview of literature conducted in this chapter 2, part 1, contains an overview of maintenance management elements, MoOSTs existing trends, gaps, and the knowledge management challenges that are specific to MoOSTs activities. However, since each of the "results'' chapters (1.e. Chapters 2, (part 2), 4-7) is self-contained, a more specific review of literature related to the questions addressed by the individual chapter in focus is again provided, so that it can be read without reference to the rest of the thesis. This chapter contributes to addressing the first research objectives of the thesis.

**Chapter 3 - Methodology**

This chapter discusses the research philosophy, research design and the methods selected to achieve the research objectives. It explains the rationale of research design, selection, data collection and analysis, and discusses the generalisation aspects of the research outputs. However, since each of the results'' chapters (1.e. Chapters 4-7) is self-contained, a more specific methodology section related to the questions addressed by the individual chapter in focus is again provided, so that it can be read without reference to the rest of the thesis.

**Chapter 4 – Knowledge Management and Experience Transfer in Major Maintenance Activities: A Practitioner's perspective (Iheukwumere-Esotu and Yunusa-Kaltungo, 2021b).**

This chapter has been published in *Sustainability* journal. The focus of the study was to examine the extent of alignment between findings from literature as it relates to the challenges encountered during MoOSTs, as well as probe their underlying causes in practice. It also show how relevant findings from this study would be in providing a baseline for establishing a proposal for capturing and retaining MoOSTs knowledge. The study explored three questions which were addressed by experts:

1. What knowledge management challenges, are identified in real-world practices, during MoOSTs?
2. To what extent does the knowledge management challenge in the literature identified during MoOSTs align with real-world practices?
3. Can examination of underlying cause of the knowledge management challenges in the literature identified during MoOSTs, foster the development of a proposal for a formalised platform for capture and transfer of tacit knowledge across MoOSTs organizations?

This chapter contributes to the research objectives 2: *To conduct a comparative study across diverse industries involved in MoOSTs activities to obtain the perspectives of practitioners on the knowledge management challenges are identified in real-world practices during MoOSTs, to validate the findings generated from the prior SLR;*

**Chapter 5 – Assessment of barriers to knowledge and experience transfer in major maintenance activities (Iheukwumere-Esotu and Yunusa-Kaltungo, 2020a).**

This chapter has been published in *Energies* journal. The study discusses the importance of successfully capturing and retaining MoOSTs knowledge as well as perceived barriers to achieving this crucial activity. It then demonstrates the effectiveness of utilising engineering failure analysis approaches i.e fault tree analysis (FTA), reliability block diagram (RBD) and multi-criteria decision analysis (MCDA) techniques to identify and rank the barriers to knowledge management and experience transfer in MoOSTs. The study explored three questions which were addressed to experts;

1. What are the barriers to knowledge management and experience transfer in MoOSTs?

2. Do the identified barriers contribute equally to failure of the entire knowledge management system or could their causal effects be prioritised based on significance of impact?
3. Are these barriers specific to MoOSTs or do they equally affect other engineering projects?

The chapter contributes to addressing Objectives 3: *To identify and rank barriers to knowledge management and experience transfer based on the perceptions of experts who have significant involvements in MoOSTs, to enable the selection of appropriate solutions specific to the ranked barrier.*

**Chapter 6 – Knowledge Criticality Assessment Framework for Major Maintenance Activities: A Case Study of Cement Rotary Kiln Plant (Iheukwumere-Esotu and Yunusa-Kaltungo, 2021a)**

This chapter has been published in *Sustainability* journal, as well as an extract from its findings which was presented at ASME's International Mechanical Engineering Congress & Exposition (IMECE) virtual conference 2021 and also published in the conference proceedings online. The focus of the study was to identify elements of maintenance activities during MoOSTs and prioritise them in a bid to establish criticality by adopting hybrid criticality assessment approaches. This was to provide information leading to continuous improvements and enhance the maintenance organization's ability to undertake crucial decision-making efforts. The chapter contributes to addressing Objectives 4: *To identify crucial attributes of maintenance activities during MoOSTs and develop a framework that prioritise them with the aim being to establish task criticality.*

**Chapter 7 – Development of an Interactive Web-Based Knowledge Management Platform for Major Maintenance Activities: A Case Study of Cement Manufacturing Systems**.

The study focuses on designing an interactive web-based platform for managing knowledge in MoOSTs. The most critical MoOSTs activities are identified and relevant information that can ultimately assist knowledge capture are preloaded into the platform, including scope to capture emergent and/or discovery work. The knowledge platform-MoOSTsKP has been designed to foster knowledge retention; to overcome the issue of time constraints that limits knowledge capture due to chaotic MoOSTs environment; to enable integration with other IT systems that might exist within MoOSTs without creating additional workload. Hence the proposed MoOSTsKP is simplified, concise, and inexpensive to deploy, and accessed with handheld devices as well as desktop applications. The chapter contributes to addressing Objectives 5: *To design and evaluate the implantation of an interactive web-based knowledge management platform for MoOSTs*, to foster experience transfer and minimise loss of expertise.

**Chapter 8 - Summary and Implication for Practice**

This chapter concludes the thesis by providing synthesis of the findings of each of the results chapter (i.e Chapters 4 to 7) in the context of the research aims and objectives proposed in section. It proposes the implications of the study for both research and practice. Limitations of the study and recommendations for future work are also presented in this chapter.

## 1.9 Contribution of Author to the Journal Format Thesis

This thesis is not presented in the traditional PhD thesis format, but rather presented in the journal format thesis (JFT) where the core context is provided in the form of published/submitted research and peer-reviewed conference papers in line with The University of Manchester ‘Presentation of Theses Policy Guidelines’, the nature and extent of the candidate's own contribution and the contribution of co-authors and other collaborators to the publications have been presented and can be found in the Appendix at the end of the thesis. This was denoted by these codes: C1-Conceptualization; C2-Methodology; C3-Validation; C4-Formal data analysis; C5-Investiagtion; C6-Writing-Original draft preparation; C7-Writing review and editing; C8-Supervision, which all represents individual elements within each publication and the contribution of each authors (The academic supervisor, was the only collaborator on all the research output).

# 2 GENERAL LITERATURE REVIEW AND SYSTEMATIC LITERATURE REVIEW (SLR)

This chapter is split into two parts. **Part 1**: presents a general background of maintenance, which includes definitions of maintenance terminologies, the evolution of maintenance and in-depth explanation of what MoOSTs entails. **Part 2:** Contains the SLR and is based on identifying knowledge trends in major overhauls, outages, shutdowns and turnarounds. The SLR protocol, inclusion and exclusion criteria, classification framework and results are also presented in part 2 of this chapter along with its significant findings.

**PART 1**

## 2.1 Background of Maintenance

The BS EN 17485:2021 [63] defines maintenance as the function which includes all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. In order to provide an overview showing how maintenance has evolved in the past decades and to provide a standalone perspective into the SLR conducted and presented in this chapter, it was important to gain understanding of what maintenance is, and provide the available definitions of maintenance terms which have impacted on the approaches implemented while considering MoOSTs management.

## 2.2 Definitions of Maintenance Terminologies

There are lots confusions when it comes to the terminologies used to precisely define some maintenance terms and the need to have simple but encompassing definitions have been deemed necessary to enable the full understanding of the evolutionary trends in maintenance. These issues were particularly addressed by [64] who adopted three maintenance terminologies from the wide range of preceding terminologies available in the full overview of literatures. They presented these definitions from their review with the aim of not imposing or dictating a bias but to provide simple and concurrent definitions. The three maintenance terminologies, maintenance actions, maintenance policies and maintenance concepts have thus been defined as follows;

Maintenance Action - is defined as basic maintenance interventions whereby primary task are performed, in essence this could be said to be ‘what to do’. They are majorly two types of maintenance actions namely, corrective maintenance actions or precautionary maintenance actions. Precautionary maintenance actions could be preventive, predictive, proactive and passive maintenance respectively.

Maintenance Policy involves the rule or set of rules describing the triggering mechanisms for different maintenance actions. The underlying principles and formulation of policies which were consistent to the definition adopted can be reviewed in these researches by [65], [66]. The commonly adopted maintenance policies are failure based maintenance also known as corrective maintenance, time based maintenance also known as preventive maintenance, and condition based maintenance known as predictive maintenance.

Maintenance Concept are sometimes referred to as philosophies and they are the set of maintenance policies and actions of various types which provides the structure for planning, controlling and improving existing polices. Maintenance should be customized to fit the companies need, and having the right maintenance concepts is vital [67]. Maintenance concepts are developed overtime in response to the changing demands and requirements of the organization. Maintenance concepts that gained popularity over time include; Reliability centered maintenance (RCM), total productive maintenance (TPM), risk based maintenance (RBM), value driven maintenance (VDM), effective centered maintenance (ECM).

## 2.3 Evolution of Maintenance

Maintenance management have been influenced in each generation partly by the perspectives in which maintenance is viewed. Erkoyuncu et.al., [68] stated that the evolution of maintenance requirements by maintenance organization have being strongly dependent on the correct functioning of modern technical systems, based primarily on the type of maintenance being performed. In the 1940s maintenance evolutionary trends were identified through the start of World War II and the need to establish a routine for maintenance. Niu et.al., [68] and Pintelon and Parodi [64] identified the period around the 1960s to 1970s where changes to the way maintenance was seen originated with more thoughts put into formulating maintenance policies and defining maintenance actions. These changes were mostly influenced by the revolutionary trend of maintenance embracing technical reforms which produced optimal solutions thereby, leading to the embracing of time based/planned preventive maintenance when planning maintenance actions.

As organizations started facing competition and the need to maintain profitability became popular, another paradigm shift in maintenance function occurred in the 1980s-1990s. The maintenance department were encouraged to imbibe certain cultures such as, waste reduction, decrease in number of maintenance interventions and profit maximization. Deshpande and Modak [69], as well as Pun, et.al., [70] were of the opinion that these interventions resulted in the developments and acceptance of maintenance concepts such as total productive maintenance and reliability centred maintenance for further insights see works by (Nakajima 1988, Nowlan and Heap 1978). The early 2000s, until now have seen the rise in stringent regulatory requirements, and the drive to maintain profitability, as well as the establishment of cooperative partnerships within the organization. These have resulted in to the streamlining and refinement of older maintenance concepts and the development of newer maintenance concepts (see literatures from, Waeyenbergh and Pintelon 2002, Sharma et.al., 2011 on this important subject). This is because the importance of maintaining competitive advantage in the face of globalisation, and satisfying customers and regulators demands cannot be over emphasised.

Furthermore, Garg and Deshmukh [49] conducted a literature review of about 142 published papers with one of the objectives being to identify emerging trends in the field of maintenance management. The observation from that review was, that the evolution in maintenance trends leading up to the 1940s considered corrective maintenance (CM) which relied on deliberately waiting for something to break or fail as the major method for carrying out maintenance.

Other observations from their study showed that the requirements from the assets and the perceptions of stakeholders were in line with those of the customers, have greatly impacted on the maintenance policies and actions adopted in each emerging decade. Their final summarization from the study were that maintenance have evolved into a multidisciplinary activity involving the integration of existing trends like total productive maintenance (TPM),and reliability centred maintenance (RCM) e.t.c. and led to the emergence of newer approaches like effective centred maintenance (ECM) and risk based maintenance (RBM) etc.

Another research, by [64] considered the fundamental elements of maintenance as it relates to the environment and transformation which occurred through a thorough review of literature on the underlying principles and models employed overtime. This led into the grouping of the evolution of Industrial maintenance from different decades starting from the 1940s -50s, 1960s-1970s, 1980s-1990s and then the 2000s. The findings from the research, indicated that maintenance as a discipline had witnessed several transformation and was no longer seen as ''unavoidable'' but as a requirement of the maintenance functions strategic concern. This was because, organizations sought to increase their competitive advantage. Other related studies have traced the evolution of maintenance through three generations covering the periods of World War II, to the new expectations ($4^{th}$ generations) of the 2000s. These studies have depicted the paradigm shift from considering maintenance as just a cost centre to the progress made by maintenance today, where many organizations are now starting to consider the environment and safety of their personnel's' along with the need to satisfy the quality requirements and profitability objectives [69], [71].

There are also studies that have made progress in examining the evolutionary trend of maintenance (see for instance; [67], [70] for better insights into this rhetoric). The changes in maintenance and the resulting effect on how maintenance activities are being planned, controlled and improved on to tailor the rapid changing market environment which many maintenance organizations operate within. Figure 2.1 depicts the impact of changing perceptions in the scope of maintenance management over time and its influence in the development of maintenance management through several generations.

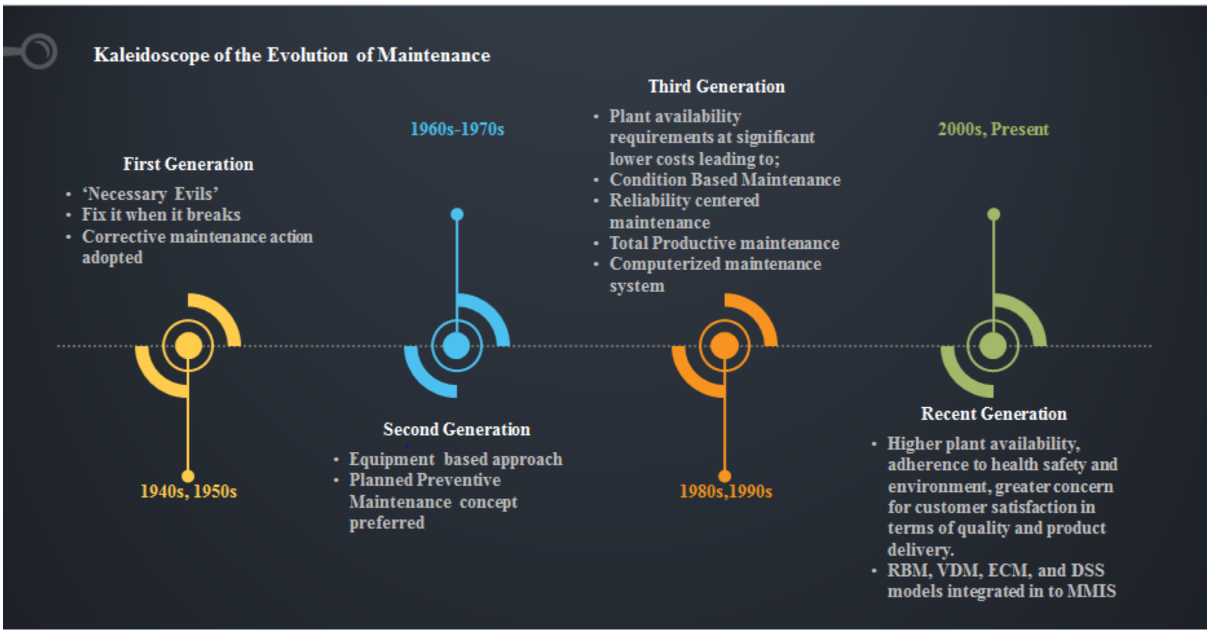


Figure 2. 1 Kaleidoscope showing the evolution of maintenance

RBM-Risk based maintenance, VDM-Value driven maintenance; ECM-Effective centred maintenance, DSS-Decision support system and MMIS-Maintenance management information system

The changing perception in the scope of maintenance policies, leading actions and development of maintenance concepts, have significant impacts on the management of maintenance interventions in large maintenance activities, take for instance, MoOSTs. This is because the adoption of concepts and techniques derived from just a single school of thought might not be convincing enough to bring about the desired improvement necessary to survive and grow amidst stifling circumstances which has led to the adoption of several approaches and refinement of older approaches.

## 2.4 Maintenance Actions, Policies and Concepts

The development and refinement of maintenance concepts and policies which have influenced how maintenance is being performed have been reviewed and summarised below in 2.3.1 to 2.3.9.

### 2.4.1 Corrective maintenance (CM)

Corrective maintenance usually termed as 'run-to-failure' is a maintenance policy which is triggered from adopting a failure based maintenance policy and follows the approach of replacing a failed part with a new part only when it is no longer functional [72]. CM has been described as a type of maintenance policy which involves on the spot decision to replace a failed part and is usually not planned [73]. It is usually at its best when it is performed in non-critical areas, with small capital costs and very low consequences of failure, where failure identification is fast and repair immediate. It is a traditional method for carrying out maintenance, and is still a very applicable and popular maintenance policy for maintaining non-critical parts even today, as it is an economical alternative amongst maintenance policies when dealing with very low consequences of failure. It comes in useful when decisions have been backed with sufficient plant data that could dictate that consequences of run to failure would have very little effect on the desired objectives and lead to savings in terms of cost and time.

### 2.4.2 Planned preventive maintenance (PPM)

This is a type of maintenance that is carried out at predetermined intervals and involves the periodical planning of replacements of parts, and scheduling at regular intervals, and it is not dependent on the satisfactory performance of the component. PPM depends on the inclination that components are subject to deterioration and degradation and the aims are to replace parts before the parts reaches the end of their useful lifespan [74]. PPM activities usually involves; definition of intervals for inspection and routine maintenance. Niu et.al., [73] were of the opinion that PPM as a maintenance policy was triggered by the influence of embracing revolutionary trends in performing maintenance actions leaning towards technical reforms that would lead to optimization. The downside to PPM as stated by [72] was that it could lead to superfluous maintenance, whereby maintenance is carried out too often than might be needed, or lead to a deficient maintenance plan where the intervals for maintenance is unable to manage failure of parts as failures occur before the scheduled interval for maintenance.

### 2.4.3 Condition based maintenance (CBM)

This is a type of preventive maintenance that is not based on a predetermined interval and schedule, but rather monitors the conditions of component systems in order to generate a preventive schedule. The main similarity between PPM and CBM are that both tasks assigned under any of the two are performed at pre-set intervals. Tsang [72], emphasized on the major difference between the two tasks as the fact that CBM was non-invasive and intrusion into the equipment for actual maintenance only occurred when the CBM actions indicated an on-set of failure. CBM, was further explained by [42] as the application of a maintenance program which recommends the necessary predictive maintenance actions to implement based on the information which are collected during condition monitoring to avoid unnecessary maintenance actions on an otherwise perfectly running equipment/systems. It emerged as organizations reflected on cutting down maintenance costs, without affecting the intended outcome from maintenance as it provided the opportunity to reduce the frequency of performing maintenance. The process involved collection and analysis of data generated from plant in order to conduct diagnosis and make prognosis. Condition monitoring tasks such as vibration monitoring, process-parameter monitoring, thermography, tribology, visual inspection, are all tasks which are undertaken when implementing CBM [75].

### 2.4.4 Reliability centred maintenance (RCM)

This is a maintenance concept that was developed in the US from the 1960s, and evolved into an overall RCM program performed by the maintenance group of commercial airlines in the early 1970s, with the aim of reducing downtime, cost and improving flight safety [63], [76]. At the time, it was designed as MSG-1, with updates leading to MSG-2 and MSG-3. Subsequently, the military aviation sector adopted the concept, and eventually the concept was embraced by other industries such as; nuclear, process, and oil and gas industries. Desphande and Modak [69] shared insights into the development of RCM as a response to the trends in the 1960s which were leaning towards setting up maintenance as a discipline that embraced a system function approach to maintenance rather than equipment based approach. This resulted in increased reliability and safety while decreasing maintenance costs chiefly because RCM sets out to be proactive in its approach and investigates the root causes of failures that would trigger maintenance actions and the consequences of each event.

RCM is described as the logic–based methodology for determining what type of preventive maintenance actions were required to maintain the reliability of equipment and systems through a systematic approach [77]. Maintenance concepts such as RCM have been adopted by several industries as they are seen to be proactive and are usually committed to long-term improvements of maintenance management. Popular literatures from these authors (see; Nowlan and Heap 1978; Anderson and Neri 1990 and Moubray 1997 for developments of these concepts) contributed to the development and mainstream industry acceptance in the application of RCM. However, there are many flaws associated with setting up RCM, the major ones being, it lacks prioritisation needed for general industry applications, it is expensive to implement and requires TPM to sustain its full potentials [76].

### 2.4.5 Total productive maintenance (TPM)

Ahuja and Khamba [78] in a literature review focused on the development and directions of TPM, stated that it was a unique Japanese concept to support its lean manufacturing system and was developed and introduced by M/s Nippon Denson Co. Ltd of japan, a supplier of M/s Toyota Motor Company, Japan in 1971. TPM was developed from the planned approach of preventive maintenance as an optimisation technique that optimises equipment effectiveness, eliminates breakdowns and promotes autonomous maintenance by operators through day to day activities. They traced the development of TPM, to being largely driven by the need for maintenance to form part of the strategic investments made by organizations when enhancing their competitive market position. At first, only a small number of firms took notice and implemented TPM, but with the severe economic crisis in the early 1970s its propagation was accelerated.

The translation and description by Nakajima in 1988 [79] was a major contributor to TPM development as it alerted the western world to understand the importance of TPM. This followed on from the adoption of the total quality management (TQM) intervention that was earlier on developed by the American (Deming). Ireland and Dale [80] depicted the link to successfully achieving world class performance in support of production philosophies such as; Total quality management, (TQM) and Just in time management

(JIT) through the application of TPM. The adoption of concepts and techniques derived from just a single school of thought might not be convincing enough to bring about the desired improvement necessary to survive and growth amidst stifling circumstances and this have led to the adoption of several approaches and refinement of older approaches. This has mostly encouraged the trend of linking maintenance quality improvement strategies such as TQM to maintenance policies using TPM philosophy.

### 2.4.6 Risk based maintenance (RBM)

Maintenance management techniques has evolved over the years and recently this evolution has been influenced by the increase in the complexity of manufacturing processes, increase awareness of the effect of maintenance on the environment and safety, and profitability of the business and quality of products [81]. In response to this, RBM started to emerge in the 1990s and gained popularity beyond the early 2000s developing into a maintenance concept which involves a methodology aimed at reducing the overall risk and consequences of unexpected failures of operating facilities. It involves two main phases; risk assessment and maintenance planning based on risk [76]. As stricter requirements of maintenance grew, a paradigm shift from RCM and CBM have occurred and an integration of heterogeneous approaches have occurred which have led to the subsequent emergence and adoption of RBM as a maintenance policy [82]. RBM deals with the risk assessment approach of the integration of reliability and consequences of failures. It combines the fundamentals of RCM and CBM applications to the assessment of the assets and the overall risks generated from performing maintenance actions to the overall business activities.

### 2.4.7 Effectiveness Centred Maintenance (ECM)

ECM is a maintenance concept, which focuses on system functions and customer service improvements. It stresses on ‘’doing the right things’’ instead of just ticking the box by ‘’doing things right’’ during maintenance [70]. The approach involves the identification of equipment failure modes which can defeat the system’s required functions and prioritises the importance of failure modes backed by the use of statistical and mathematical tools. The need to adopt a heterogeneous approach as a contrivance for developing organizational capabilities is a major response to the drastic changes occurring in the market place being advocated within maintenance research [83].

This has resulted in the adoption of ECM as a maintenance concept combining core tenets from TQM, TPM and RCM and being more comprehensive, whilst sharing practical tips of ways to enhance performance management to meet the business objectives. ECM utilises RCM to develop the TQM strategy by improving the system availability and stressing on the life cycle profits and maintenance efficiency and effectiveness.

### 2.4.8 Value driven maintenance (VDM)

VDM is a maintenance concept which was developed with the intention of providing four maintenance values namely; asset utilization, resource allocation, cost control and health, safety and environment (HSE) [84]. VDM is utilized to calculate the value of maintenance strategies using the formula of net present value (NPV). To build up adequate knowledge of the four drivers an effective maintenance performance measurement is required. Rosquist,et.al., [85] introduced a value driven maintenance planning approach using a case study of a gasification plant in Finland, where they stated that the primary reasons for plant managers to be interested in maintenance performance goal-setting as well as it's measurement to enable continuous improvement and maintenance performance within the industry.

### 2.4.9 Decision support system (DSS)

A DSS is a tool which assists management decision by combining the use of analytical models and available data from the Maintenance management information systems (MMIS) through the use of a user friendly software which can support semi-structured and/or unstructured decision making abilities. A method for identifying critical components and a decision support tool for managing maintenance activities of critical components in manufacturing systems was demonstrated as being different from traditional reliability function technique in [86]. Clemente et al., [87] put forward a decision support tool for maintenance management, and the system enables maintenance actions that best suit the scenarios analysed to be visualized and identified. Iheukwumere-Esotu and Yunusa-Kaltungo [21] employed the use of secondary data obtained from a cement plant computerised maintenance management system (CMMS), combined with expert opinion and a multi-criteria decision tool, the analytical hierarchy process (AHP) to develop a criticality analysis DSS for prioritising critical maintenance activities.

## 2.5 Major Overhauls, Outages, Shutdowns and Turnarounds (MoOSTs)

The requirements and technology complexities have been on the rise according to trends across industries and are imposing new challenges in the requirements of major industrial maintenance projects. These emerging requirements are constantly evolving and businesses are continuously required to adapt, putting it succinctly [88] proposed that individuals 'in this new world' tasked with delivering projects in large scale safety critical industries needed to navigate through myriads of uncertainties in order to achieve desired project outcomes. Organizations involved in continuous productions are now paying critical attention to previously ignored industrial maintenance projects. MoOSTs is one of such projects and based on the description by [25], it involves the periodic plant shutdown to allow for crucial activities which involves; inspections, repairs, replacements and overhauls etc., in order to sustain the reliable process for the whole supply chain and cater to a wide range of customers' needs. MoOSTs are referred to as the set of maintenance policies of various types which provides the structure for planning, controlling and improving existing polices in making appropriate maintenance decisions as well as performing maintenance actions on technical capital assets [11].

The reliability and integrity of equipment used in the process and continuous production industries deteriorates over time due to excessive wear and tear and thus MoOSTs are required to ensure the reliability and safety of such plants. According to Wenchi et.al., [7] (2015) performing MoOSTs as at when due are crucial in sustaining the long term stability and continuous production of a plant. Pokharel and Jiao [12] emphasized on the seemingly importance of MoOSTs in the petrochemical industry in avoiding unscheduled breakdowns that can impact significantly on revenues. Through the review of literatures [10], [11], [89] the three major types of works which are performed on equipment and plant facilities are identified to be;

i. Work on equipment that are critical to the operation of the plant and cannot be taken down without shutting the plant down;

ii. Work on equipment whereby defects are identified through routine maintenance checks, or a condition monitoring system but cannot be taken down whilst in operation; and
iii. Work on equipment which do not require the plant to be taken down, but are performed based on the opportunity provided during MoOSTs.

The level of planning and preparation required for the three major types of works differs and usually the first type of work is ranked on the priority list as being most critical. There are widespread misconception on the differences and similarities of engineering, procurement and construction (EPC) projects and MoOSTs. Knowledge have been shared in the practices across the two areas by researchers from both spectrums and several literatures argued that the main difference between the MoOSTs and traditional EPCs lies in the fact that MoOSTs have large fluctuation of scope which increases the levels of uncertainties [9]. This level of uncertainty and the lack of opportunity to quickly react to unforeseen circumstances due to the compressed schedules significantly increases the challenges for effectively managing MoOSTs [51]. Obiajunwa [90] stated that although traditional project management competencies were critical for the success of MoOSTs and organizations consciously adopted project management skills, however the uniqueness of MoOSTs required a mixture of skills along with the capability to understand the situation and people and then dynamically integrate leadership behaviors and or historical estimates.

Table 2.1 was adapted from [9] it shows the differences between EPCs and MoOSTs. Thorough analysis of Table 2.1 shows the unique features of MoOSTs when compared to EPCs in terms of uncertainty and fluidity in each area of comparison. This attributes requires that the MoOSTs organization be dynamic and able to anticipate, manage and control the whole process.

Table 2. 1 Distinctions between MoOSTs and EPCs

| S/N | MoOSTs | EPCs |
|---|---|---|
| 1 | Risks of uncertainties via emergent jobs | Logical steps interrelated to an end result |
| 2 | Scope during execution is dynamic and changes frequently | Scope is static once execution has begun |
| 3 | Planning and scheduling can only be finalized after scope approval | Planning and scheduling can be done well in advance of the project |
| 4 | Extensive requirement for safety permits in each shift | Lesser need for safety permits and clearances |
| 5 | Schedules are compressed leaving little or no room for adjustments | Schedules are not compressed, and acceleration can be used to correct slippages in the critical path |
| 6 | Staffing requirements can vary | Staffing requirements are fixed |
| 7 | Very difficult to define and measure KPIs as variables changes quickly | Measurement of KPIs are easier and done at the beginning |

MoOSTs are usually classified into four phases and there are some common activities which are peculiar to these phases which involve the integration of strategic planning, decision-making, project management, and maintenance actions etc [13], [91]. The description each phase within MoOSTs as well as the activities involved in each of these phases have been comprehensively described and can be found in these literature (see, Lenahan 1999:2011) for more in depth discussion on this subject). Figure 2.2 is a diagram showing the common activities in each of phase of MoOSTs.

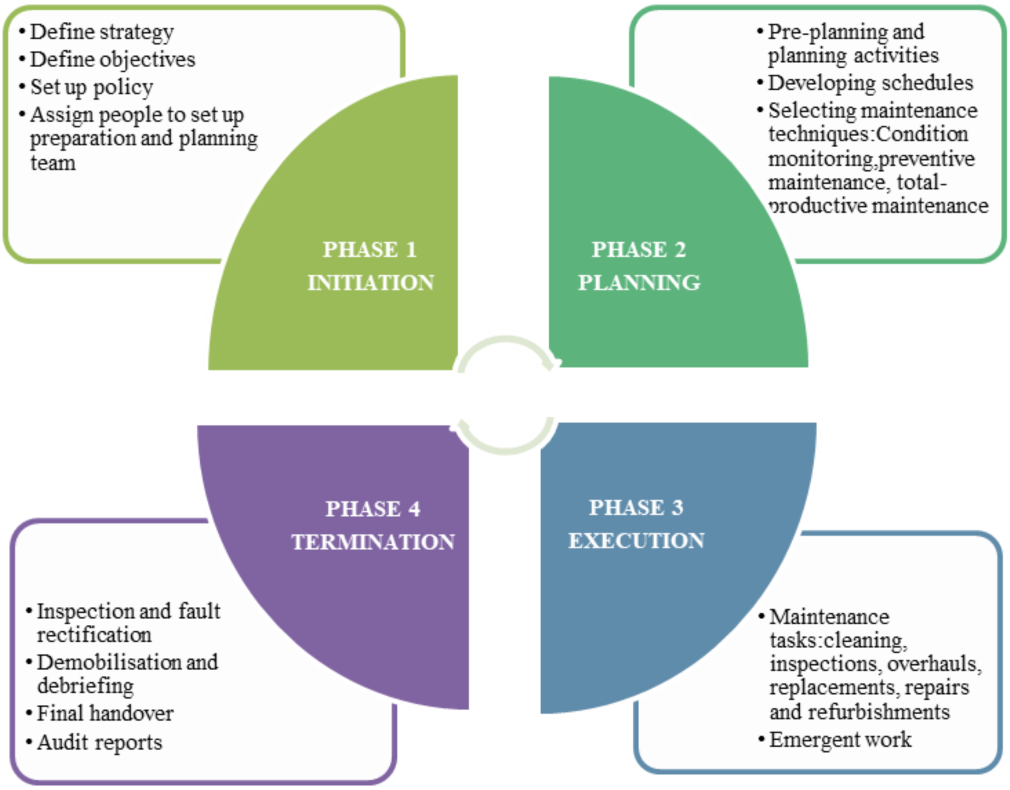


Figure 2. 2 Common activities in MoOSTs

The initiation phase which is the stage at which the MoOSTs organization is formed. It is also the phase where plans are set for stakeholders who have been appointed and are tasked with defining the strategy, objectives, balancing constraints, assessing progress reports, providing funds and determining decision makers. Obiajunwa [90] listed the necessary skills which are required to manage the MoOSTs event in order to ensure desirable outcomes. Zulkipli and Halib [92] developed the use of an analytical framework using fundamental sociology concepts as opposed to technical aspects to describe the formation of the MoOSTs event, as the use of social science was scarcely addressed when setting up the MoOSTs organization.

The planning phase is the phase were work objectives are developed. Amendola [91] stated that about 65% of the total expended by large corporations are within this phase. The activities involved in the planning phase include; inspections, testing, shutdowns, planned outages, de-bottlenecking projects, revamps and overhauls. Despite the efforts put into this phase there are always uncertainties associated with surmounting the challenge of exceeding budget and time restrictions [93], [94]. Studies within MoOSTs are now more concerned with achieving optimal plans and schedules that can accommodate as well as anticipate scope variations.  Studies within this phase, demonstrate the applications of mixed integer linear programming methods by [95], [96] targeting medium and long term planning which addresses the element of uncertainty, production decision and manpower considerations.

The execution phase implements and tests the superiority of the initiation and planning phase. At this phase lapses in the organization, preparation and planning phases becomes evident. This phase requires that experienced and qualified people are designated with the appropriate task, that there are proper documentations, that tasks are executed on schedule with the required resources and that the MoOSTs organization are experienced enough to manage uncertainties and implement appropriate, contingency strategy, change management and maintain the chain of command [24], [97], [98]. At the point of execution uncertainties arising from emergent works are dreaded as they could lead to catastrophic disruption of the entire project schedule and budget estimation To quote Lenahan [99] “there are only two types of outcomes during MoOSTs, routine and unexpected. If the routine is under control there is time to deal with the unexpected but if the routine becomes unexpected then there is no control.”

The Termination, Close out & Review phase in summary, involves the handing over of equipment back to the owners, receiving the contractors final report which captures their part in the overall project, their observation of what went well, or wrong and what needs to be improved on, challenges, and changes initiated. It is the duty of the organization to set up an audit to investigate and document important feedbacks, and use in subsequent MoOSTs cycle. Upon completion of the work, the team then sets out to demobilize the work area and bring the plant back online. Amendola [91] summarized that only about 2% of efforts are expended in this phase based on available evidences from reviewing literature. Furthermore, based on evidences in the wealth of scholarship available it can be inferred that MoOSTs rarely achieve all their stated objectives, which is a significant challenge in this discipline [100], [101].

## PART 2

**Reformatted Version of this paper:**


| | |
|---|---|
| Paper title: | **A Systematic Analysis of Research Based Evidences of Major Overhauls, Outages, Shutdowns, Turnarounds (MoOSTs) Management** |
| Authors: | **Lilian Iheukwumere-Esotu and Akilu Yunusa-Kaltungo** |
| Published in: | **Proceedings of IncoME-V & CEPE Net-2020. IncoME-V 2020. Mechanisms and Machine Science, Springer, Cham.** |
| Volume: | **105** |
| DOI | **10.1007/978-3-030-75793-9_60** |



## ABSTRACT

Major overhauls, outages, shutdowns and turnarounds (MoOSTs) represent a distinct and critical class of industrial projects, performed periodically to ensure the reliability and safety of physical assets. Typical MoOSTs are large-scale fusions of routine maintenance activities (e.g. planned preventive maintenance, condition monitoring, plant expansions, corrective maintenance, etc.), which in turn increases risk profiles and capital intensiveness. However, despite the criticality and significant cost implications commonly attributed to MoOSTs, management of the interface of knowledge development trends in this discipline is still limited in comparison to other elements of industrial operations.

Therefore, this study uses a systematic approach to present a harmonization of existing knowledge trends in this field. A total number of 122 most representative MoOSTs related articles over a 7-decade timeline and extracted, through application of carefully defined inclusion and exclusion criteria. Key revelations from the review are twofold - inadequate emphasis on the need to align existing theoretical and practice-based perspectives as well as the underrepresentation of articles that investigate mechanisms for experience transfer within MoOSTs organizations.

## 2.6 Need for a SLR within MoOSTs

Major overhauls, outages, shutdown and turnarounds (MoOSTs) are essential maintenance activities that enhance the ability to achieve predefined production goals [4]. Typical MoOSTs activities include functional inspections, repairs/replacements, overhauls and part replacements on incredibly large and carefully planned phases [7], [8]. Despite its criticality and financial implications, current body of knowledge suggest an underrepresentation of frameworks that are specific to MoOSTs management when compared with other strands of industrial operations [8]. This challenge has been described as an inhibitor to the provision of evidence-based solutions for tackling inherent failures to meet preset MoOSTs objectives [12], [13]. Further compounding to this, is the indiscriminate adoption and implementation of general project management guidelines for MoOSTs, without adequately accounting for its peculiarities. Although earlier efforts from [9], [11] towards providing better distinctions between EPCs and MoOSTs have been attempted, there still exists a general misconception of its core requirements. Besides providing an overview of the current state of MoOSTs-related research, depiction of the overall knowledge trend provided here would serve as a roadmap that could potentially dictate areas of future research interests.

The purpose of the SLR in this study is to provide an overall outlook of research within MoOSTs as well as uncover the challenges specifically related to knowledge management. This was achieved by particularly investigating the trends of research articles across various industries and countries. This way, the author scrutinized the research work done by various authors and researchers on MoOSTs over the past seven decades. Through such systematic investigation, the issues, trends, and antecedents of MoOSTs activities as well as those specifically related to knowledge management will be examined.

Following the analysis of a wide range of databases for MoOSTs-related articles, there was a glaring underrepresentation of concise literature review articles except for the much earlier review of power plants best practices [41] and the recent compilation of MoOSTs planning trends [25].

However, as useful as the information triangulation performed in these aforementioned studies are, they were too streamlined to a particular industry [41] and theme [8], thereby leaving significant knowledge gaps with regards to key facets such as:

i. Critical examinations to quantify the adequacy of current research in fulfilling the practical needs required for the management of MoOSTs.
ii. Identifying common trends of studies, author's inclinations, standard approaches towards the overall management of MoOSTs as it relates to each phase and distinct themes, in order to provide a holistic view of the state of affairs in this disciplines
iii. Despite the universal recognition of the usefulness of experience as a key element of successful MoOSTs implementation, none of the existing studies considered knowledge transfer and retention, but rather focused on lagging indicators that are often easy to measure.

Therefore, to establish substantial knowledge trends and bring the discipline of MoOSTs on par with other industrial maintenance elements that capture significant systematic knowledge trends such as is found in these disciplines, condition monitoring [31], [102], maintenance planning [45], maintenance optimisation [47], general maintenance management [49], [103] maintenance decision support systems [104], [105] and engineering asset management; [106], e.t.c. There needs to be conscious efforts to harmonise relevant MoOSTs based articles. This is of importance because harmonising knowledge trends could be useful in improving the understanding in this discipline.

## 2.7 Overview of the Systematic Literature Review (SLR)

The ability of systematic reviews to enhance evidenced-informed knowledge management without necessarily compromising the comprehensiveness of content has made it quite popular in recent times. Authors such as [107], [108] emphasised that one of the fundamental reasons for the rise in popularity of systematic literature reviews, could be attributed to its ability to logically identify, evaluate, and interpret data of all available studies relevant to a particular research question, topic, area or phenomenon. Despite the attractiveness of this approach to the review of literatures, the quality of systematic reviews significantly hinge on the ability of the researcher(s) to adequately eliminate biases that may originate from sources such as, selection performance, measurement and attrition [109]. A common way to achieve this is by clearly setting out clear criteria (often referred to as the review protocol) for ensuring that evidences of studies gathered during the review process meet stipulated restrictions. A good guide for the development of such protocols is the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement [108].

## 2.8 Systematic Literature Review (SLR) Protocol

The first stage in SLR involved planning the review and it involved setting up justification for the review which is an important process when setting up the objectives for the review. This led to preparing background literatures that supports the evolution of maintenance trends in the research. The next stage was conducting the review and involved setting out the review protocol, determining the sources/ databases where information would be retrieved. This was followed by the imposition of restrictions on the results by strictly adhering to the available definitions of MoOSTs were selected, thus providing the basis for the inclusion and exclusion criteria. The complete bibliography of 122 articles considered for the SLR are provided at the end of the thesis to aid in the process of transparency and independent assessment of the classification analysis. The efforts in compiling the review took over 9 months through the extensive search of databases for relevant literatures, reference checking appropriate classifications and structuring of the review. However, it is possible that an article could escape the review process and not be surveyed in the review, based on the databases selected.

**Stage I** Planning the review

Step 1 Justification for the need for a review

Step 2 Preparation/Development of background Literature

**Stage II** Conducting the Review

Step 3 Preparing the review protocol

Step 4 Identification/searching of research articles

Step 5 Selection of articles based on inclusion /exclusion criteria

Step 6 Data extraction based on selected article classifications and review measures

Step 7 Analysis of selected articles

**Stage III** Concluding the Review

Step 8 Findings/Implications

Step 9 Conclusion and Future work direction

Figure 2. 3 Stages in the SLR Process

A critical challenge often associated with SLRS is on how to balance the identification of a niche area and justification for the review. This challenge was resolved by providing an in-depth background into MoOSTs as well as to ensure that the poised research question was appropriate. The next step was design of a literature review protocol shown in Figure 2.4. The search terms for this study was, major overhaul*, outage*, shutdown*, turnaround*, with articles extracted from Web of science (WoS), ProQuest and Engineering village (Compendex, InSpec, GeoRef and GeoBase) owning to their inclinations and specificity to general engineering articles. Search for articles within the databases was restricted to a time frame of 1940-2019, so as to capture the evolution of maintenance during the 1$^{st}$ - 4$^{th}$ revolution. As earlier stated, the main focus of this systematic literature review element of this study was to capture research dimension to MoOSTs, which later formed a basis for comparison against practice.

Based on this premise, 122 articles were selected after the overarching inclusion/exclusion was intentionally skewed to suit this purpose and the detailed refinement processes are shown in the schematic diagram of the systematic review protocol in Figure 2.4.

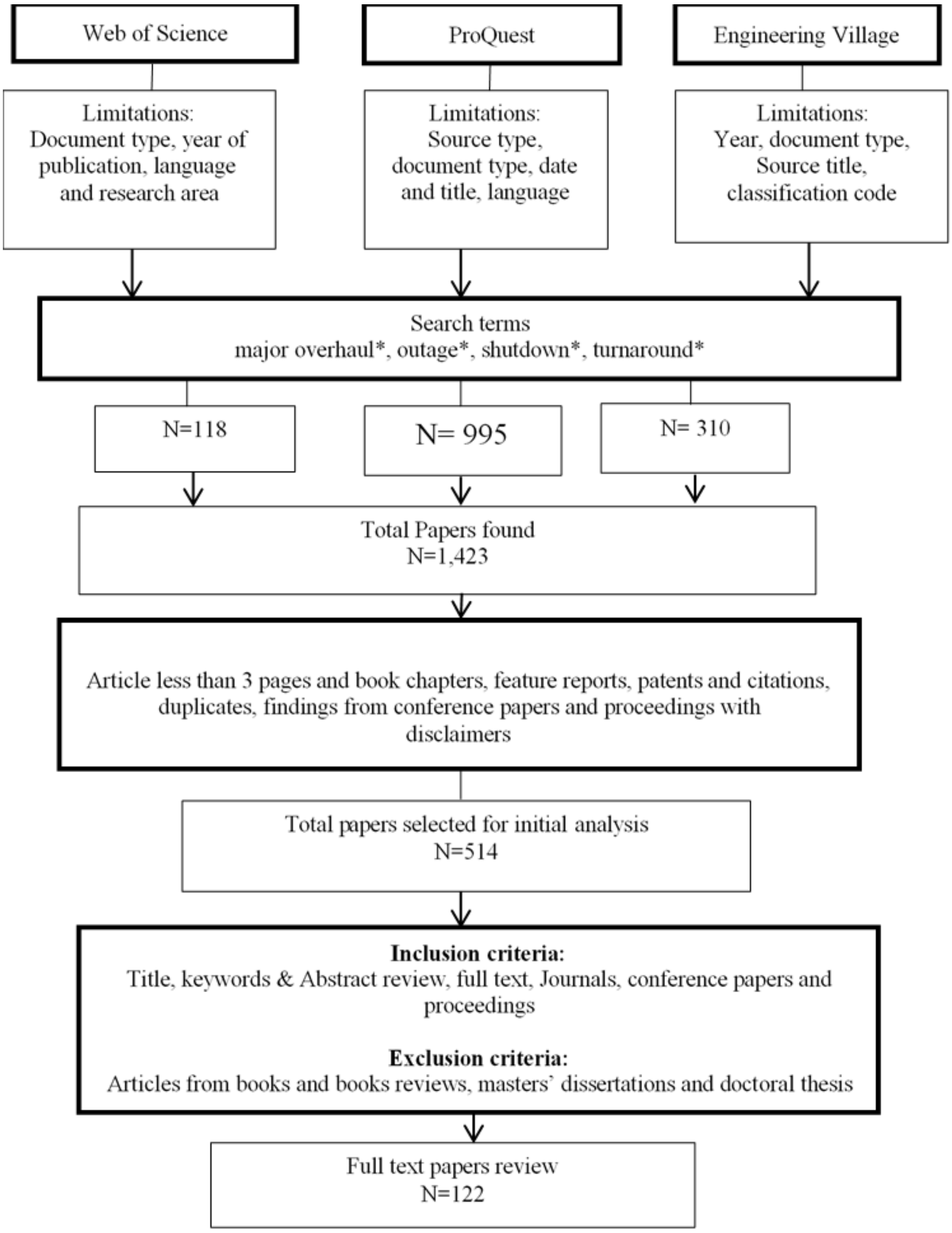


Figure 2. 4 Schematic diagram of the SLR protocol

## 2.9 Article Classifications

The analysis of the main findings from the systematic review were performed according to ten main headings. This approach for classification under ten main headings was assumed necessary, because it provided a logical overview to the knowledge trends within the field of MoOSTs. The classifications are as follows, type and frequency of publication (Figure 2.5), country of origin (Figure 2.6), year of publication (Figure 2.7), industry of focus (Figure 2.8), author's demography (Figure 2.9), common terminology used to characterise MoOSTs (Table 2.2), application area and scope of work (Figure 2.10), relationship matrix of MoOSTs themes (Table 2.3) research approach employed (Table 2.4) and principal finding and/or contribution to knowledge (Table 2.5).

The classification results in Figure 2.5 showed an 80%-20% split between journals and conference articles respectively. The countrywide spread of articles shown in Figure 2.6 indicated that 23% and 8% of the 122 analysed articles were attributed to the United States (US) and Canada respectively. United Kingdom (UK) and Malaysia both represented 7% respectively, while Germany, China, Italy, Saudi Arabia and India accounted for 3-5%. Other countries such as the UAE, Spain, South Africa, Brazil, Iran and South Korea represented 1-2% of all articles analysed and those articles with mixed origins accounted for 5%.

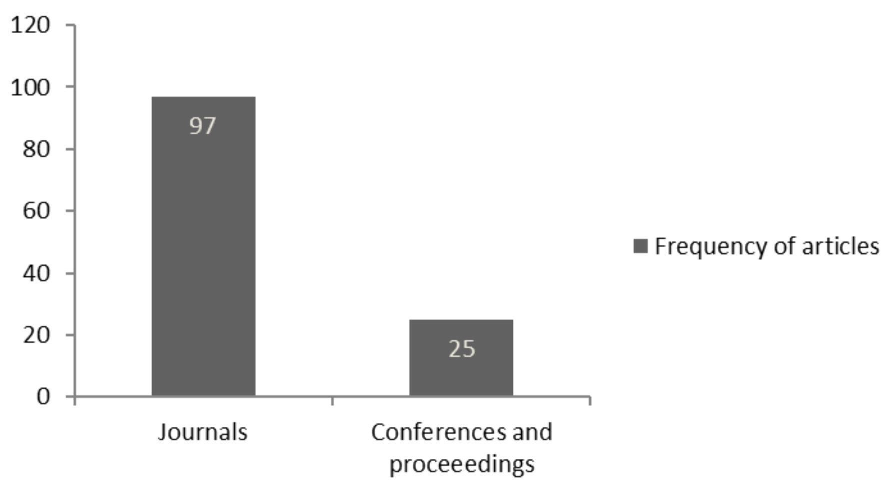


Figure 2. 5 Type and frequency of publications

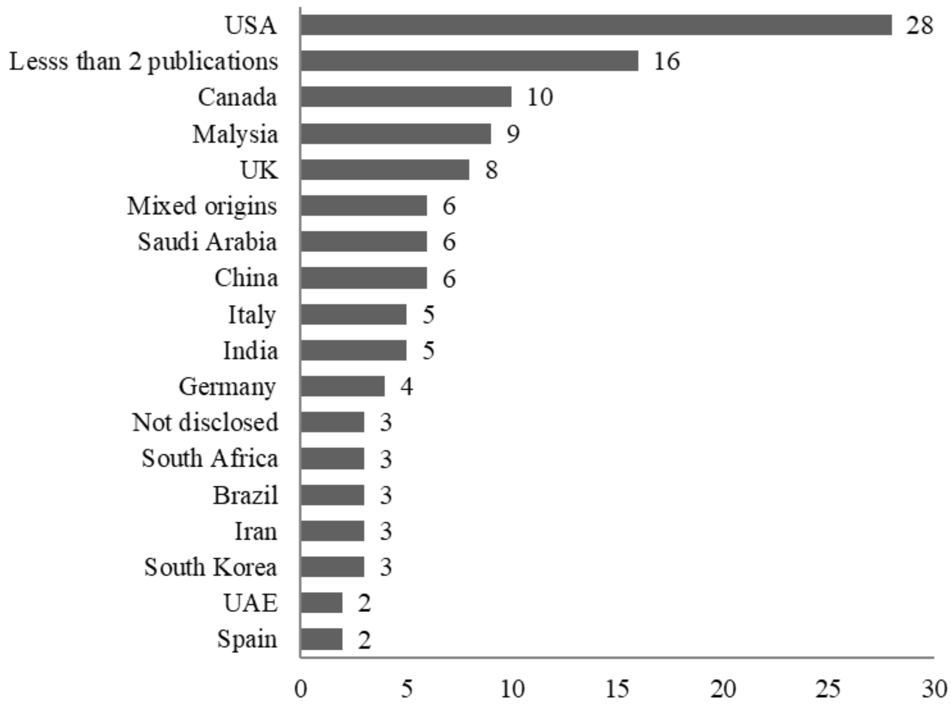


Figure 2. 6 Country of origin

Another key revelation from the data classification is the number of articles published over the years shown in Figure 2.7 and the possible justifications. For instance, the appearance of MoOSTs related articles from the late 20th century and early 21st century can be attributed to landmark maintenance disasters such as Bhopal (1984), Chernobyl (1986), Piper Alpha (1988), Concorde (2000), Texas City refinery explosion (2005), BP Macondo blowout (2010), etc., which triggered the need to explore alternative and safer work practices. Figure 2.7 also showed a steady rise in the number of articles from 2009 through 2016 which may be attributed to the release of standardised asset management frameworks such as PASS 55 (2008) and ISO 55000 (2014).

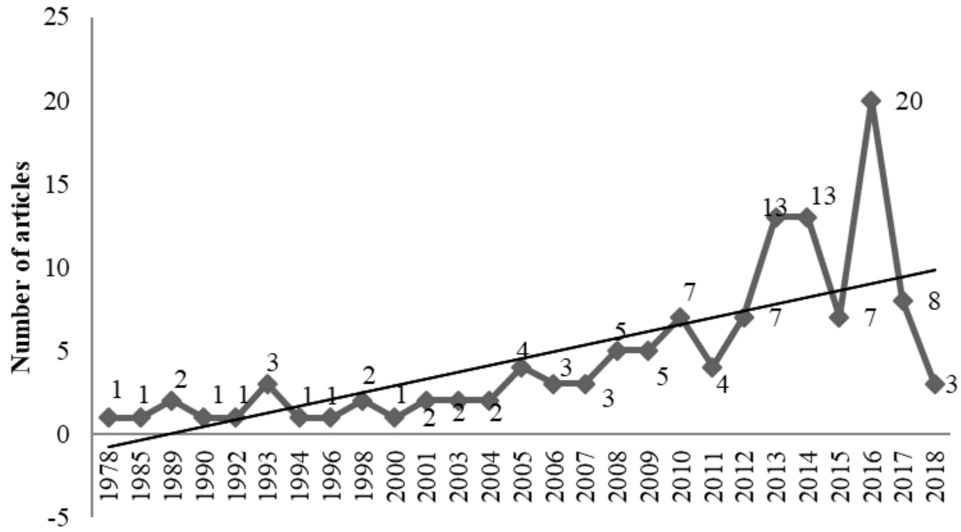


Figure 2. 7 Year of publication

The industry of focus was another factor which was considered owing to the significant concentration of MoOSTs critical companies (across different sectors including power, nuclear, aerospace, manufacturing, and petroleum, etc.) as illustrated in Figure 2.8.

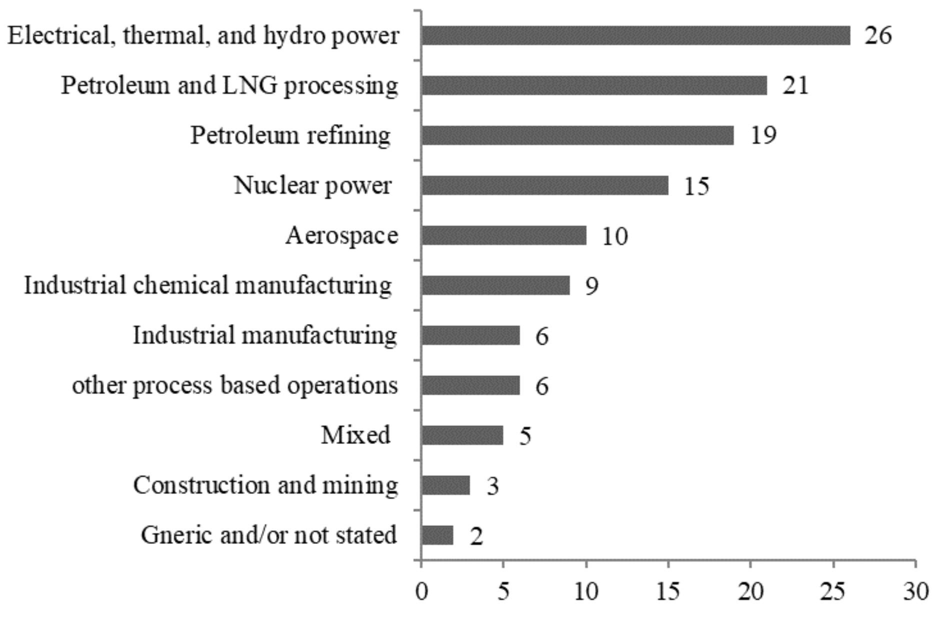


Figure 2. 8 Industry of focus

MoOSTs is an applied discipline hence it was important to consider the demography of authors as well as extent of collaboration between academic researchers and industry professionals and the results is shown in Figure 2.9.

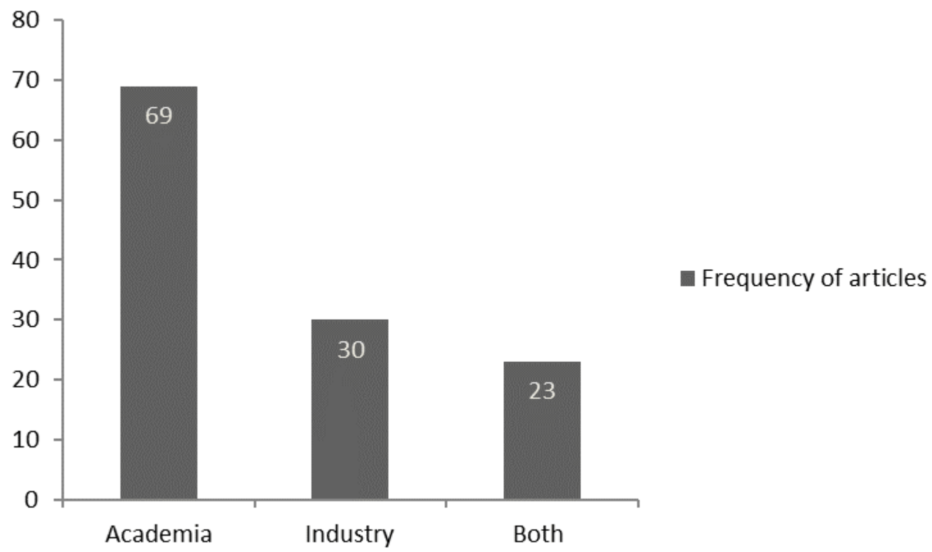


Figure 2. 9 Author's demography

A very crucial element of any literature-based knowledge gathering exercise is the ability of the compilations to reliably represent the entire field of interest. Therefore, it was necessary to observe the commonalities and variations of the terminologies used in practice across different industries. While Table 2.2 shows a wide range of terms in use, it was evident that MoOSTs offers a near perfect integration irrespective of industry.

Table 2. 2 Common terminology used to characterise MoOSTs

| Industry/Terminology | Major overhauls | Outages | Shutdowns | Turnarounds |
|---|---|---|---|---|
| Aerospace | 10 | | | |
| Chemical manufacturing plant | 1 | | 4 | 4 |
| Construction & mining industry | 2 | 1 | | 2 |
| Electric, thermal & hydro power plant | 2 | 19 | 3 | |
| Generic and not stated | 2 | | | |
| Manufacturing plant | 2 | | 3 | 1 |
| Multi sectors | 1 | | | 4 |
| Nuclear power plant | 2 | 12 | 2 | |
| Petrochemical, petroleum & LNG plant | | | 7 | 12 |
| Process based plants | 2 | | | 4 |
| Petroleum refinery | | 1 | 6 | 13 |

The application area and scope of work covered by each study was shown in Figure 2.10 which indicated that schedule and work scope management made up 34% while performance evaluation, inspection and quality management made up 15% of the entire articles respectively. The implication of the high volume of studies covering these areas lends credibility to the study by [110] that discussed the continued reliance of managers on effective work schedules, monitoring and evaluation as important routines to achieving desired outcomes.

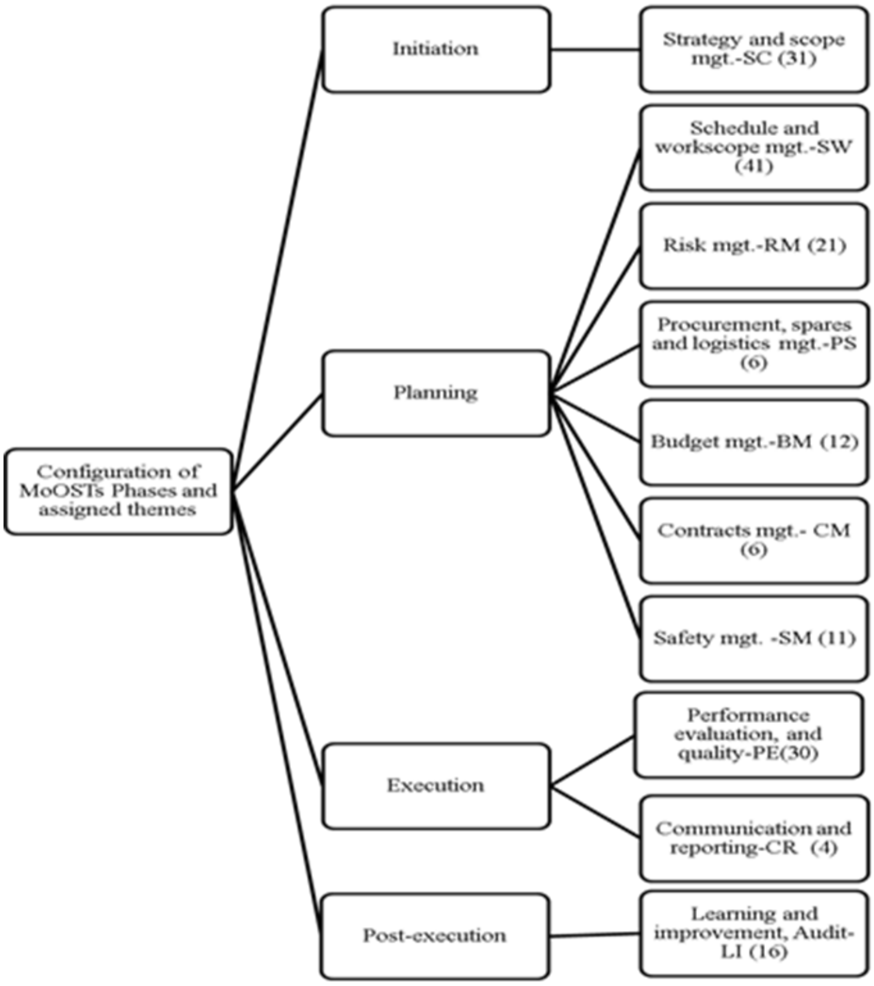


Figure 2. 10 Summary of the reviewed articles based on MoOSTs phase, assigned theme and frequency of appearance

Additionally, definition of themes (i.e. application areas), as well as, corresponding number of articles previously shown in Figure 2.10, have been applied in generating a relationship matrix shown in Table 2.3. These were based on, alternative quantitative data characterizations of reviewed articles and concisely examines correlations between primary and secondary themes (i.e. if an article studied more than one theme and presented findings on each of them). The relationship between two areas is a function of the ratio between number of articles that relate to a secondary area and the total of the primary articles of interest, whereby a zero value represents weak or no correlation between two areas of interests and values tending towards unity signify strong correlation [111].

Table 2. 3 Relationship matrix of MoOSTs themes

| | SC | SW | R1 | PS | BM | CM | SM | PE | CR | LI |
|---|---|---|---|---|---|---|---|---|---|---|
| **SC** | 1 | 0.16 | 0.03 | 0.03 | 2 | 0.03 | 0 | 0.16 | 0 | 0.12 |
| **SW** | 0.12 | 1 | 0.2 | 0.05 | 0.07 | 0.02 | 0.02 | 0.02 | 0.02 | 0.07 |
| **RI** | 0.05 | 0.38 | 1 | 0 | 0.19 | 0 | 0.05 | 0.10 | 0.05 | 0 |
| **PS** | 0.17 | 0.33 | 0 | 1 | 0.17 | 0.17 | 0 | 0.17 | 0.17 | 0 |
| **BM** | 0.17 | 0.25 | 0.33 | 0.08 | 1 | 0.08 | 0 | 0.17 | 0 | 0 |
| **CM** | 0.17 | 0.17 | 0 | 0.17 | 0.17 | 1 | 0.17 | 0 | 0 | 0 |
| **SM** | 0 | 0.09 | 0.09 | 0 | 0 | 0.09 | 1 | 0.18 | 0 | 0.09 |
| **PE** | 0.17 | 0.03 | 2 | 0.03 | 0.67 | 0 | 0.67 | 1 | 0.67 | 0.67 |
| **CR** | 0 | 0.25 | 0.25 | 0.25 | 0 | 0 | 0 | 0.5 | 1 | 0 |
| **LI** | 0.25 | 0.19 | 0 | 0 | 0 | 0 | 0.06 | 0.13 | 0 | 1 |

Furthermore, the type of research approaches employed in the reviewed studies are shown in Table 2.4, this element was also deemed an important parameter to consider enabling the complete assessment of the empirical validation of reported findings. Please note that it was possible for one study to apply more than one research approach. Finally, Table 2.5 showed the contributions of each study.

Table 2. 4 Research approach

| Technique | Code | Frequency |
|---|---|---|
| Theoretical | TH | 36 |
| Mathematical models | MM | 31 |
| Modelling and simulations | MS | 20 |
| Unstructured observation | UO | 16 |
| Documents analysis | DA | 10 |
| Survey | SV | 13 |
| Interviews | IN | 9 |

Finally, Table 2.5 showed the overall contributions and research areas of the studies compiled from the SLR..

Table 2. 5 Principal findings from the reviewed articles

| Main principles and Ideas | Frequency |
|---|---|
| Techniques to determine chemical exposure and safety issues during MoOSTs | 7 |
| Identification and assessment of performance and productivity in MoOSTs | 14 |
| Modelling set of rules for workflow, information and communication protocol | 5 |
| Risk based inspection and analysis framework | 14 |
| Optimised approach for managing resources constraints and allocation problems | 10 |
| Communication satisfaction dimensions, management and control | 5 |
| Methodology for improving and optimising MoOSTs planning and scheduling | 29 |
| Improving quality and reliability of MoOSTs | 8 |
| Enhanced contract design methodology and requirements | 5 |
| Enhanced forecasting models | 3 |
| MCDM to identify and rank causes of uncertainties affecting project quality | 6 |
| Promoting consistency of approach and human skills requirements in MoOSTs | 9 |
| Establishing factors influencing management's decision, and social practices | 4 |
| Best practices for risk assessment, and quality management | 5 |
| Organizational structural approach and process for managing people and issues | 1 |
| Documenting lessons learned | 4 |
| Decision support tool to select the best trade off decision | 1 |
| Prioritisation of criteria within the critical chain | 2 |
| Cost analysis | 1 |
| Structured benchmarking assessment process | 1 |
| Business process re-engineering | 1 |
| Computer scheduling concepts and extensive preparation | 2 |

## 2.10 Significant Findings from the Systematic Literature Review

The review of existing literatures revealed three main gaps in the research of MoOSTs management, which are detailed as follows:

### 2.10.1 Inadequate emphasis on the need for integration and conversion of research findings into practice.

The analysis of data in Figure 2.8 indicated that 57% of the reviewed articles were from academia, 25% industry based and 19% combination of both streams. Despite the spread and capture of articles representing the two streams (academia and industry), convergence or adequate integration between the two streams is not widely observed, (that is, of application of academic research generated findings in practice). In contrast what is exhibited is the exhibition of a mono-directional split of either research generated theories or practical infused applications from industry.

This might be a major contributor to the low uptake of theoretical propositions by practice based professionals owning to a number of issues including but not limited to; inability of existing research to demonstrate usefulness in mirroring realities of MoOSTs problems in practice, as well as, ease with which these theoretical propositions are successfully implemented by same practice based professionals.

### 2.10.2 Underrepresentation of articles that investigate mechanisms for experience transfer within uncertainties management in MoOSTs.

Uncertainties in MoOSTs may cause serious disruptions and arises from different sources; scope disruptions (identification of unplanned or emergent work), activity disruptions (change in estimated durations), resources disruptions (unavailability or late arrival of raw materials), delays due to weather conditions etc. [112], [113]. While the uncertainties in MoOSTs mirror those ones exhibited in typical EPCs [114] but, with far reaching consequences [115], due the distinctions between the two, as was highlighted in Table 2.I. The existing research on managing uncertainties in MoOSTs depend to a large extent on the stochastic and permanent estimation of MoOSTs planning and scheduling techniques [6], [116], [117]. However, based on contemporary understanding of uncertainties, especially with the definition put forward by [118], overt dependence on these strategy stochastic and permanent estimations do not often represent optimal strategies for managing uncertainties in most MoOSTs operations. Therefore, there is need for providing suitable MoOSTs decision framework embedded in sound knowledge management and experience transfer techniques to bridge the gap in the knowledge of managing uncertainties. This potential decision framework which would depend on the knowledge about preceding activities gained from experience over time would complement existing efforts in tackling the challenge of making optimal choices among alternative actions.

### 2.10.3 Inadequate emphasis on articles that consider knowledge management and experience transfer within MoOSTs for learning and continuous improvement.

The classification of studies according to their scope as depicted in Figure 2.10 revealed that only 9% of the total articles highlighted learning, improvement and audit management as a central theme of focus in their discussions. Besides the limited number of articles in this crucial application area/scope, an in-depth analysis of articles indicates that the primary focus of even these identified studies within MoOSTs were on lagging indicators, focused on generating audit and/or post mortem reports, as well as, suggestions for storing such captured information. While such lagging indicators are quite useful and easy to measure, their ability to support prognosis and sustainable experience management are quite limited. Studies by [110], [119] are of the opinion that, the challenge of promoting knowledge transfer would not only be overcome by collecting and storing information alone, but by the reusing of captured knowledge. This is because promoting knowledge capture and transfer is significantly linked to attainment of business goals and individual job goals, this clearly makes a strong case for the need to capture and reuse experience. Considering that MoOSTs activities are often characterised by extended planning and correspondingly short execution periods, their success significantly hinges on the experiences and familiarity of execution teams [11], [14]. Therefore, there is a need to develop a specified framework that supports experience transfer and retention throughout the entire MoOSTs supply chain to manage such complex, dynamic and transient environment.

## 2.11 Chapter Summary and Implication for Future Research

In general, the current body of knowledge is skewed significantly towards rationalisation of limited number of MoOSTs themes, such as, planning frequency, schedule rationalisation, performance evaluation, and quality optimisation, etc. While these themes are of immense importance to the success of MoOSTs, their ability to sustainably achieve success and widespread acceptability in practice significantly hinges on availability of an adequately managed knowledge management system that encourages experience transfer.

At present, a distinct type of framework, which systematically converts tacit knowledge of practitioner (experience transfer) into explicit knowledge, through conversion and integration of theoretically generated models in practice, is almost none existent. Thus, an important aspect for future research in this study would be demonstration of a practice-based research, through which the gaps identified from this study can be bridged. This could stem from the application of a case study based methodology in order to determine the extent of alignment between theory and practice, and might establish a unique and concise platform for better identification of strengths, weaknesses and common omissions from both facets.

# 3 RESEARCH METHODOLOGY

## 3.1. Introduction

This chapter provides an overview of the research philosophy, approach, method and design to achieve the proposed research objectives in Chapter 1. It explains and justifies the rationale of research design selection. The sampling technique, data collection, and data analysis techniques utilised for the research are also discussed. It concludes by discussing the reliability, validity, and generalisability aspects of the study.

## 3.2 Research Philosophy and Approach

The research philosophy to be adopted is of utmost importance when designing a coherent scientific study for three crucial reasons [120]. Firstly, the research philosophy provides a framework that clarifies the proposed research design. Secondly, it enables researchers to understand the limitations of the study, and thirdly it assists researchers with adapting the study of their design to more adequately address the objectives of their research. The proponents of research philosophies [121], [122] have engaged and displayed their knowledge and beliefs in what appeared and got interpreted as “paradigm wars.” However, their definitions of ontology and epistemology have a common theme with a bit of different meaning and emphasis, but there seem to be no consensus among them in the classifications of the paradigms [123]. Epistemology comes from the Greek word epistêmê, their word for knowledge. According to [124], epistemology poses some of the following questions centred on what the nature and forms of knowledge was, the ways it could be acquired, and finally on ways it could be communicated to human beings. Ontology, constitutes the very first set of assumptions and is concerned with the very nature or essence of social phenomena being investigated.

At the deepest layer of philosophical consideration lies the debate between two contrasting paradigms known as positivism and interpretivism [125]. The ontology of positivism is realism. Positivists’ researchers believe that social reality exists independently of the observer, and can be measured and studied objectively through scientific means [126]. As it assumes that social phenomena are measurable, positivism is associated with a quantitative approach which applies statistical analysis [127].

The ontology of interpretivism research is relativism and interpretive researchers believe that objects depend for their existence on the perception of people, the viewers [124]. According to this view, the researcher is not independent of the object being researched since it is impossible to separate the two [128]. Rather, than focusing on measuring social phenomenon, interpretivism emphasises on exploring the complexity of the phenomenon with the aim of acquiring interpretive insights [127]. Interpretivists apply methods that seek to describe, translate and otherwise come to terms with the meaning, not frequency, of certain more or less naturally occurring phenomena in the social world [129].

This study was mainly influenced by interpretivism to capture complex phenomena and due to the exploratory nature of the research objectives. The author's research philosophy, as asserted by [130], was influenced by her personal preferences (i.e author's underlying belief about a phenomena and how it should be investigated, the research problem, and by practical concerns (e.g. access to data). However, according to [131], there need not be a dichotomy between qualitative and quantitative research, rather the research method selected should be selected on the basis of its effectiveness in addressing the research objectives. Within this research, the approach implemented combines both attributes of quantitative and qualitative approaches to achieve the research objectives. Such an approach is called the mixed methods' and its application on this research enhanced the understanding of the problem being studied to enable a more comprehensive conclusion to be made [125]. Furthermore, the approach helped counter any potential limitations of each research method [132].

## 3.3. Research Method

The research purpose and research questions are good suggestions of starting points to develop a research design because they provide important clues for the researcher. The research method consists of a set of specified procedures, tools and techniques to gather and analyse data. According to Tuli, [131] these methods could be quantitative and so would be concerned with attempts to quantify social phenomena by collecting and analysing numerical data or they could be qualitative methods, concerned with understanding the meaning of social phenomena.

### 3.3.1 Quantitative research

Quantitative research are characterised by the assumptions that human behaviour can be explained by what may be termed “social facts” which can be investigated by research methods that utilise “the deductive logic of the natural sciences [133]. Generally, it employs strategies like surveys, structured interviews and other modes of research resulting in statistically significant contributions. In quantitative research the data collected takes the form of measurements or counts which is statistically analysed. The process of quantitative research follows standard procedures, methods, forms of analysing and reporting results of the research undertaken [134].

### 3.3.2. Qualitative research

Qualitative research is considered “subjective” due to its nature. The approach within qualitative research emphasises meanings, experience (often verbally described), descriptions etc. [134]. According to [134], qualitative research is concerned with collecting and analysing information in as many forms, chiefly non-numeric, as possible. The methods of qualitative research includes structured and unstructured interviews, group interviews and focus groups. Qualitative methods can highlight key themes or patterns emerging in the project which are used to comprehend and manage data and use to develop and test hypothesis.

### 3.3.3. Mixed method research

Mixed methods research emerged from the 1990s onwards, establishing itself alongside the previous paradigms so that ‘‘we currently are in a three methodological or research paradigm world, with quantitative, qualitative, and mixed methods research all thriving and coexisting’’ [135]. It is a research approach that has emerged as a ‘’third paradigm/approach’’ for social research and provides credible and distinctive alternative to quantitative and qualitative paradigm [136]. Several influential studies have been written on mixed methods and research findings have been further stimulated by the founding of the specialist ‘Journal of Mixed Methods Research’[120]. Initially the mixed methods was viewed as two separate strands of research-quantitative and qualitative with clear divisions between the two, but this perspective changed in the mid-1990s as researchers became concerned on how to link the two pre-existing strands [137]. However, as soon as the idea of mixed methods research elicited positive responses, different perspectives on what constituted the nature of mixed methods emerged [135]. A recent perspective that have emerged is the trend of those who combine mixed methods with more traditional designs as can be seen with its adoption amongst ethnographers, case studies researchers, experimental health science investigators, and narrative researchers [135]. Consequently, Saunders et.al., [130] described a mixed-method research, which uses both quantitative and qualitative data collection and analysis procedures applied either in concurrent or in sequential design. Figure 3.1 shows a typical mixed method research approach [133].

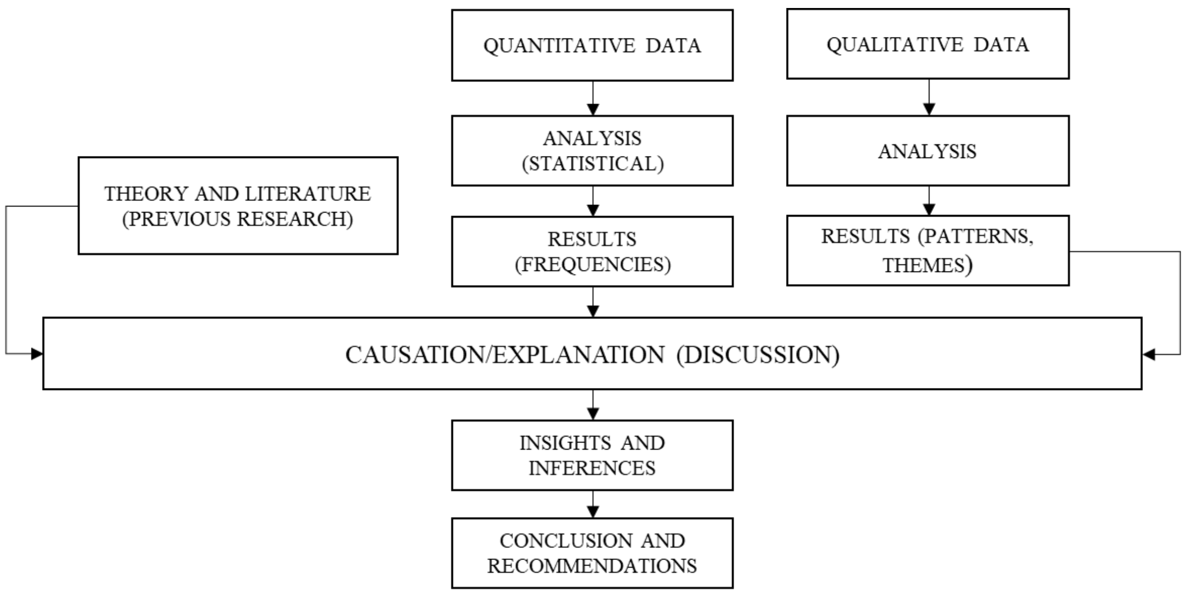


Figure 3. 1 Mixed-methods research process

## 3.4. Phasing of the Research

The phases of this research and their relationship can be seen in the methodology flowchart Figure 3.2 The first phase was the SLR (Chapter 2) involving the review of secondary data and development of theoretical framework. The main purpose of this phase was to present an overview of knowledge trends and identify gaps within MoOSTs.

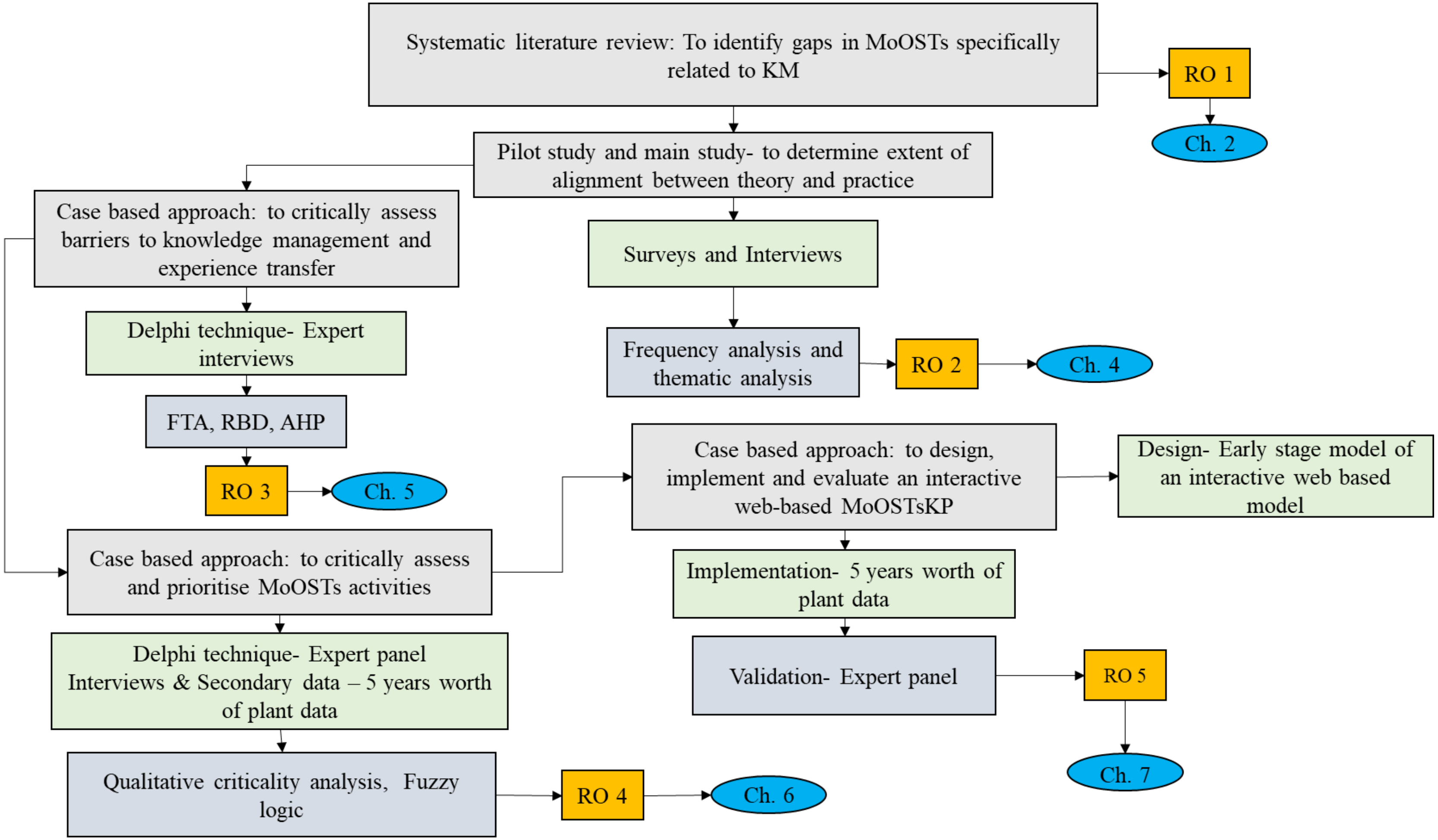


Figure 3. 2 Research methodology flowchart

The second phase (Chapter 4) was a mixed method approach involving the use of primary data (i.e. administration of survey and interviews) to obtain the perspectives of experts on the extent of alignment between theory and practice based on the issues identified from the SLR. Prior to the main study, a pilot investigation with 15 participants was conducted to provide sufficient methodological evidences about the design, planning and justification which was used to develop questionnaires as well as interview questions. The main study in the second phase (Chapter 4), involved the administration of surveys to industry professionals across five industries, as well as interviews. In total, 49 professionals completed the surveys, while 44 professionals were interviewed.

The third phase of the study (Chapter 5), was also a mixed method research that utilised focus group interviews (qualitative approach) to obtain the perspectives of professionals on their assessment of barriers to knowledge management and experience transfer in MoOSTs. Data analysis of the obtained responses was undertaken by integrating engineering failure analysis statistical tools (FTA, RBD) and multi-criteria decision-making analysis techniques-AHP (Quantitative approach) to quantify the responses of panel members.

The fourth phase of the research (Chapter 6), involved a mixed method approach to obtain the criticality assessment values of MoOSTs activities. This was following the integration of traditional qualitative approach to obtain primary data using a focus group interview, as well as secondary data (collation of historical plant data- 5 years' worth). Data analysis was achieved through the refinement/standardisation of the qualitative data using a quantitative approach (fuzzy logic).

The fifth and final phase (Chapter 7), was the culmination of the research efforts in the prior four phases, which involved the design of a knowledge management platform termed "MoOSTsKP" and its validation by professionals in the industry using focus group interviews to obtain responses. Table 3.1 shows the approach adopted for mapping research objectives to different phases of the research.

Table 3. 1 Mapping of different phases and chapters of this study to the research objectives

| Research Objectives and Study Type Description | Phases | | | | |
|---|---|---|---|---|---|
| | **Phase 1** | **Phase 2** | **Phase 3** | **Phase 4** | **Phase5** |
| | **Chapter 1** | **Chapter 4** | **Chapter 5** | **Chapter 6** | **Chapter 7** |
| RO 1:Theoretical framework- SLR to provide overview, identify trends and gaps in MoOSTs | O | | | | |
| RO 2:Pilot study- to determine extent of alignment between literature and practice based on practitioners perspective | | O | | | |
| RO 2: Main study- to determine extent of alignment between literature and practice based on practitioners perspective | | O | | | |
| RO 3: Main study- to develop an assessment model for ranking barriers to knowledge management and experience transfer in MoOSTs | | | O | | |
| RO 4: Main study- to develop a criticality assessment model for MoOSTs activities | | | | O | |
| RO 5: Main study- to design, implement and evaluate an interactive web-based MoOSTsKP | | | | | O |

## 3.5. Selection of Research Method

A mixed method approach is best suited for this research. There are however different research strategies applicable to both qualitative and quantitative approaches. A case study methodology was utilised in this research as a qualitative research strategy, on the other hand a survey research, which acts as a descriptive type of quantitative research was also adopted.

### 3.5.1. Case study methodology

Case study methodology is an empirical inquiry focused on a particular feature, issue, unit or group of people in an organization or setting to investigate a contemporary or social phenomenon within its real life context using multiple sources of evidence in order to gain a holistic view [138]–[140]. It is worthy to note that the case study methodology is not actually a data gathering technique, but it is a methodological approach that incorporates several research methods such as qualitative data-gathering measures and technologies such as, (in-depth interviews, participant observations, and document text analysis) and might also include quantitative data gathering techniques [141], [142]. According to McCutcheon and Meredith [140] it is a prime means of developing well-grounded theories is through empirical, and field based research.

### 3.5.2 Overcoming difficulties associated with case study research methodology

Although, case study research methodology is proven to be a very useful, several researchers have criticised the application of case study methodology due to its inability to generate casual relationships such as those found in controlled experiments, and they also state that it was impossible to generalise findings from it [143]. Some of the points used to discredit case studies were based on the how tedious it was to design and scope the case study so that the research question could appropriately be answered, and on how difficult it was to accumulate and analyse the large amounts of data collated [138], [142]. However, McCutcheon and Meredith [144] provided the basis for ensuring that the respective validity and reliability as it relates to case study methodology was met. Flyvbjerg [145] also asserted that these difficulties could be countered by applying proper research methods, practices and also reconsidering that knowledge was more than statistical significance. Table 3.2 depicts the typical difficulties associated with case study research and the proposed suggestions for overcoming them [142].

Table 3. 2 Typical difficulties associated with case study approach and suggestions for overcoming them

| Difficulties associated with case study methodology | Suggestions for overcoming difficulties associated with case study methodology |
|---|---|
| The type of research that can be addressed using the case study methodology | In-depth probing of an area of interest to provide rich cases of information. |
| Determining how to use case study methodology to answer the research question appropriately | Useful to establish the purpose of research and to delineate scope from theoretical framework. Also significant assessments of technical knowledge level of participants to determine how many questions can measure the theoretical framework constructs and to deduce and proposition relevant independent and dependent relationships. |
| The appropriate approach for data collection | Formulate interview schedule and protocol from research questions and present accordingly-structured, semi-structured and open ended. Then design a pilot study where research issues can be identified |
| Establishing rigour in writing to enable the acceptance by peers of the case study methodology findings. | Develop and maintain a detailed case study design protocol, publish preliminary data collected and findings to be reviewed by peer researchers and spend sufficient time with the cases and look for theories to contradict findings. |

## 3.6. Assessment of Mixed Method Design for Data Collection and Data Analysis- Taxonomy of Structure, Function, and Process

Through applying a SLR, GAPS were identified in Chapter 2 (the article was published in a peer reviewed conference as ; (Iheukwumere-Esotu and Yunusa Kaltungo 2021a) The first gap is “Inadequate emphasis on the need for integration and conversion of research findings into MoOSTs practice.” The second gap is “underrepresentation of articles that investigate mechanisms for experience transfer within uncertainties management in MoOSTs.” The third gap is “inadequate emphasis on articles that consider the usefulness of knowledge management and experience transfer within MoOSTs for learning and continuous improvement.”

The mixed method design's assessment of study structure was based on Morse's study [146], which describes the timing and weighting of the research method, i.e. a symbol denoting "→" signifies sequential timing. On the other hand a symbol denoting "+" signifies simultaneously. Under the mixed method design structure, the weighting could be all capital letter (primary) or small letters (secondary). The assessment of function of mixed method design was based on whether two methods were being used to answer a question, in order to determine if the aim of using the mixed method design corresponded to the five types of mixed method design described by Greene et al.[132] (triangulation or convergence, complementarity, expansion, development, and initiation or sampling). The assessment of process or strategies of mixed method design, was assessed using the typology proposed by Cresswell and Plano Clark [147], which include;

i. merge or converging the two dataset (qualitative and quantitative) i.e convergence-triangulation for validation;
ii. connecting the two datasets by building upon them i.e complementarity-elaboration, transformation, or
iii. expansion, initiation/sampling or embedding one dataset within the other to enable one type of data provide a supportive role for the other data set.

The representation of the mixed method taxonomy is shown in Figure 3.3.

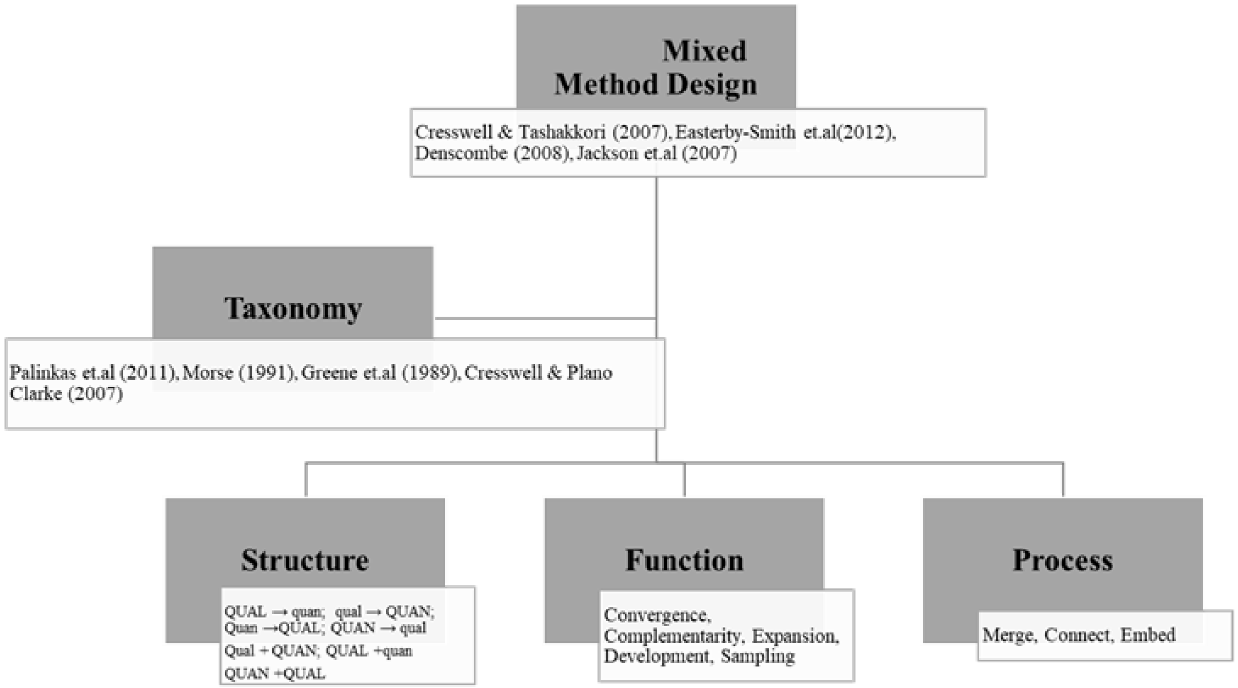


Figure 3. 3 Visual model and procedure of mixed method design

Firstly in chapter 4, a timing and weighting of "quan → QUAL" in was adopted, this involved the sequential collection and analysis of quantitative and qualitative data, beginning with quantitative data for primary purpose of further exploration/theory generation i.e seeking extent of alignment between theoretical and practice based findings as well as other underlying causes. The quantitative approach for data collection was used to obtain demographic information of participants such as, qualifications, level of expertise, job class, industry, years of experience, size of organization, staff turnover, and locations were gathered in the first section of the questionnaire. The later section of the questionnaire covered MoOSTs related questions such as, drivers for performing MoOSTs, causes of delays, estimated use of contracted services, MoOSTs frequency, MoOSTs budget, common approaches for documenting lessons learned, approximations of targeted performances of MoOSTs, based on duration and cost objectives [4], [10], [91], [93], [148].

The qualitative approach for data collection was by means of semi structured interview, each participant was asked open ended questions, some of which were earlier presented in the survey as close-ended questions. Some of the questions presented to participants during the semi-structured interviews tried to ascertain commonalities about commonly adopted names for maintenance activities across industries, reasons for delays in MoOSTs, frequency, financial implication of delays, dynamics of maintenance team, mode of communication, and barriers to learning [8], [10], [149]. Data analysis, of the quantitative data was through frequency analysis method [150], the most widely adopted method to efficiently organize the descriptive data were utilized. In this technique frequency charts were widely used to represent the frequencies of the data. While data analysis of the qualitative data was by thematic analysis (TA), which is a method of identifying, analyzing and reporting patterns (themes) within data [151]. The popularity of TA is partly due to its ability to explore variety of research questions and topics at a level of depth that quantitative analysis lacks, while offering flexibility in interpretation of data.

The assessment of function adopted for chapter 3 was sampling, where one type of method (survey) was used to define and identify the participant sample for collection and analysis of data representing the other type of method (e.g selection of interview participants based on responses to survey questions). While the assessment of process adopted is connect, meaning that the quantitative data was used to build upon the qualitative data. Hence to determine the extent of alignment between theory and practice on the major challenges in MOoSTs that were specifically related to knowledge management and experience transfer.

Secondly, in chapter 5, the assessment of structure is denoted as “QUAL → quan” a sequential collection of qualitative data from expert panel interview to rank and prioritise barriers to knowledge management and experience transfer, and data analysis was through quantitative method using traditional failure analysis tools of RBD, FTA and AHP for weighting and ranking. The assessment of function is by development, whereby the qualitative responses received from the expert panel, enabled the use of the other quantitative method i.e using quantitative data set to weigh and rank the responses generated from the qualitative data. The assessment of process “embed”, where the quantitative data provided supporting role for the qualitative data.

Thirdly, in chapter 6, the assessment of structure is dentoted as “QUAL → quan” a sequential collection of qualitative data from expert panel as well as secondary data (5 years worth of plant data) to critically assess maintenance activities during MoOSTs. The assessment of function was by convergence, whereby traditional qualitative criticality assessment was undertaken to rank the most critical MoOSTs activity, as well as quantitative analysis (fuzzy logic) to rank the most critical MoOSTs activity. This was done to compare the results from the two methods, as well as to convert qualitative data into quantitative data (quantify/qualify qualitative data). The assessment of process is by “Merge”, by bringing them together to validate the qualitative dataset.

Finally, in chapter 7, based on the findings from Chapter 4 to 6, an interactive web-based model was developed. The validation of the MoOSTsKP was achieved by means qualitative data (interviews) to generate feedback, about the perception of experts on the early stage knowledge platform mode.

## 3.7. Sampling Strategy, Data Collection and Analysis

The sampling strategy which was adopted in this study was the non-probability sampling, where randomisation is not relevant in selecting sample from the population and what is considered is a subjective method in deciding which participants are included in the sample. According to Etikan et.al. (2016) a non-random technique that does not require underlying theories or set number of participants is the purposive sampling. It is also referred to as judgement sampling and is described as the deliberate choice of a participant due to qualities that the participant possesses. There are several other accepted non-probability sampling techniques; quota, snowball and convenience [88], [123], [130]. However, the purpose sampling technique was adopted in most of the studies, except for the Pilot study which combined the purposive and convenience sampling technique. The sampling strategy was designed to meet the following predefined objectives;

i. to represent locations where the researcher could gain access to high number of participants involved in MoOSTs, who were also willing to participate in the study,
ii. to reflect industries with very high to medium frequencies for performing MoOSTs,
iii. to represent practitioners who have significant MoOSTs experiences, and
iv. to include practitioners with decision making capacity based on their responsibilities during MoOSTs.

Table 3.3 shows the sampling method, case organization, size and rationale.

Table 3. 3 Sampling method, size, and rationale

| Phase of research | Sampling method | Case organization | Sample size | Rationale |
|---|---|---|---|---|
| Phase 2- Pilot study- | Convenience, and Purposive | Cement Manufacturing | 15 | To determine the usefulness, duration, representativeness and ease of interpretation of the survey and interview questions, a pilot investigation was initially conducted for calibration purposes |
| Phase 2- Main study- | Purposive | Oil & gas<br>Utilities<br>Manufacturing/Construction<br>Transportation/Logistics<br>Aerospace/Defence | 49 (survey)<br>44 (Interviews) | To determine extent of alignment between literature and practice based on practitioners perspective |
| Phase 3- Main study- | Purposive | Cement Manufacturing | 10 (Expert panel) | To develop an assessment model for ranking barriers to knowledge management and experience transfer in MoOSTs |
| Phase 3- Main study | Purposive | Cement Manufacturing | 10 (Expert panel) | To develop a criticality assessment model for MoOSTs activities |
| Phase 3- Main study | Purposive | Cement Manufacturing | 9 (Expert panel) | to design, implement and evaluate an interactive web-based MoOSTsKP |

The selections of case organizations in this study are focused on representatives across manufacturing and process based industries, namely, cement manufacturing, oil and gas, defence, water utility and transportation were deemed to be the most relevant industries owning to the frequencies of studies that were extracted within the review.

Take, for instance the cement manufacturing company in the UK which was routinely used as a case organization was selected not only due to its accessibility to the decision makers in the company, but also because cement manufacturing companies perform large numbers of MoOSTs in a calendar year. Therefore, this provides the researcher an opportunity for observations as well as lots of data gathered over the years. This is in contrast with many other industries where the execution of MoOSTs sometimes takes up to 3 to 5 years intervals, and other factors such as accessibility is really low. Furthermore, in terms of units of analysis to be examined, case in point the participants in the case study, careful selections were made to ensure that each participant was significantly involved in their area of expertise for a specified length of time.

## 3.8 Importance of Pilot Investigations

To determine the usefulness, duration, representativeness and ease of interpretation of the survey and interview questions, a pilot investigation was initially conducted for calibration purposes. Pilot and feasibility studies have an important role to play in empirical studies because they can provide sufficient methodological evidence about the design, planning and justification of the main study, and can also inform critical elements of the main design to reduce or eliminate problems at later stages of the research [152], [153]. Approximately 15 participants, with nine of the participants coming from the manufacturing industry (cement plant) and six participants from the utilities industry (water plant) were recruited for the pilot studies. Before the pilot investigation commenced, participants were emailed documents, which explained the study's purpose and content.

They were advised that they could withdraw from the study at any time and reassured that none of their identifiable personal details would be shared during the study. The approval of document content and consent to participate in the investigation was obtained by appending one's signature to the proposal and replying to the email sent out by the researchers. The incorporation of both open-ended and closed-up questions were deemed to be one of the most effective approach to obtain concise responses [154], [155]. Whereby appropriate open- ended questions were used in the semi-structured interview to avoid generic answers and to obtain detailed responses. For instance, "if yes/no, can you explain" following certain closed questions. Likewise, with the survey, although most questions were limited to single answer options, but some questions permitted multiple choices as well as text box entries with the option "others, please specify" so as not to limit participants responses for some crucial questions. All interviews were conducted in

English and kick off date was from the first week of October 2020 and lasted for about 2 weeks. The proposed content of the interview, as well as the length of each interview mapped against relevant job classes were discussed with key personnel from each selected industry, minor adjustments were made according to the feedback obtained from participants. Based on feedback and practicality, interview durations were pegged to last for between 30–60 min depending on the information required from the participant based on their job class and level of expertise.

## 3.9. Ensuring Good Quality of Qualitative Research Design

According to Golafshani [156] "Although, reliability is a concept that is used for testing or evaluating quantitative research, the idea is often used in all kinds of research.'' Stenbacaka, 2001, p.551), explained that the concept of reliability relates to good quality research with the purpose of explaining when it is used as a tool of measurement in quantitative research, but in qualitative research it is used for the purpose of generating understanding. Delineating between the two purposes might lead to the conclusion that reliability is irrelevant in qualitative research because reliability and validity per se cannot be practically used as criteria to assess qualitative research [125]. However, Patton [157] has suggested that validity and reliability are important criteria that should be considered when designing a qualitative research. Healy and Perry [158]. maintained that the quality of a study should be judged based on its own paradigm terms. Therefore, reliability and validity which are important criterion for quality in quantitative paradigms should be considered as qualitative paradigm terms of Credibility, Neutrality or Confirmability, Consistency or Dependability and Applicability or Transferability [156]. According to Wahyuni [159] credibility parallels internal validity, transferability resembles external validity, dependability parallels reliability and confirmability resembles objectivity. Winter [160] stated that the concept of validity could be described by a wide range of terms in qualitative studies. As a result many researchers have developed their own concept of validity as well as adopted appropriate terms such as quality, rigor and trustworthiness in qualitative research [161]. Further explanations have been provided on these terms as follows:

**Credibility**

Qualitative research is concerned with if the study actually measures what it is intended for. This study considers the careful selection of a case organisation to be the first practical step towards credibility. Care was taken to ensure that the case organisations selected had significant and appreciable involvements in MoOSTs management. Furthermore, apart from the interviews, secondary data such as document analysis were employed to enhance the credibility of findings.

**Transferability**

This relates to the level of applicability into other settings or situations in qualitative research. This study ensured that vivid descriptions of attributes and/or characteristics of the case organisations were provided.

**Dependability**

This corresponds to the notion of reliability and promotes replicability or repeatability. To ensure dependability, the list of interview questions has been provided and the same sets of questions administered to the different case organisations.

**Confirmability**

This refers to the extent to which others can confirm the findings from the research to ensure that the results reflects the understanding and experiences from observed participants, rather than the researcher's own preferences [159]. In this study, an inquiry audit which is a measure which can be used to examine the process and the product of the research, by verifying items such as the raw data, the data reduction products and process notes was conducted to satisfy this criterion.

## 3.10 Ensuring Reliability and Validity in the Design of Quantitative Research

To ensure that reliable and valid results are produced, careful wording of questions would be adhered to. Double barrelled, loading/leading, negative, unnecessary and dead giveaway questions respectively were identified to be the problem associated with question wording and would be eliminated so that participants are able to understand the intended meaning of questions [162]. According to Sarantakos [163] reliability refers to the consistency of a question in terms of how high the probability of obtaining the same results if duplicated. Thus, as Mann [88] suggested should involve 'internal testing' and requires preliminary assessment by colleagues so that ambiguities, leading questions and general criticism are discussed and corrected. Asking similar questions in different forms and checking for consistency is also a procedure for assessing reliability. Validity on the other hand refers to the degree to which the question answered measures what it was intended to Sarantakos [163]. Provision for this was initiated in this study and all questions for this research were reviewed and assessed by colleagues who are familiar with the field and the research.

## 3.11. Ethics Approval

Researchers should consider their research as a reflective process which requires them to take stock of personal actions, as well as their role in the research process and subject them to the same critical scrutiny as the rest of their collected data. Easterby-Smith et.al.[120] raised some vital points that should be considered in the process of designing the research protocol. Voluntary participation, anonymity and confidentiality, which are research ethics principles [125], [127] were offered to research particpants and their informed consents obtained. The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics committee panel of Mechanical, Aerospace and Civil Engineering Department, University of Manchester, UK (Ref code: 2020-8009-13470) and date of approval 9 March 2020. These approvals can be found in the Appendix at the end of the thesis.

## 3. 12. Chapter Summary

The research philosophy adopted in this study was mainly interpretivism to gain a comprehensive understanding of MoOSTs environment and implementation principles from multiple perspectives. However, the analysis of data was influenced by a positivist philosophy in order to quantify the qualitative data. On the basis of the philosophies, this research was divided into five phases: systematic literature review (Phase 1), practice based approach to determine extent of alignment between research and practice (Phase

2), assessment of barriers to knowledge and experience transfer (Phase 3), knowledge criticality assessment of major maintenance activities (phase 4) and design and evaluation of a MoOSTsKP (Phase 5). Elements of ethics and reliability, validity, and generalisability of the findings were considered in designing the research. In the four following chapters (Chapters 4, 5, 6, 7) the results of this study are presented and discussed. The findings are then synthesised in Chapter 8 to address the five research objectives (ROs) proposed in the first chapter. The following chapter (i.e. Chapter 8) presents the design and evaluation of an interactive web-based knowledge platform.

# 4 KNOWLEDGE MANAGEMENT AND EXPERIENCE TRANSFER IN MAJOR MAINTENANCE ACTIVITIES: A PRACTITIONER'S PERSPECTIVE

**Reformatted Version of this paper:**


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|---|---|
| Paper title: | **Knowledge Management and Experience Transfer in Major Maintenance Activities: A Practitioner's Perspective** |
| Authors: | **Lilian Iheukwumere-Esotu and Akilu Yunusa-Kaltungo** |
| Published in: | **Sustainability** |
| Volume: | **14** |
| DOI | **10.3390/su14010052** |


## ABSTRACT


Major overhauls, outages, shutdowns and turnarounds (MoOSTs) are significant maintenance interventions needed on a periodic basis to optimise the performance of physical industrial assets (PIAs). However, uncertainties in the forms of emergent and discovery work which sometimes cause delays and cost overruns are quite common partly because, MoOSTs are characterised by inherent challenges such as, but not limited to, short execution spans, volatility in ever-evolving schedules, task complexities as well as huge offline production and/or operation costs etc. Furthermore, in the literature, other complex elements which further constrains decision-makers in MoOSTs from satisfactorily achieving predetermined objectives have been identified, one of which is the lack of a formalised approach for capturing tacit knowledge from experienced practitioners. Consequently, because MoOSTs is an applied discipline, significant human endeavours are required in the planning and management, which makes it pertinent to examine and obtain the perspectives of experienced MoOSTs practitioners. Therefore, the aims of this study are two folds; firstly, to examine the extent of alignment between findings from literature as it relates to the challenges encountered during MoOSTs, as well as probe their underlying causes in practice. Secondly, to show how relevant the findings from this study would be in providing a baseline for establishing a proposal for capturing MoOSTs knowledge and the transfer of experience. The research approach adopted; thematic synthesis of themes which emerged from knowledge management challenges in MoOSTs identified via an earlier systematic literature review (SLR); and then, the identified challenges were validated through conducting interviews with practitioners. Demography analysis as well as specific MoOSTs related questions were administered via questionnaires, which were then analysed using frequency analysis method. Additionally, semi-structured interviews were conducted to investigate the perceptions of practitioners on pertinent MoOSTs issues. Both questionnaires and interview questions were formulated by findings obtained from the SLR, so as to examine whether the knowledge management challenges identified in the literature exist in practice, and if they do to what extent. In total, the selected responses of 49 practitioners, with origin across five industries were examined to determine the extent of alignment between literature and the practice-based perspectives. Based on the results, nine challenges were identified as critical themes, six of which were associated with managing knowledge. The study identified not only known constraints from literature but also their underlying causes based on the perspective of practitioners involved in multiple MoOSTs, which is crucial for developing sustainable mitigation. A unique contribution of this research is the mapping of demographic information such as industry, country, job class, years of experience, MoOSTs organization size, frequency for performing MoOSTs, etc., to responses obtained from participants, which has not been shown in literature prior to now. The importance of such rigorous efforts in the research design, is crucial for enabling the adoption of holistic approaches to eliminating the underlying causes of challenges encountered in MoOSTs, based on first hand reporting of people involved. In addition, the relevance of such first-hand analyses of responses obtained from this study; serve as baseline for the introduction of the proposal to adequately manage knowledge management issues in this discipline.

*Keywords*: knowledge management; experience transfer; maintenance activities; MoOSTs; practitioners perspectives

## 4.1. Introduction

The move towards sustainable activities across different sectors has generated increased interests in recent times [164], [165]. Large amounts of work towards achieving sustainability have been focused on energy consumption, materials, and environmental considerations [165], [166]. However, in terms of real-world applications, knowledge management (KM) practices within organizations have shown to be vital in determining how well sustainability targets are met. According to Kordab et al., [167] knowledge management practice and organizational learnings are significant factors to achieve sustainable organizational performance in rapidly changing business environments. In continuous production industries, sustainability is crucial, because physical industrial assets (PIAs) are prone to degradation and eventual failures due to repetitive loads and the harsh environments in which they operate. These failures often result in disruption of production and an inability of organizations to deliver contractual obligations to their clients on time, which might lead to a compromise in budget over-estimation as well as undermine their reputation [18], [19], [50].

To reduce the impacts of such disruptions and achieve maintenance efficiency, industrial maintenance activities such as, major overhauls, outages, shutdowns or turnarounds (coined as the acronym MoOSTs here) has emerged as an area of research for both the industry and academia [168]. MoOSTs can be described as an important maintenance management strategy for the total periodic shutdown of plant facilities for a certain time to conduct rare and routine maintenance activities such as inspections, replacements, overhauls, de-rating, renewals and repairs, based on very prudent work packages in order to achieve total asset life cycle optimization [6], [25]. However, due to continuity features of most industries that perform MoOSTs, shutdown of operations for a definite period is expensive from a planning, execution and logistics point of view. Furthermore, because MoOSTs offers one of the few instances whereby all the elements of routine as well as complex maintenance tasks are performed at a single instance, it is both capital and labour intensive. It can be easily plagued with delays, cost overruns, as well as uncompleted activities due to brief and strict execution regimes, that are often, associated with reduced margins for errors [7].

Although MoOSTs have attracted the interest of many researchers and practitioners mostly due to its significant impact on plant performance [11], [18]–[20], the inability to achieve predicted outcome is still very common. The many challenges associated with planning and management of MoOSTs, are not limited to but include management of uncertainty, resource constraints, unavailability of spares, activity relationships, and organizational behaviours [23]. Traditional project management techniques such as critical path method (CPM), and programme evaluation review technique (PERT) have been used to manage MoOSTs [168]. Unfortunately, delays, cost overrun and uncompleted activities in MoOSTs are commonly observed, thus limiting the effectiveness of applying traditional project management methods alone [18], [24].

Hence, it was pertinent to conduct inquiries (empirical studies) to probe persisting issues and provide new perspectives that would shape the directions of future research in MoOSTs. A systematic literature review (SLR) is a useful technique for gap analysis of literature within a research discipline. When conducted properly, SLRs can minimise errors and bias and most importantly leave an audit trial that can be checked by an independent reviewer [109]. Prior to this study, an SLR was conducted by [50] to probe the representation of MoOSTs activities and knowledge trends within MoOSTs management literature as well as identify opportunities for bridging the gaps that currently exist between theory and practice. The SLR identified several classifications, including but not limited to, the origin of research (country related), industry focus, terminologies and research focus. One of the most pertinent SLR finding was the underrepresentation of articles that investigate mechanisms for knowledge management and experience transfer within MoOSTs. The importance of capturing knowledge and expertise during project executions and subsequent transfer within temporary project environments such as MoOSTs cannot be over-emphasized, due to the ratio of tasks-to-duration typically permitted as well as workload uncertainties. Evidence abound that suggests that adopting effective and specific knowledge management and experience transfer attributes related to MoOSTs could improve predetermined outcomes by reducing the occurrence of uncertainty, commonly known as scope creep in traditional project management [18], [25], [41].

Furthermore, the inherent characteristics of temporary project environment creates associated risks of loss of knowledge and critical expertise if not properly captured, formalized, codified and transferred. According to Ruiz et al., [169] it is often easier for people involved in an activity to validate expertise extracted from lived experiences than to directly structure knowledge, which in turn makes management of past knowledge a strategic need for organizations. The importance of effective classification systems for knowledge before subsequent storage cannot be over-emphasised because acceptance of knowledge by the end users after dissemination and future reuse are tied to many knowledge maintenance parameters including, long term applications, relevance, completeness, and accuracy [170].

### 4.1.1. Overview of knowledge management (KM) challenges in MoOSTs

Despite the wealth of contributions available within existing MoOSTs management literatures, the problem of its effective management and execution persists. This is because despite advances in the development of techniques for predicting deterioration and loss of integrity of critical physical industrial assets (PIAs), there are still associated risks of discovering additional or emergent work, due to reasons such as oversight in determining project work scope, equipment deteriorating faster than predictions made from predictive tools analysis, and/or damages associated with disassembling PIAs for inspections, etc.[25], [33], [97]. A major research challenge that impacts on effective decision-making during MoOSTs is characterised by the need to effectively capture tacit knowledge, in several forms, including lessons learned, technical know-how and general information generated from previous MoOSTs and subsequent reuse [25], [34], [171]. This is because MoOSTs knowledge is held by collective groups of individuals (experts) and due to the nature of MoOSTs activities, the anticipated loss of knowledge and specialists skills are constant [172].

Furthermore, because MoOSTs activities are periodic, large amounts of information generate large amount of data. Please note that the ‘information’ referred to here, is experience, technical know-how and insights which comprises of knowledge [173], a KM system that aims to provide complementary solutions for prognosis and enhanced decision-making during the execution of MoOSTs activities is crucial.

It is important to emphasise that most organizations are not bereft of data, information and explicit knowledge, rather, the challenge is usually on varying reasons including but not limited to; identifying knowledge sources, as well as effective knowledge maintenance actions that can foster knowledge relevance and reuse [19], [62], [174].

### 4.1.2. The Importance of knowledge management (KM) in MoOSTs

Knowledge management (KM) facilitates the systematic identification, acquisition, storage/retention, transfer and utilization of knowledge by individuals, teams and entire organizations to reach their strategic and operational goals [37]. KM is not an end in itself, but fundamentally entails capture and reuse which in turn help organizations to prevent failures as well as identify new solutions to problems already faced by the organization [35]. KM is particularly important for project-based learning, because the systematic identification of knowledge and retention of project experiences enables an organization to compare the performance of its various projects, document its most effective problem-solving mechanisms for future use and gain competitive advantage [36], [37]. According to Ambani et al. [18] knowledge is the most valuable asset of an organization, as it enables it to differentiate itself from competitors and to compete efficiently and effectively to the best of its ability.

However, due to the inherent characteristics of MoOSTs the applications of KM in practice could be unattainable due to contrasting elements and objectives. The inherent characteristics of MoOSTs [9], [11] that make knowledge management applications challenging including but not limited to, task uncertainties, compressed schedules, dynamic and frequent scope changes; selection of highly experienced practitioners to perform critical tasks and many others. Several, research studies have identified the inherent characteristics of MoOSTs as barriers to knowledge management, take for instance heavy workload is a major reason for having limited or no time for knowledge sharing [36], [175]. Ambiguity in the content and context of knowledge along with uncertainty, act as barriers to knowledge [176]. Task uncertainty that can arise from factors including, discovery of large amount of unplanned and/or emergent work which can affect identification and distribution of knowledge elements.

Consequently, dynamic and frequent scope changes commonly experienced during MoOSTs can create ambiguity in the content and context of knowledge as variables change quickly. In addition, because plant and production activities are shutdown during MoOSTs task execution and handover activities are crucial leaving little or no time for either learning or reflections during or in between cycles.

Furthermore, due to the complexity of some maintenance tasks that are performed during MoOSTs, selection of highly experienced staff to perform critical tasks is quite common with the challenge being that only few people are in possession of critical skills as well as expertise. According to Peng [177], when knowledge is centred around an expert it can lead to psychological ownership, that is, the belief of an individual that he/she has ownership rights to the object (knowledge) in question.

### 4.1.3. Knowledge management process (KMP) in MoOSTs

In the literature, knowledge management process (KMP) has in general maintained two major streams of focus in the past, with the first being on knowledge itself, exploring knowledge creation and conversion process in organizations. The second stream of focus takes an approach that investigates activities such as knowledge generation, capture, sharing and utilization to gain competitive advantage [178]. From the second stream of focus, knowledge is only meaningful when it is codified, classified, given a shape, put in a useful format, stored for future use by the right person, at the right time, and in the right way [179]. Much has been written on the importance of managing knowledge processes, that is, about the processes that are used to identify, capture, share and use project-based knowledge, but considerably less has been written on the exact mechanisms for managing this process in MoOSTs [172], [178], [180].

A review of the literature has identified different elements of KMP, but they can all be distinguished under four key KMP elements, namely, knowledge creation (KC), knowledge transfer (KT), knowledge storage/retrieval (KSR) and knowledge application (KA) [181]–[183]. KC refers to accumulation of knowledge, in project-based organizations such as MoOSTs, knowledge identification (KI) and KC do not have clear boundaries separating them, and mostly have similar connotations [39]. KT refers to the measures and procedures for transferring and sharing knowledge. According to Bell

[172], KT techniques can be broadly categorised as either ‘capture’ or ‘share’. KSR involves the activities of documenting and codifying knowledge that has been identified in the organization in order to stem loss of knowledge that might arise as a result of factors such as, infrequent use of knowledge, staff retirement and/or departures [39].

KA is concerned with the forms and procedures of applying appropriate knowledge within an organization to create value both internally and externally [182]. A major consideration for MoOSTs organizations, is the effective integration of the four KMP into their business process to improve organizational learning and performance [27]. Consequently, a major requirement of the KMP is to establish an effective KM system and appropriate technologies to facilitate the four KMP areas.

### 4.1.4. Experience transfer in MoOSTs

According to [36] an organization can develop competitive advantage by building capacity to harness the knowledge possessed by its employees. This is because effective knowledge capture requires turning personal knowledge into corporate knowledge that can be shared and properly managed throughout the organization [38]. Personal knowledge possessed by employees are mostly tacit knowledge and employers who leave, take away such valuable knowledge, resources, skills and experiences [39]. The distinction between tacit and explicit knowledge is important because it influences the adoption of different transfer techniques for developing effective KM systems. Explicit knowledge can be easily articulated and codified and is expressed in words, numbers, and symbols, which can be shared as theories, principles, specifications, data and others [184]. Conversely, tacit knowledge is difficult to express and/or codify, because it is rooted in the individual’s actions and experiences, as well as emotions, and values [184].

Consequently, because it is very easy for knowledge to be lost within organizations, it is of immense benefit to capture tacit knowledge before it is lost through mergers, reorganizations, downsizings and/or culture changes [38], [185].
MoOSTs is characterized by large number of staff and contract workers performing large-scale as well as complex maintenance activities at an instance [13]. These workers depend on the organization’s explicit knowledge and protocols when dealing with standard

issues, in contrast, when dealing with unexpected and/or non-standard problems, they develop work related tacit knowledge [172], [186] which include but not limited to, practical know-how, work experience, procedures, as well as skills in specific contexts.

While creation and transfer of explicit knowledge are mostly captured in many studies, capture and subsequent transfer of tacit knowledge, in this instance "expertise" is still scant despite its importance to MoOSTs organizations. Since the importance of expertise in MoOSTs has been highlighted, going forward, expertise coordination and knowledge codification would amount to significant contributions to this discipline, because, at present MoOSTs organizations favour a personalization strategy, associated with the routinization of actions and roles as well as sharing of knowledge through personal contacts [187]. However, routinization of actions and roles which is common in MoOSTs because each team member know their jobs and there is no need for anyone else to know anyone else's job since only experts are assigned to specific tasks, as well as sharing of knowledge based on personal relationship, leaves the knowledge holder with too much power. Elements from adopting such personalization strategy has been identified as barriers to knowledge management and experience transfer in MoOSTs [22]. However, organizations can adopt a codification strategy, and make knowledge an organization resource by depersonalizing it. This view of expertise codification significantly reduces the challenges of coordinating expertise by limiting knowledge related dependencies between groups [187].

### 4.1.5. Knowledge management (KM) in industry 4.0 and Its relationship to employees competencies in MoOSTs

Industry 4.0 implies a revolution where industrial processes integrate computer tools to facilitate the handling of large amounts of data and related information, as well as their transfer and interpretation, because previous means for storing information are restrictive for handling large data that are generated due to, the interconnectivity of most organizations global systems [188]. The rapid advancement and development of information and communication technologies (ICT) and integration of maintenance process within these frameworks, means most organizations are facing challenges and at the same time competency needs [30], [31]. Such integration, which is called cyber-physical systems (CPS) are systems that can measure and process information up to the level that makes it usable for the end users [29], [189], [190]. Hence there is need to rethink new employee competencies that will allow development of a CPS structure capable of implementing big data predictive analytics for transformation of data to information to knowledgeable action such as those advocated by internet of things (IOT), cloud computing, and augmented reality, to improve decision-making [30], [189], [191]. This is because, predictive and prescriptive maintenance of production systems including equipment and physical assets which will be the most important application areas of industrial analytics within the next three years [29].

Thus, there is need for developing knowledge-based decision support systems to improve efficiency and effectiveness of industrial processes [29], [192]. KM is a key enabler in this age of rapid technological innovation learning and since man-machine interface is a cornerstone of industry 4.0, it has become even more imperative to answer fundamental questions of "who does what, when and under which conditions?" [27]. KM in the era of industry 4.0 (KM 4.0) in both human and technology-oriented perspectives is a strategic and operational function, and the revival of artificial intelligence (AI) and emergence of autonomous and learnable technologies challenge the unique role of humans as knowledge actors, decision-makers, problem solvers and learners [27]. MoOSTs organizations are considered high knowledge-intensive organizations, based on the number of activities they perform and large the amounts of information they possess, but to be successful in the era of industry 4.0, increase in information technology expenditure, developing intranets, data warehousing, and use of internet to create effective and efficient knowledge management practice is key [193].

In literature, three main categories to classify core employee competencies exist namely, technical competencies which comprises of job-related knowledge and skills, for instance in industry 4.0, coding skills, knowledge management, and large information handling, etc. [194], [195]. Secondly, managerial competencies include all skills for problem solving and decision-making. Thirdly, social competencies, the bedrock upon which expectations for future interactions with others would be built and include skills such as social and interpersonal communication, which are crucial to managing MoOSTs. However, due to the development of new technologies which trigger improvements in existing KM systems and rapid digitalization, identifications of the competencies of future managers and engineers involved in MoOSTs (especially maintenance of complex manufacturing systems, special IT and technologies for managing knowledge, more creativity, strategic thinking, etc.) needs to constantly reassessed [191].

Therefore, the aim of this study is twofold; firstly, to conduct an empirical study across diverse industries involved in MoOSTs activities to obtain the perspectives of practitioners, in order to validate the findings generated from the SLR. This should help determine the extent of alignment between research and practice, as well as probe underlying causes of any alignments or misalignments. Secondly, because there are limited proposals investigating tacit knowledge capture and transfer as a possible mechanism for managing uncertainties in MoOSTs, a new proposal for capturing tacit knowledge and facilitating experience transfer is briefly presented in this study. Thus, the research questions for the empirical study are as follows:

1. What knowledge management challenges, are identified in real-world practices, during MoOSTs?
2. To what extent does the knowledge management challenge in the literature identified during MoOSTs align with real-word practice?
3. Can examination of underlying cause of the knowledge management challenges identified during MoOSTs, foster the development of a proposal for a formalised platform for capture and transfer of tacit knowledge across MoOSTs organizations?

Following the investigation, and exploration of emerging themes, a proposal establishing a platform for formalising tacit knowledge capture in MoOSTs is detailed. It is the belief of the authors that, the unique cross-correlation of theory and practice allows for the identification of strengths, weaknesses and common omissions from both facets (i.e., theory and practice).

This paper is further organized as follows; section two contains details of the research design, pilot investigation, sampling technique and sample size, section three demonstrates the implementation of data analysis methods and results for both surveys and interviews data, Section 4.4 is discussion of findings, Section 4.5 is concluding remarks and a brief proposal introduction for a knowledge management platform.

## 4.2. Research Design

The research design involved two main approaches for data collection, questionnaires [196], [197] administered via a web-based platform and semi-structured interviews [154], [198] conducted remotely. In total, 49 professionals involved in MoOSTs across five industries based in the UK, USA and Nigeria were respectively recruited. The period for data collection was between February and July 2021. The study investigated pertinent issues relevant to the management of MoOSTs. The questionnaires were administered through "Qualitrics" (**www.qualtrics.manchester.ac.uk**; accessed on 14 December 2021), a University of Manchester approved survey platform due to its conformance with global data protection regulations (GDPR). The demographic information of participants such as, qualifications, level of expertise, job class, industry, years of experience, size of organization, staff turnover, and locations were gathered in the first section of the questionnaire. The later section of the questionnaire covered MoOSTs related questions such as, drivers for performing MoOSTs, causes of delays, estimated use of contracted services, MoOSTs frequency, MoOSTs budget, common approaches for documenting lessons learned, approximations of targeted performances of MoOSTs, based on duration and cost objectives [4], [10], [91], [93], [148].

Furthermore, during the semi-structured interviews, each participant was asked open ended questions, some of which were earlier presented in the survey as close-ended questions. Some of the questions presented to participants during the semi-structured interviews tried to ascertain commonalities about commonly adopted names for maintenance activities across industries, reasons for delays in MoOSTs, frequency, financial implication of delays, dynamics of maintenance team, mode of communication, and barriers to learning [8], [10], [149]. Each participant was aware of the study purpose and gave informed consent. Figure 4.1 is a flow chart diagram-depicting construct of this study's research methodology.

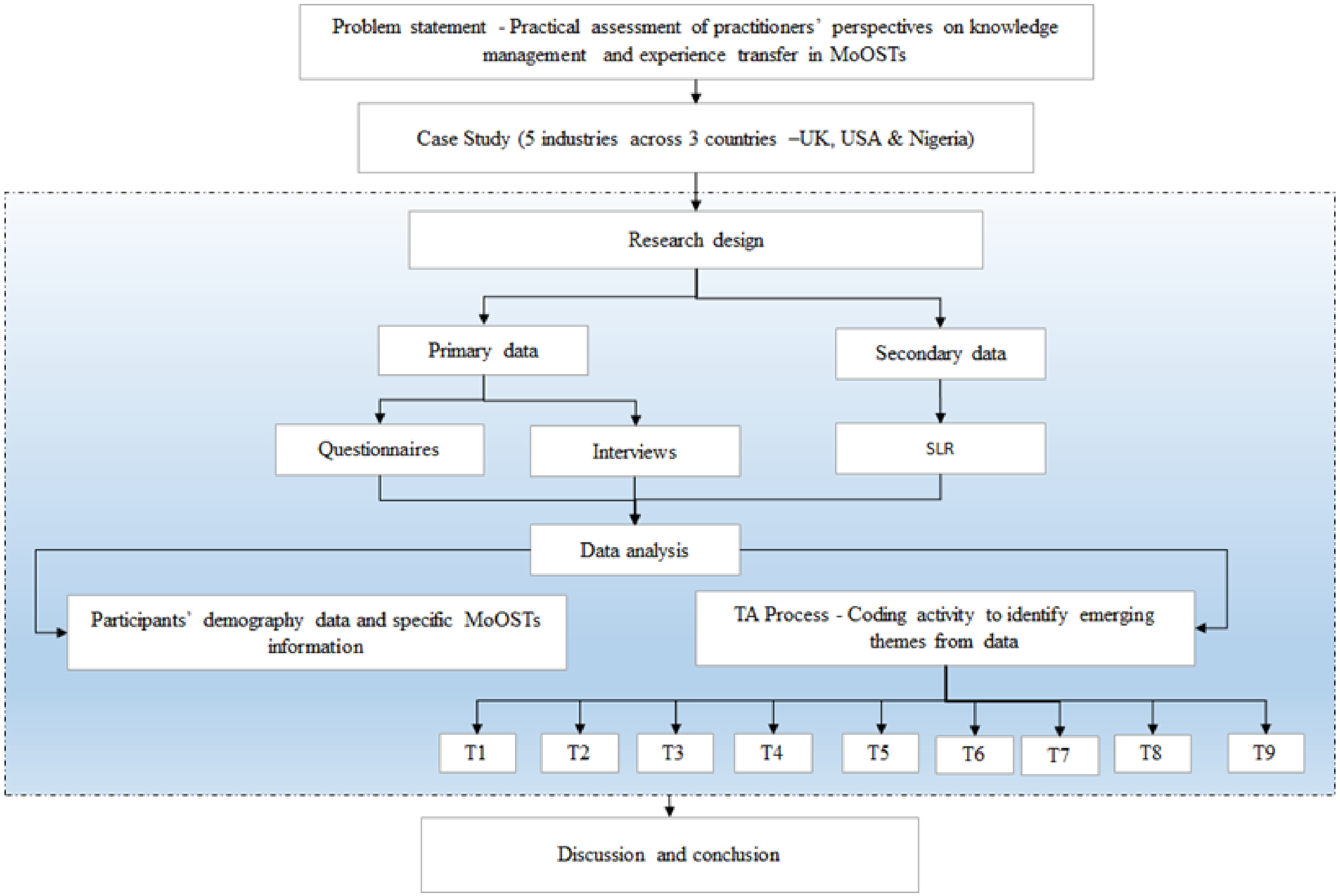



Figure 4. 1 Flow diagram of research design

Note: T1—nomenclature; T2—mode of communication; T3—dynamics of maintenance team; T4—impact of delays; T5—causes of delay and budget overspend; T6—responsibility for knowledge and experience maintenance management; T7—personal experience of learning; T8—formalized approaches for knowledge capture and experience transfer and T9—barriers to learning

### 4.2.1. Pilot investigation

To determine the usefulness, duration, representativeness and ease of interpretation of the survey and interview questions, a pilot investigation was initially conducted for calibration purposes. Pilot and feasibility studies have an important role to play in empirical studies because they can provide sufficient methodological evidence about the design, planning and justification of the main study, and can also inform critical elements of the main design to reduce or eliminate problems at later stages of the research [152], [153]. Approximately 15 participants, with nine of the participants coming from the manufacturing industry (cement plant) and six participants from the utilities industry (water plant) were recruited for the pilot studies. Before the pilot investigation commenced, participants were emailed documents, which explained the study’s purpose and content. They were advised that they could withdraw from the study at any time and reassured that none of their identifiable personal details would be shared in the course of the study.

The approval of document content and consent to participate in the investigation was obtained by appending one’s signature to the proposal and replying to the email sent out by the researchers. The incorporation of both open-ended and closed-up questions were deemed to be one of the most effective approach to obtain concise responses [154], [155]. Whereby appropriate open- ended questions were used in the semi-structured interview to avoid generic answers and to obtain detailed responses. For instance, “if yes/no, can you explain” following certain closed questions. Likewise, with the survey, although most questions were limited to single answer options, but some questions permitted multiple choices as well as text box entries with the option “others, please specify” so as not to limit participants responses for some crucial questions.

All interviews were conducted in English and kick off date was from the first week of October 2020 and lasted for about 2 weeks. The proposed content of the interview, as well as the length of each interview mapped against relevant job classes were discussed with key personnel from each selected industry, minor adjustments were made according to the feedback obtained from participants.

Based on feedback and practicality, interview durations were pegged to last for between 30–60 min depending on the information required from the participant based on their job class and level of expertise. Table 4.1 shows the characteristics of interview participants involved in the pilot investigation.

Table 4. 1 Characteristics of interview participants involved in the pilot investigation.

| Industry | Category and Job Class | Number |
| --- | --- | --- |
| Manufacturing-cement | A- Maintenance manager (mechanical engineering), reliability engineer (electrical engineering), finance manager (cost), health, safety and environment (civil engineering) | 4 |
| | B- Maintenance supervisor (mechanical) maintenance planner (project controls) | 3 |
| | C- Mechanical fitter, electrician | 2 |
| Utilities-Water | A- Maintenance manager (mechanical engineering), contracts and procurement | 2 |
| | B- Method and inspection (electrical and mechanical), maintenance planner (project control) | 3 |
| | C- Electrician | 1 |
| **Total** | | 15 |

Where job Category A represents management staff directly involved in MoOSTs, B—staff involved in implementation of engineering methods and/or techniques and equipped with decision making ability during MoOSTs and C—staff with experience with handling plant assets and knowledgeable on the schematics and working of the plant.

### 4.2.2. Ethics approval

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics committee panel of Mechanical, Aerospace and Civil Engineering Department, University of Manchester, UK (Ref code: 2020-8009-13470) and date of approval 9 March 2020.

### 4.2.3. Sampling technique

Participants were selected through a purposive or maximum diversity sampling strategy, owing to the specificity of MoOSTs activities and the job classes involved. In addition, this sampling approach offers the opportunity to explore anthropological scenarios that can intuitively guide the emergence of new meanings [199]. In this study, the sampling technique selected was designed to meet the following predefined objectives; (1) to represent locations where the researcher could gain access to high number of participants involved in MoOSTs, who were also willing to participate in the study, (2) to reflect industries with very high to medium frequencies for performing MoOSTs, (3) to represent practitioners who have significant MoOSTs experiences, and (4) to include practitioners with decision making capacity based on their responsibilities during MoOSTs. It is worth mentioning that some organizations and participants who were approached declined participation due to work commitments and COVID-19 related restrictions. Interviews were conducted remotely and the links to the anonymized questionnaires sent out.

### 4.2.4. Sample size

There are important factors to consider, when determining sample size including degree of accuracy (based on sampling error and confidence interval) as well as extent of variations with regards to important attributes of the study [196]. However, because a non-probability sampling technique, in this case purposive sampling was selected, randomization was not considered relevant but rather based on expert judgment. Hence, statistical assumptions about sampling errors do not apply [196]. In total, 49 carefully selected experienced practitioners in the UK, US and Nigeria working across diverse industries identified from a prior SLR in MoOSTs were selected. Figure 4.2 is a snapshot from the survey design and management platform that is authorized for use by the University of Manchester (i.e., Qualitrics) to depict the total number of completed responses received.

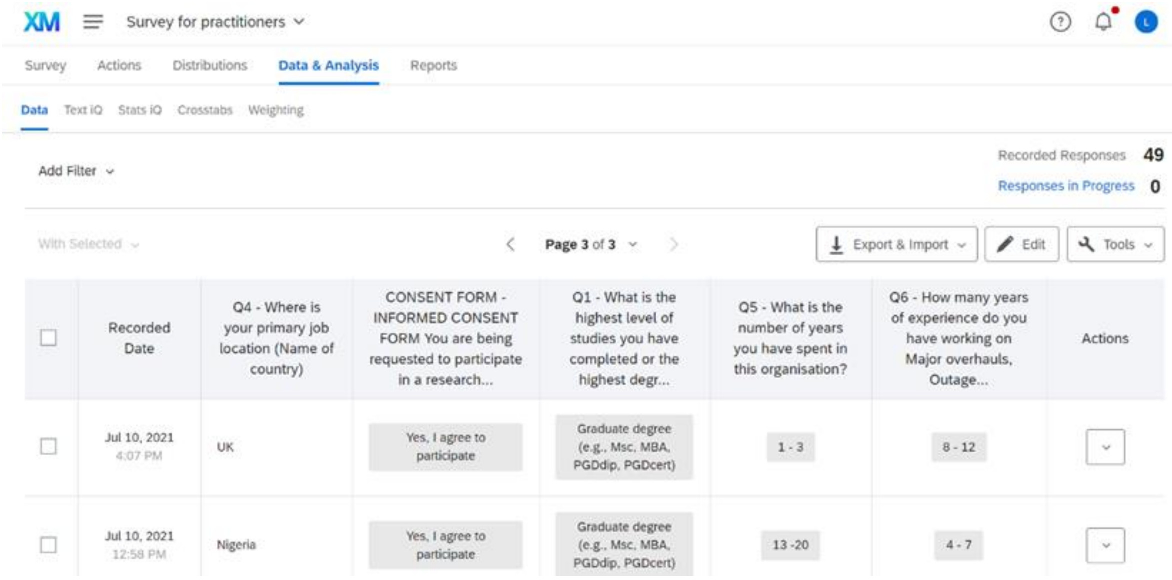



Figure 4. 2 Snapshot from the survey design and management platform (Qualitrics)

Subsequently, after completion of the survey, interviews were conducted and each transcribed interview was entered into Nvivo 12 Pro software (QSR International, www.qsrinternational.com) for storing, and coding of data. Each transcript was read several times, and based on the coding strategy, themes emerged. The themes were formed from combination of perceptions, responses, or experiences related to the questions on the management of MoOSTs from the professional's perspectives based on theoretical constructs including but not limited to these areas from within literature, overview of MoOSTS [6], [10] delays in MoOSTs [149] and knowledge management in MoOSTs [7]. During analysis some themes were submerged with other themes, while some were discarded or reframed as data supporting each decisions emerged. Figure 4.3 is a diagram that depicts the build-up to the development of thematic analysis coding process using the Nvivo (12) software.

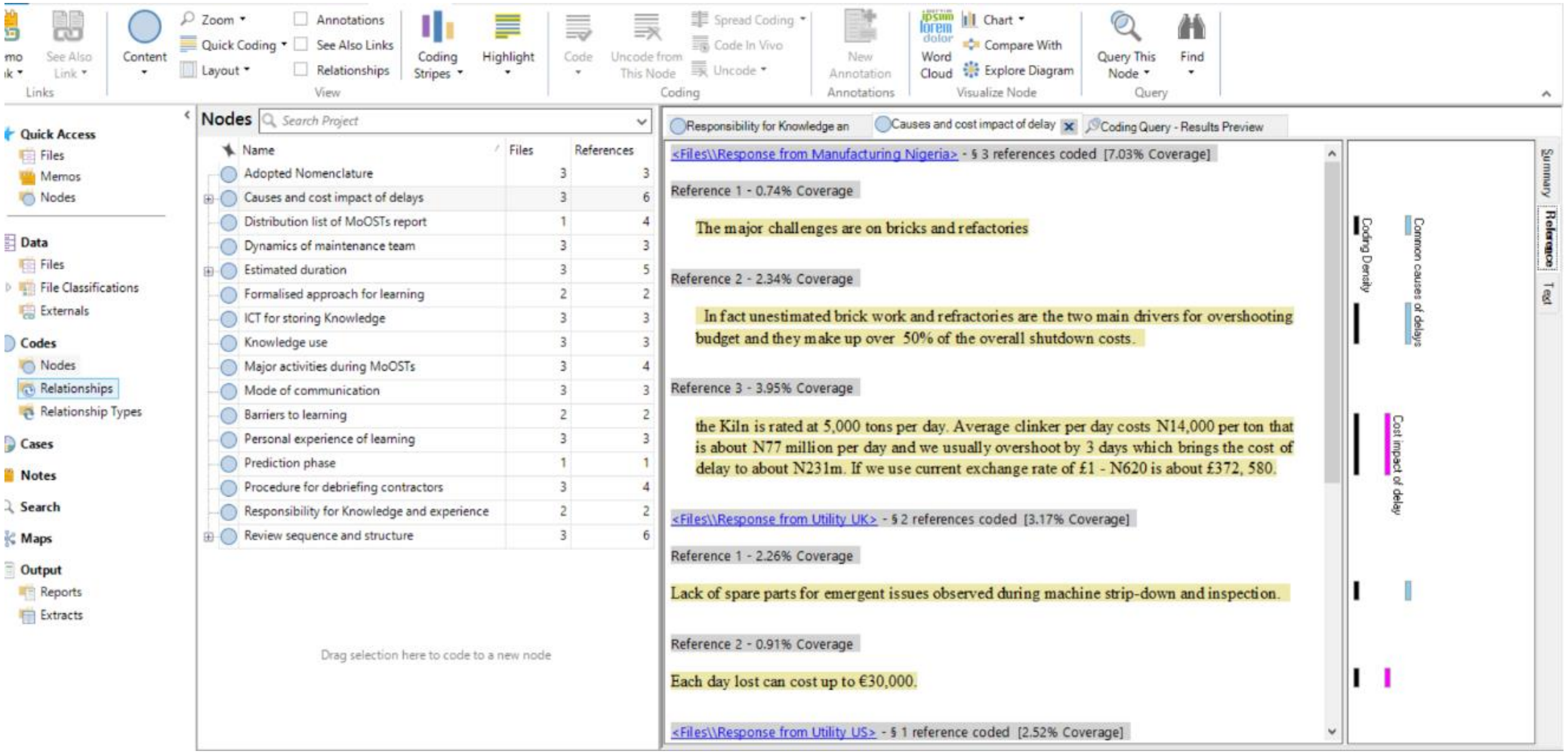



Figure 4. 3 Illustration to the build-up of thematic analysis coding with Nvivo (12) software

## 4.3. Data Analysis

This section highlights the data analysis methods utilized for analyzing data collected from the survey and interviews. The results emanating from both methods are depicted and rationalized.

### 4.3.1. Data analysis of survey response (frequency analysis)—Participant demographics and MoOSTs characteristics

The representation of demographic data collected from the survey, with specific information on participants including, academic levels, job class, industry, location of operations, remaining years until retirement, as well as total number of MoOSTs performed are depicted in Figure 4.4. A frequency analysis method [150], the most widely adopted method to efficiently organize the descriptive data were utilized. In this technique frequency charts were widely used to represent the frequencies of the data.

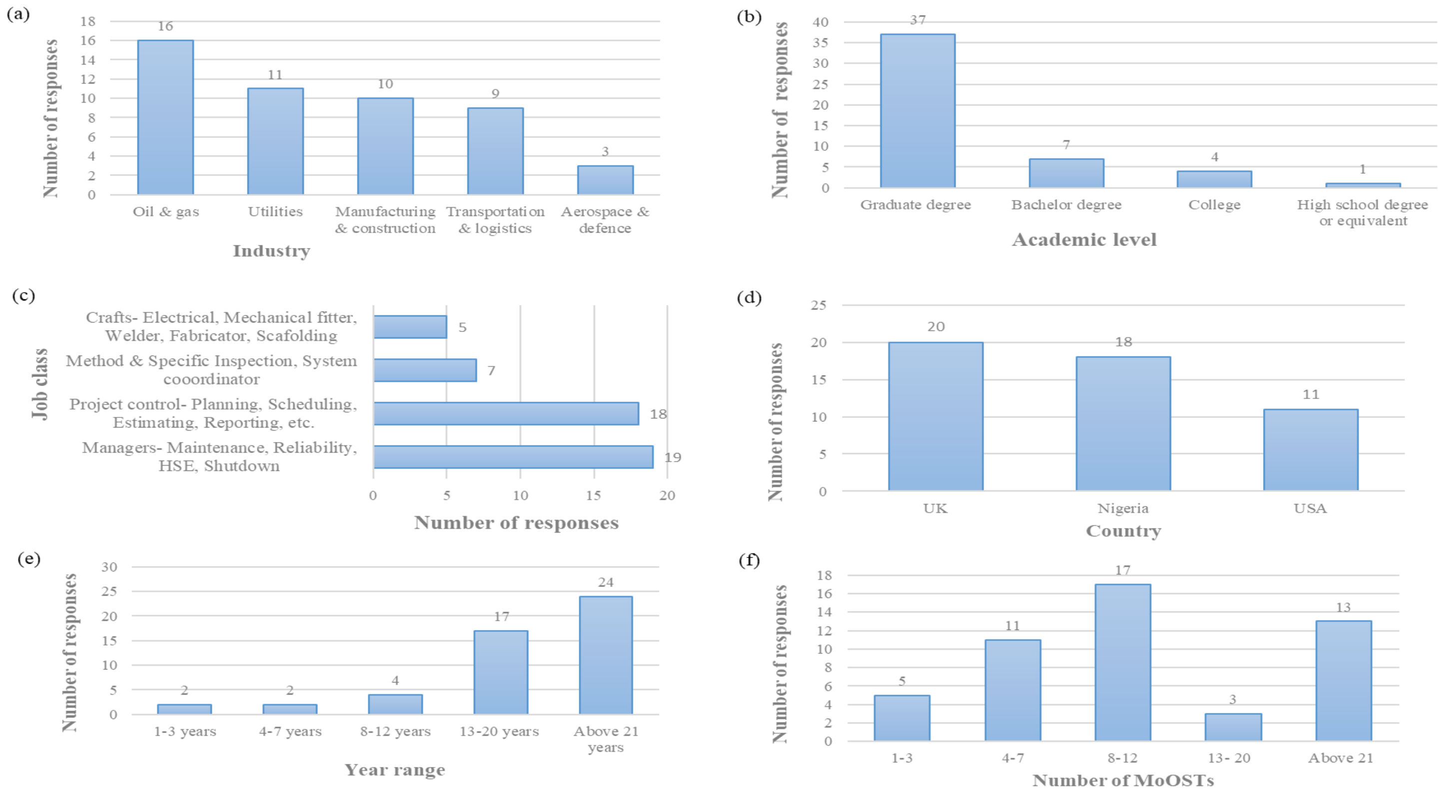



Figure 4. 4 Participants' demographic information

Notes: (**a**) industry of operation; (**b**) academic level; (**c**) job class; (**d**) location; (**e**) number of years left till retirement and (**f**) number of MoOSTs performed.

Participants involved in the study were located in three countries, with the UK having 20 participants, 18 from Nigeria, and 11 from the USA, representing distributions of a fully industrialized country (USA), majorly service oriented (UK) and import based economy (Nigeria). Among the pool of participants, 37 of them, representing (75.5%) of the total number of participants had post-graduate degrees. Another seven (14.3%) had at least bachelor's degree, this showed selection of high academic literacy among participants. Likewise, 19 participants (38.8%) held managerial positions although their background were within core engineering disciplines of mechanical, electrical, civil as well as in environment, health and safety (EHS). In addition, 18 participants (36.7%) held job roles in project controls, a crucial job class in MoOSTs. These selections reflected the desire of the researchers to interview participants with high technical expertise and decision-making capabilities during planning and execution phases of MoOSTs. Participants from oil and gas were 16 in total representing 32.7%, utilities were 11 (22.4%), manufacturing and construction—10 (20.4%) and transport and logistics—9 (18.4%).

The major aim of recruiting participants from these industries being to reflect industries where there are high and medium frequencies for performing MoOSTs. The number of MoOSTs that each participant has been involved in was included in the survey to obtain years of experience, five participants chose the 1–3 years option (lowest number of years) and thirteen participants chose the option for above 21 years (highest number of years).

The frequency for performing MoOSTs across the five industries were highlighted, six participants (12.3%) indicated 0–6 months as the time interval between cycles, 10 participants (20.4%) went with the twice a year option, another 13 (26.5%) indicated frequency of once a year, 10 participants (26.5%) selected the once every 2 to 5 years frequency option and 7 (14.3%) indicated a frequency of once every 5 years and above. The huge capital intensiveness of MoOSTs activities were scoped against the total maintenance budget, 23 (57%) of responses acknowledge that estimated MoOSTs costs could be as high as 11–50% of maintenance budget representing huge capital costs which if managed improperly would significantly impact on the organization's profit and loss statement of account.

The huge number of labour requirement which characterizes MoOSTs was a critical element that needed to be examined. The number of personnel peaks during the execution stage whereby manpower requirement may reach up to 1000 or more depending on plant size, technology and scope of work [92]. Hence, the estimated number of staff involved in MoOSTs within the maintenance organization, which could be a fraction of the entire labour due to outsourced labour in very large and complex cycles was examined. Consequently, the estimate of sub-contracted activities from the total number of maintenance activities during MoOSTs was also examined. The percentage of staff turnover in MoOSTs, which examined probable rates of knowledge loss within the organization was included in the questionnaire. Finally, the main causes of delays during MoOSTs were examined, from the available options each participant could select more than one causes of delay.

The causes of delays and budget overspend were discussed at length in [200], based on the responses, 22 participants selected unplanned work, 32 selected discovery work, 15 went for inaccurate allocation of time and resources within the schedule, 17 chose labour, spares and materials delays, five selected weather or adverse environmental conditions. An extra element of delay has been introduced due to emergence of the COVID-19 pandemic five participants went for this option. Figure 4.5 depicts the specific MoOSTs related information obtained from the survey responses.

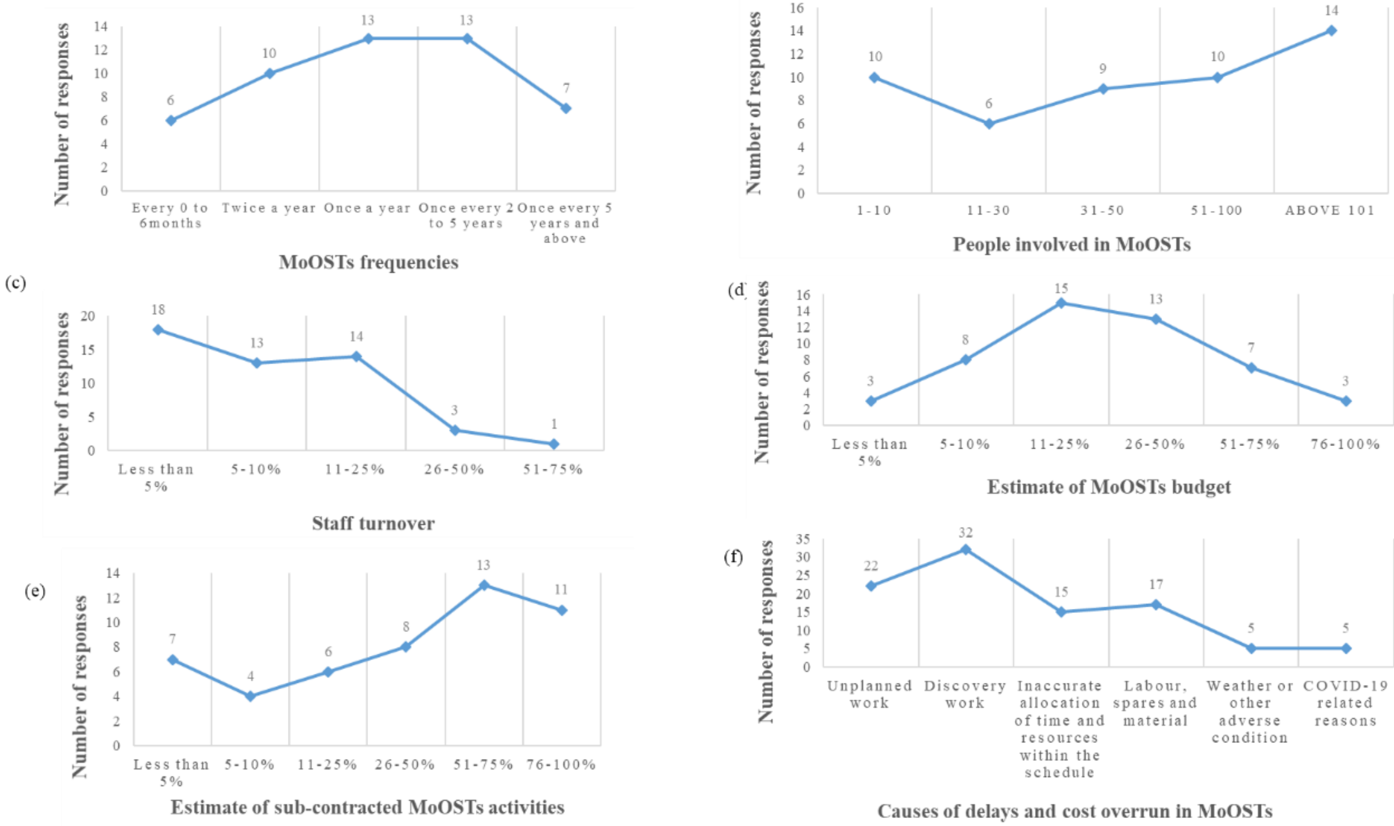
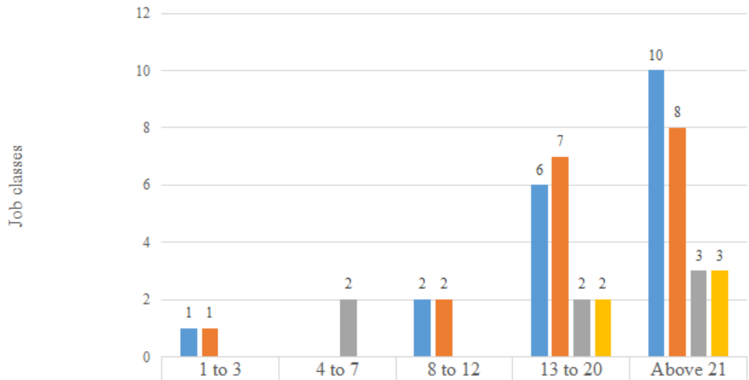



Figure 4. 5 Specific MoOSTs related information obtained from the survey

Notes: (**a**) frequencies for performing MoOSTs; (**b**) people involved in MoOSTs within the maintenance organization; (**c**) turnover of staff involved in MoOSTs; (**d**) estimated cost of MoOSTs as a percentage of the entire maintenance budget; (**e**) estimate of sub-contracted MoOSTs activities in different industries and (**f**) major causes of delays and cost overruns (participants could select more than one reasons).

Literatures in the body of knowledge highlighted loss of expertise due to staff retirement or high staff turnover as major risks facing project environment [172], [201]. Therefore, a crucial information that was obtained from participants was to determine how much time they had before retiring and comparing responses across job class, in order to identify job class that were most at risk from losing expertise in future. Figure 4.6 is the cross analysis of responses received between the number of years left for retirement mapped across relevant job classes.

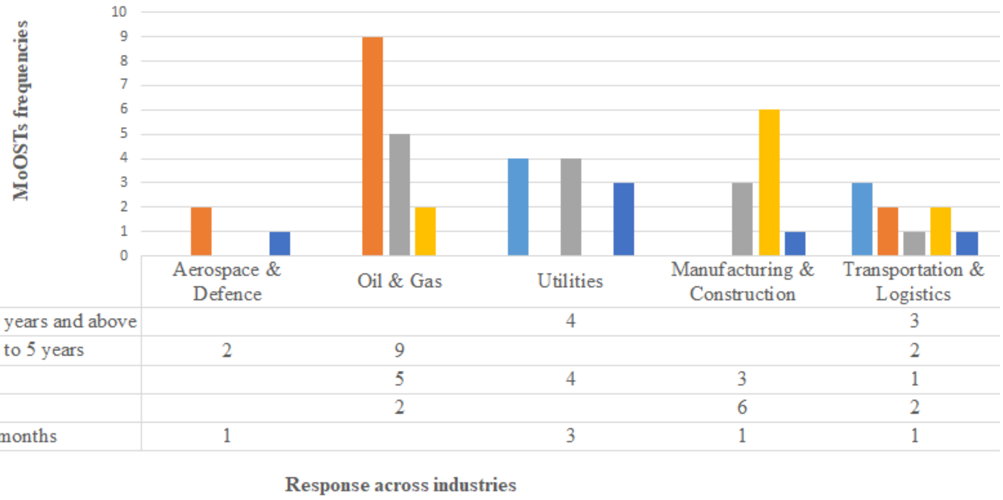



| | 1 to 3 | 4 to 7 | 8 to 12 | 13 to 20 | Above 21 |
|---|---|---|---|---|---|
| Managers-Maintenance, Reliability, HSE, Shutdown | 1 | | 2 | 6 | 10 |
| Project control-Planning, Scheduling, Estimating, Reporting, etc. | 1 | | 2 | 7 | 8 |
| Method & Specific Inspection, System cooordinator | | 2 | | 2 | 3 |
| Crafts- Electrical, Mechanical fitter, Welder, Fabricator, Scafolding | | | | 2 | 3 |

Figure 4. 6 Number of responses based on cross analysis of job class and years before retirement

The responses from participants indicated that although 13 participants (26.5%) had performed above 21 MoOSTs but just two participants (4.1%) had 1–3 years left before retiring. This was despite the pool of highly experienced professionals included in the study. The probable implications might include that, if knowledge management and experience transfer are prioritized in the nearest future, there is still time for experts to contribute to the knowledge pool and for new entrants to adapt.

Further analysis undertaken to determine the link between MoOSTs frequencies across industries, was to determine correlation with literature. The determination of the predetermined time horizon for performing MoOSTs is based mainly on the mean time to fail of the production systems, and this can vary from plant to plant as well as across industries [202]. Figure 4.7 is a cross analysis of responses of participants based on frequency for performing MoOSTs and industry.




| | Aerospace & Defence | Oil & Gas | Utilities | Manufacturing & Construction | Transportation & Logistics |
|---|---|---|---|---|---|
| Once every 5 years and above | | | 4 | | 3 |
| Once every 2 to 5 years | 2 | 9 | | | 2 |
| Once a year | | 5 | 4 | 3 | 1 |
| Twice a year | | 2 | | 6 | 2 |
| Every 0 to 6 months | 1 | | 3 | 1 | 1 |

Figure 4. 7 Number of responses based on cross analysis between frequency and industry

Furthermore, participants were asked to select common documentation and reporting approaches implemented to manage knowledge and document lessons learned during MoOSTs in their respective organizations. Figure 4.8 shows the distribution of these responses.

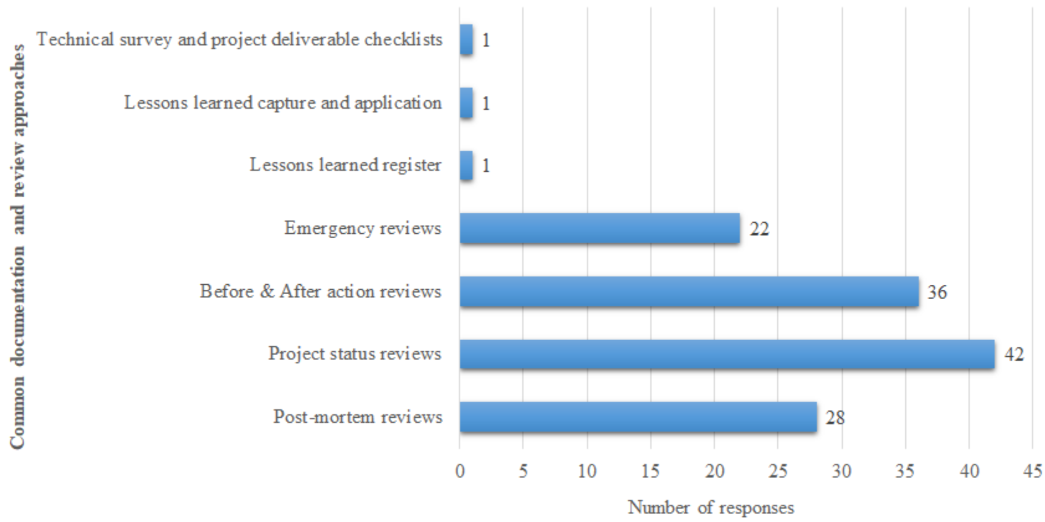


Figure 4. 8 Analysis of responses obtained for common documentation approaches during MoOSTs

Note: participants could select more than one option for this question.

Finally, because decision makers involved in MoOSTs have to balance critical factors including but not limited to, time, cost and quality of work [89]. In the event of delays and reworks which could arise due to many reasons including but not limited to, unplanned work as well as poor quality of works, the probability of cost overruns is increased. Participants were asked to choose estimates based on the percentages of MoOSTs that had exceeded timelines or costs in contrast with estimates for MoOSTs that had been completed ahead of scheduled timelines and below cost. Their responses are displayed in Figure 4.9.

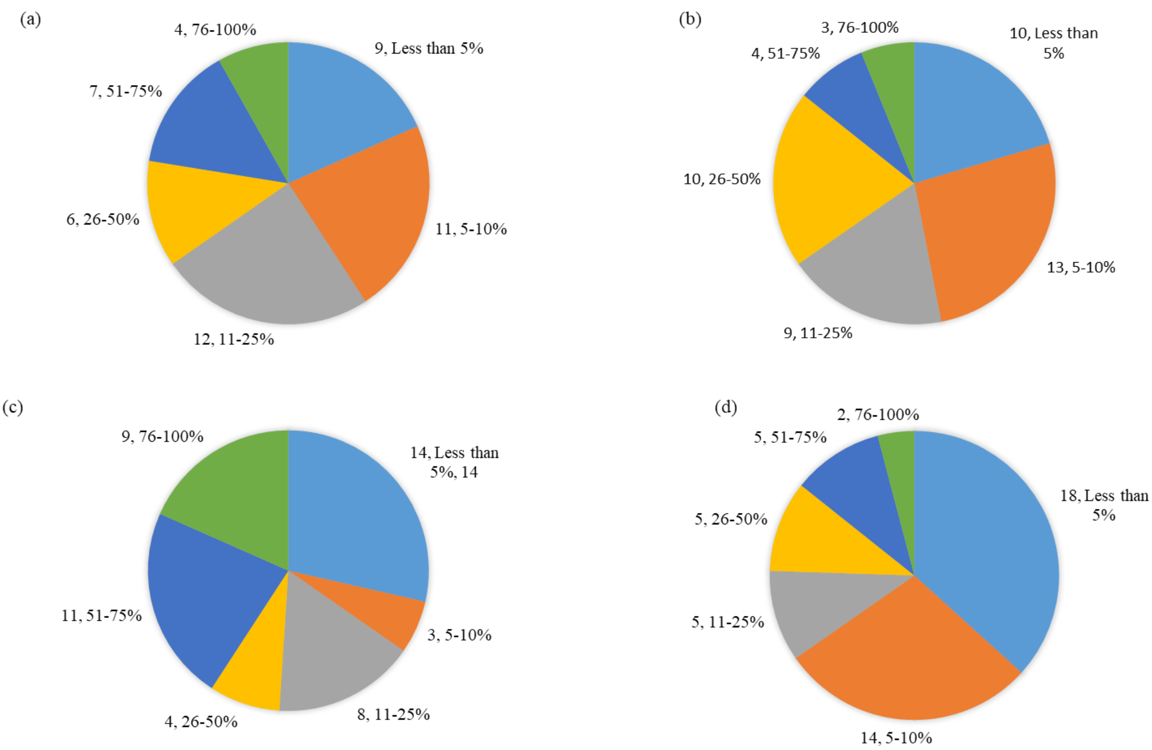



Figure 4. 9 Analysis of responses obtained for estimated timelines and cost during MoOSTs

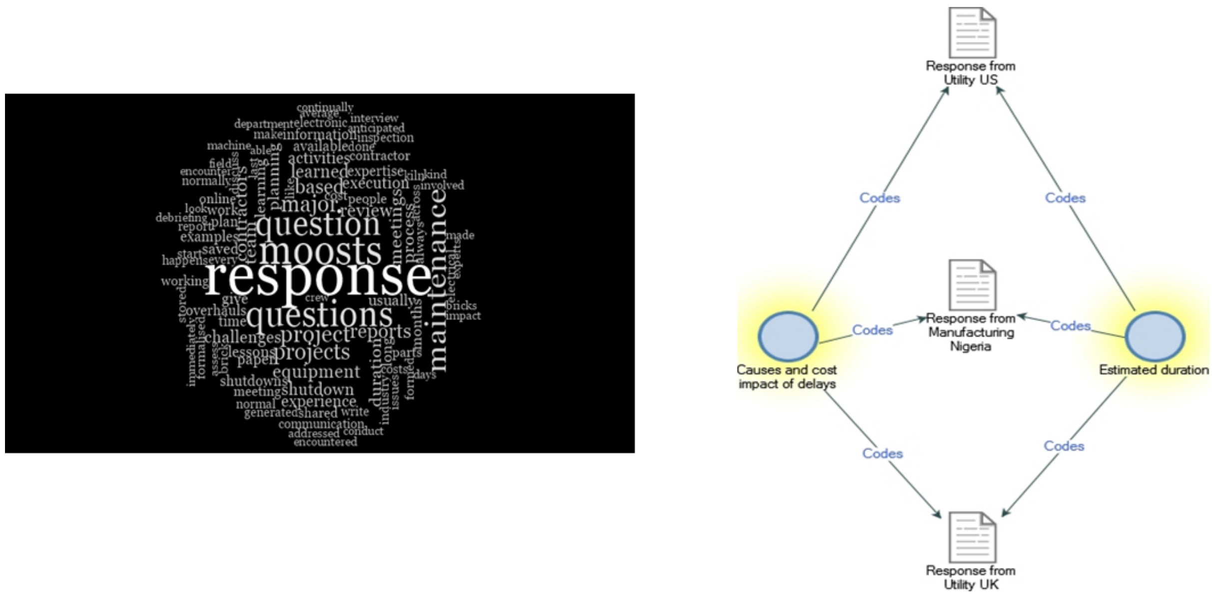
Note: (**a**) Number of responses and percentage of MoOSTs that exceeded estimated timelines; (**b**) number of responses and percentage of MoOSTs that exceeded estimated cost; (**c**) number of responses and percentage of MoOSTs that have been completed ahead of estimated timelines and (**d**) number of responses and percentage of MoOSTs that have been completed below estimated cost.

### 4.3.2. Data analysis of semi-structured interview-Thematic analysis

Thematic analysis (TA) is a method of identifying, analysing and reporting patterns (themes) within data [151]. The popularity of TA is partly due to its ability to explore variety of research questions and topics at a level of depth that quantitative analysis lacks, while offering flexibility in interpretation of data. However, the application of TA, needs to be carefully performed under the watchful eyes of an experienced researcher. In general, analysis of qualitative data could be outlined in five steps; compiling, disassembling, reassembling, interpreting, and concluding, which are described within the thematic analysis process [203].

The first step, compiling the data into a usable form include, transcription of interviews and it is recommended that this exercise is personally performed by the researcher, to engender familiarization with data [198]. In this study, data from the interview sessions was automatically transcribed by the technology utilized for conducting interviews remotely. However, the transcripts, was read and re-read many times to ensure that all responses and intended meanings had been captured accurately. The next step, disassembling of data involved tearing the data apart and creating meaningful groupings. This is often achieved through coding. According to Sutton and Austin [204] coding, is defined as "the process by which raw data are gradually converted into usable data through identification of themes, concepts or ideas that have some connections with each other".

A coding strategy can be established before the coding (priori) begins based on review of literature, or it can be an open or emergent meaning that is created as coding ensues, which develops during the coding process [203]. Another coding strategy is "in-vivo" coding approach that uses phrases from participants' descriptive responses. In this study, a combination of coding strategies was taken into account, definition of codes based on literature were identified and supplemented with emerging codes from the interview data. The third step is reassembling, which requires that codes are mapped against a context to create themes (characteristics). In this context, a theme captures all important aspects about the data with respect to the research question. Examples of output from the qualitative data analysis software "Nvivo" having applied the five steps within TA process is depicted in Figure 4.10 as a word cloud diagram of interview responses alongside a node comparison of responses.




a. Word cloud diagram of interview responses

b. Node comparison of responses

Figure 4. 10 Word cloud diagram of interview responses and node comparison of responses obtained from Nvivo software

A very critical step in TA, is interpreting the reassembled data, and it involves making analytic conclusions based on the data presented as codes and themes. Although it might feel that steps leading up to a TA are listed in liner sequence, but it does not mean that interpreting occurs after the first three steps, rather it is performed concurrently along with other steps within the TA process [205]. The final step is concluding, which involves examining responses to the research questions or study objectives. The interview questions guide for the semi structured MoOSTs practitioners interview can be found in **Appendix**. The summary of the nine themes that emerged from data analysis exercise and selected illustrative data extracts from interviews is discussed as follows:

Theme 1: Nomenclature

This theme describes the adopted nomenclature for comparable large-scale maintenance activities across industries. Based on responses from participants, for maintenance activities commonly referred to as major overhauls in the utility industry, turnarounds in the oil and gas industry and shutdown in cement manufacturing.

*"...in the utility industry (e.g., water distribution/sewer collection and treatment) we conduct maintenance and overhaul on large pumps, motors bar screens, large exhaust fans, tanks, dams, compressors, transmission/distribution pipes and reservoirs".*
Maintenance planner, utility plant, US

*"...in cement manufacturing, we have major maintenance for Kiln shutdown KSD, some call it major overhauls".*
Reliability engineer, manufacturing plant, Nigeria

"*…shutdowns of the bulk work.*"
Shutdown manager, manufacturing plant, UK

Theme 2: Mode of communication
This theme described the prevalent mode of communication across MoOSTs organizations. Due to the emergency of COVID-19, most of the participants interviewed stated that their organizations had fostered the gradual transition from paper-based communication to electronic system to remote working, while introducing social distancing measures where possible.

*"Since COVID its move things forward and move them on dramatically and it's a massive improvement, where we will have a small number of people in a room and then everybody else joining via teams so we can have can have large numbers of people at the meeting and only a small number in a meeting room. We've got better control over our meeting".*
Maintenance manager, manufacturing plant in UK

*"It used to be paper based probably, but now we're pretty much fully electronic".*
Document controller, transport and logistics plant, UK

*"Since obviously COVID-19 happened and we couldn't have lots of people in one room while we used to do this before, now the online shutdown meeting I mean, so now the contractors, usually the supervisor were issued with like an iPad or similar".*
Knowledge expert, manufacturing plant, UK

*"So a lot of it's now electronic…there's very, very little paper because it's not a live document once you print something off, you know there's any changes to it and it can be tracked".*

Overhauls planner, utilities plant, US

Theme 3: Dynamics of maintenance team

The responses from participants were split across industries, for instance, in manufacturing, where there were likely to be backlogs and complexity in maintenance tasks, there was an understanding that relevant expertise might need to be sub-contracted based on maintenance demands. On the other hand, activities performed in utility industry was more predictable and the team was fairly stable.

*"You know, we might go through a period of three or four years of using someone then we've done a lot of that work, and then we've gained this skills ourselves to be able to then supervise it ourselves. Alternatively, we get a different expert in to then help us with the next part, once we gain the skills we can then do the work going forward and it's sort of picks up like that".*

Maintenance supervisor, manufacturing Plant, UK

*"We don't have specific people that do shutdown, we normally categorize the task based on what we can do in house and what we sub contract…"*

Contracts manager, Aerospace, UK

*"The maintenance crew hardly changes. We do have our own internal mechanical, electrical, PDM and instrumentation maintenance crew that conduct maintenance on the assets/equipment".*

Maintenance manager, utilities plant, US

Theme 4: Impact of delays

This theme reflected the financial implications and reputational damage that might occur due to delays in major maintenance activities. This is of importance, due to the plant being offline and additional pressures from production/operation to get the plant back online.

*"…that would be on production called (CPD), cost per day, if we overshoot, just the circumstantial losses for the plant could be in the range of say £100,000".*

Maintenance manager, utilities plant, UK

*"…the Kiln is rated at 5000 tons per day. Average clinker per day costs N14,000 per ton that is about N77 million per day and we usually overshoot by 3 days which brings the cost of delay to about N231m. If we use current exchange rate of £1—N620 it is about £372, 580…"*

Maintenance planner, manufacturing plant, Nigeria

"*Each day lost can cost up to €30,000*"

Maintenance manager, utilities plant, UK

Theme 5: Causes of delay and overspend

A major challenge for maintenance organizations within continuous production industries is an inability to envisage the whole maintenance activities that need to be performed during MoOSTs. Despite advances in condition monitoring and diagnostic tools, it is often difficult to predict the actual state of an equipment. Other common characteristics of this theme identified were lack of spares, large number of people working on site performing complex tasks and more recently COVID-19 restrictions and social distancing requirements.

*"In fact under-estimated brick work on the refractories are the two main drivers for overshooting budget and they make up over 50% of the overall shutdown costs".*

Maintenance supervisor, manufacturing plant in Nigeria

*"Bit of guesswork until we can get in and have a look at the real work to do yeah, yeah, exactly…"*

Reliability engineer, manufacturing plant in UK

*"If it's not supervised correctly and things like quality of work can be affected, it can extend the shutdown if you don't keep on top of that".*

Maintenance planner, water utility plant in the US

*"The main delays can be where we have got too many people working in one area, and obviously this COVID-19 time, it was even more challenging to ensure we can maintain a safe work area. For instance, you could have mechanical team and then the scaffold team and it could be difficult to fit everyone".*

Shutdown inspector, oil and gas, Nigeria

Theme 6: Responsibility for knowledge maintenance and experience management

To develop this theme, several research-based articles [60], [206] and follow up questions were imbibed. In the context of this study knowledge maintenance and experience management process describes capture/collection procedures, which include developing suitable templates for capturing learning events and identifying critical MoOSTs activities. Subsequent activities would entail a filtering process before storage, that is, verification of knowledge and/or learning experience that has been captured, this could be by same person responsible for capture, a superior or across specific teams. There would be deliberations in between regular project meetings during MoOSTs (for live capture) and in debrief session after MoOSTs (after termination) to obtain required information. Classification, storage and publishing rights might be allocated to a team collectively or assigned to an individual.

Responses obtained from the interview, showed that some organizations (Utilities plant in the US, Railway, UK) take a more collective approach towards knowledge maintenance process (capture, filter and storage), whereby anyone could write post-mortem reports upon MoOSTs termination, then filter, verify and store in appropriate knowledge repositories. On the other hand, some of the case study organizations (aerospace in the UK and cement manufacturing plant in Nigeria) assigned responsibilities for these actions, in most cases this could be anyone within these job classes, planners, document controller or even maintenance overhauls manager.

Furthermore, ease of retrieval and adaptation to existing knowledge was examined and responses on how knowledge was accessed or shared obtained. Responses varied across skill levels, while some participants higher up in the hierarchy of skillsets stated that they had access to knowledge platforms (share-point sites, intranet and web-database). On the other hand, participants who were further down the hierarchy of skillsets, for instance crafts/trades, depended on minutes/briefs that were in circulation electronically via emails or paper based.

However, because knowledge captured today could become irrelevant or outdated in future, there needs to be a process for reviewing and updating existing knowledge, it enables deleting and/or updating functions. Responses from industries such as manufacturing as well as oil and gas highlighted that knowledge reuse process occurs during debriefs upon MoOSTs termination when learning experiences are shared, audit reports developed, and performance reviews concluded.

*"Someone will be giving ownership of certain different parts. The person that's either has a vested interest in it or is most suited".*
Reliability engineer, aerospace and defence, UK

*"We do not write reports, however before the project commence, the maintenance planner must create a job plan for the job".*
Method and specific inspection, transport and logistics, UK

*"The true purpose of the debrief exercise is to make sure that when we start the preparation and planning for the next major repair that we can put actions and recommendations in where we can improve and the report will be stored in our local network".*
Maintenance manager, manufacturing plant, Nigeria

*"…The plan is constantly fluid and live. I update the plan two or three times a day and then feedback that information. This could hamper the reuse of previous reports cause things are constantly changing".*
Shutdown planner, manufacturing plant, UK

Theme 7: Personal experience of learning
The main purpose for this theme was to deduce MoOSTs elements that have influenced participants' learning the most. Common modalities associated with this theme were but not limited to, repetitive task linked to most MoOSTs activities, limited reflections after

each cycle to pinpoint highs and lows, familiarization with asset operations were the general perceptions held by interviewees.

*"Yeah, so just from having knowledge of this plant and knowing the whole operation. So it boils down to the fact that you like understand the operations of the plants and you're familiar with the assets and things like that. So it's not just textbook knowledge".*
Inspector, utilities plant, US

*"I learnt from repetitive tasks, from personalized training and the company policy of shuffling me to different projects from my early career".*
Maintenance planner, manufacturing plant, Nigeria
*"I would say it is just from lots of experience and debriefs, as well as understanding the plant and the contractors. Then I would say continuous reflections plays a big part in how successful major repairs are. Team work and collaboration is vital".*
Maintenance manager, manufacturing plant, UK

Theme 8: Lack of formalized approaches for knowledge capture and transfer
This theme is related to identifying formalized means for knowledge capture and transfer. Participants described approaches that were informally practiced such as shadowing, coaching, peer assists, observations and mentoring. The perceived effectiveness of common approaches being practiced in most industries that perform MoOSTs was a feeling of inadequacy. A few responses captured the feelings among practitioners, who felt that a more formal approach of what they were doing now in terms of mentoring, peer assists, shadowing, etc., could be beneficial.

*"There is a lack of formalized training, so for example on the production team, if you start as a new member, the production team just the whole system where you go and do so many months in one area. ...So you're rotated round until you've witnessed all those bits. There doesn't seem to be that in the maintenance out as much".*
Maintenance manager, manufacturing plant, UK

*“…to answer, I think it’ll just be you shadow someone that’s done it before you learn from their experiences and things like that, you know you sort of have to catch up quickly”.*
Reliability engineer, manufacturing, UK

*“…there’s never been any formalized training on it”.*
Inspector, manufacturing plant, Nigeria

*“There’s not a formalized training, probably just time and experience, but also spending time with other people”.*
Document controller, utilities plant, US

*“I would say we have means people can learn from the team but it is not formalized, so it would be much more done through shadowing, mentoring and your peers assisting you”*
Maintenance manager, utilities plant, US

Theme 9: Barriers to learning

Barriers to learning is quite popular in the study of major maintenance activities, to further develop the coding strategy and understand emerging attributes from data, follow up questions based on participants’ responses and sign post from relevant studies [36], [53] were imbibed. A consistent response from participants was that there was not enough time for reflections to engender learning. Some practitioners cited inability to capture knowledge gained from one cycle to another cycle in solving similar problems or applying similar logic to different problems as limitations. A typical follow-up question to obtain the perspective of participants examined if there were peculiarities within their respective organizations that might aggravate the impact of such limited adopting of projects to learning when compared, for instance, with another organization within same industry. When responses were analysed common assertions among some participants was that majority of maintenance activities involved in MoOSTs are routine, they highlighted lack of activities prioritization based on reliability engineering and maintainability objectives as critical factors. Rather, the norm was to assign MoOSTs objectives and criticality in activities critical paths based on project objectives obtained through mathematical analysis, (usually a “forward pass,” “backward pass,” and “float calculation”).

The effect of adopting traditional project-based objectives might limit the examination of critical activities in MoOSTs if the aim is to engender experience-based learning [21]. Furthermore, lack of ownership was identified as a main barrier to learning, because MoOSTs are labour intensive, substantial number of outsourced resources are committed towards each cycle. The perception and agenda of an employee within MoOSTs organizations contrasts with that of an employee within the employment of a contractor. Typical responses of regular employees, would be that they identify areas where they require additional expertise and outsource those activities, leaving little or no room for expertise development within the organization. On the other hand, the responses of employees contracted out to different sites would identify lack of tasks continuity, coherence in organization culture, and motivation as barriers to learning.

*"I would say Time!! It takes time to reflect and look at what you are doing and some people have that ability while others don't also quite often people get caught in the moment and just become like a conveyor belt in the work without giving much thoughts to what they are doing. Cause you never stop, you finish one shut down and go back to start another one. It is almost like a roller coaster of never catching a break".*
Reliability engineer, manufacturing plant, UK

*"Not documenting and sharing the lessons learned is a major problem because there is no time. When a maintenance team moves on, the lessons learned are not transferred to the next generation. In my opinion, a barrier to learning from experience results from maintenance teams with too few members not having the time to document the lessons learned. Organizations need to understand the value of documentation practices and resource them appropriately".*
Document controller, manufacturing plant, UK

*"There is the gap from the individual aspect and organization, if the system is there to encourage but the individual impacts on the overall efficiency and the duration of learning, and it is the major obstacle for passing down key skills learned from major overhauls".*
Maintenance shutdown manager, manufacturing plant, Nigeria

*"It's a tough one, isn't it? I think previously, maybe just before my time or just as after I started do it, almost a hesitancy for people to share knowledge".*
Inspector, utilities plant, UK

### 4.4 Discussion of Findings

In this paper, the challenges of managing MoOSTs-related knowledge have been identified and probed to highlight underlying causes. The identified challenges were mapped to key demographic information of participants such as, qualifications, level of expertise, job class, industry, years of experience, size of organization, staff turnover, and location. This mapping is useful for the development of real-life knowledge management initiatives because it offers insights on where research efforts should be concentrated. For instance, the mapping exercise highlights industries and job classes across the different regions that are at risk of losing expertise, based on factors such as years left to retirement and/or staff turnover rates. This is critical because experienced practitioners contribute immensely to successive MoOSTs cycles to enable achievement of predetermined outcomes, but for some organizations this poses the risk of losing knowledge if they are unable to identify, capture, prioritise, store and reuse knowledge as well as expertise before it becomes unavailable.

The type of expertise within the consciousness of experienced practitioners is determined largely by the type of activity and or responsibility assigned to them. Staff with job autonomy in highly critical industries develop personalized approaches to performing tasks [53]. However, such types of personalized approaches to performing tasks in this instance during MoOSTs might lead to "expertise-silo effects" which inadvertently poses risks to the organization. These risks are further aggravated partly due to several reasons, including when knowledge and expertise are possessed by outsourced human resources (usually due to the large volumes and specialisation of MoOSTs activities). Other cogent reasons might be losses due to staff resignation and/or departure, as well as hesitancy to share knowledge because knowledge is rationalized for power bargains, and those in possession hoard it to retain relevance within organizations [22].

For the first research question, nine themes emerged and six were associated with the challenges of managing knowledge during execution of MoOSTs activities in practice. The results show that these themes; responsibility for knowledge maintenance and experience management, barriers to learning, lack of formalized approaches for knowledge capture and transfer, personal experience of learning, dynamics of maintenance team and modes of communication, have significant impacts on how effectively knowledge is managed during MoOSTs.

For the second research question, it was observed that while most of the identified challenges from the SLR matched the findings from this study, this study further probed underlying causes of these challenges as well as new themes that had emerged. For instance, in terms of these two themes; responsibility for knowledge maintenance and experience management, and the lack of a formalized approach to knowledge management and experience transfer within MoOSTs organizations, the responses obtained highlighted that knowledge currently lies with experienced practitioners that are involved with MoOSTs. Hence, organizations with limited abilities to harness this knowledge are increasingly at risk. Further probe of this phenomenon indicated that most of the professionals interviewed in this study who are highly experienced and equipped with good working knowledge of their respective plant operations (a major pre-requisite to being selected into MoOSTs organizations) was a true reflection of MoOSTs organization in practice.

The high level of expertise might lead to decreased motivation within organizations that have intentions to establish formalized approaches for tacit knowledge capture and learning form experience-based frameworks. This might be because, decision makers are of the assumption that there was limited usefulness in groups of highly experienced professionals who most likely are perceived not to require any formal training to kick start their role. The perception from most professionals interviewed was that compared to how knowledge is captured and learning from experience developed within production/operations, by means of job rotation across different systems and/or areas, in MoOSTs, there are no such formalized approaches. However, experience is gained overtime from familiarization within the plant as well as assessments of lessons learned from failures and/or successes in prior MoOSTs cycles.

Furthermore, due to the limited focus on knowledge management and transfer of expertise, professionals involved with MoOSTs are not adequately trained to imbibe formalized approaches for capturing and transferring their experiences over time. In terms of barriers to learning, participants believed the chaotic environment during MoOSTs restricts sharing. Some professionals described their feelings towards MoOSTs as likened to being a part of a "conveyor system". That is, there is hardly any time for reflections during MoOSTs because you are constantly racing against time to handover to the production and operations team under very strict and sometimes unrealistic timelines as well as cost control measures. Afterwards, the new cycle of pre-planning activities for the next MoOSTs commences, which is more prevalent among industries where MoOSTs frequencies are reasonably higher (e.g., the cement and rail transport industries) [192], [207].

For the third research question, it can be stated that insights provided from this study would provide significant inputs for developing a conceptual proposal for managing MoOSTs. For instance, the barriers to learning and managing knowledge that were identified from both literature and practice, a crucial step would be to prioritise (rank) factors that contribute to the barriers to knowledge management and deploy mitigating actions that would have significant impact scores. Furthermore, it was observed that for most organizations, scant attention is paid to determine which of the MoOSTs activities have the most critical impacts on successful outcomes. Hence, one of the necessary actions when developing a MoOSTs knowledge platform would be to enable the identification of critical MoOSTs activities to maximise knowledge capture from critical MoOSTs activities.

Another, important perspective obtained from this study is the fluidity of MoOSTs plans, which is constantly updated as soon as the plan goes live, sometimes up to two to three times daily, hampering reuse of previous knowledge. In the words of one such participant "the schedule becomes outdated and needs to be updated once we go live and discover some jobs we have to do". Based on this need, any proposal for developing a MoOSTs knowledge platform will need to be agile to manage the demands of the users as well as provide complementary solutions for prognosis and enhanced decision-making during MoOSTs, with intentions of establishing criticality ranking for individual activities as this can provide information leading to continuous improvement and learning from experience.

## 4.5. Chapter Summary and Proposal for a MoOSTs Knowledge Platform (KP)

The observations and underlying causes obtained from this study presents the opportunity to develop a proposal for a knowledge platform that can effectively manage challenges in MoOSTs development. Following analysis of the ample evidence obtained, it is evident that while mechanisms within existing MoOSTs databases and information management systems for identifying lagging indicators (generating audit and/or post-mortem reports, as well as suggestions for measuring and storing such captured information) exist, their ability to support prognosis and sustainable management of tacit knowledge for enhanced decision-making are quite limited.

Therefore, it is necessary to establish the usefulness of large-scale information gathering within MoOSTs and further optimisation by first developing an approach for critically analysing important parameters within MoOSTs activities, based on the identified expert criteria. Upon identification of critical MoOSTs activities, an awareness of the useful expertise that needs to be captured and the sources for capture as well as KT process is will then be initiated.

Secondly, develop a conceptual framework that can be demonstrated with the use of a case study with the aim of building an integrated web-based knowledge platform (KP) for managing both tacit and explicit knowledge during the execution of MoOSTs. The integrated web based KP should be developed with many objectives, mainly to foster the retention of knowledge possessed by experienced professionals, to overcome real-time knowledge capture limiters especially time restriction and chaotic MoOSTs environments. Additionally, the web based KP would enable integration with other IT systems, especially existing enterprise resource planning systems used for managing MoOSTs and maintenance in general. The proposed KP should be simple, flexible, concise, and inexpensive. Consequently, it is imperative to intensify research efforts towards attainment of a MoOSTs knowledge platform (KP) that aim to provide complementary solutions for prognosis and enhanced decision-making from critically MoOSTs activities.

### 4.5.1. Chapter limitations

The scope of this work was limited to include analysis of data based on specific gaps identified from a prior SLR and questions asked in the interviews were directly relevant to the study aim of aligning practice with research. Another SLR might discover additional qualitative findings which will need to be elucidated in future empirical studies with the view of obtaining other practitioners' perspectives. In addition, the qualitative research method is often criticised for not usually being generalizable, because the conditions in which it is conducted can often not be replicated. However, this is not a hindrance or limitation to the research, but it is rather a feature that can be overcome by establishing common values of transparency during data collection, analysis and interpretation of results. It is the opinion of the authors that the research direction, discussions and outcomes from this study are very relevant in examining pertinent issues raised by research and practice in the study of knowledge management and experience transfer in MoOSTs. In addition, although a proposal for a MoOSTs KP has been recommended, the application and validation of such study is beyond the scope of this present study, but the aim is to show the relevance of the findings from this study and the crucial background it provides to achieving this important task. Moreover, this study should be treated as an ongoing work which could be further extended in future as the challenges in MoOSTs are quite dynamic.

# 5 ASSESSMENT OF BARRIERS TO KNOWLEDGE AND EXPERIENCE TRANSFER IN MAJOR MAINTENANCE ACTIVITIES

**Reformatted Version of this paper:**

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|---|---|
| Paper title: | **Assessment of Barriers to Knowledge and Experience Transfer in Major Maintenance Activities** |
| Authors: | **Lilian Iheukwumere-Esotu and Akilu Yunusa-Kaltungo** |
| Published in: | **Energies** |
| Volume: | **13** |
| DOI | **10.3390/en13071721** |


## ABSTRACT

Systematic failure analysis generally enhances the ability of engineering decision-makers to obtain a holistic view of the causal relationships that often exist within the systems they manage. Such analyses are made more difficult by uncertainties and organizational complexities associated with critical and inevitable industrial maintenance activities such as major overhauls, outages, shutdowns, and turnarounds (MoOSTs). This is perhaps due to the ratio of tasks-to-duration typically permitted. While core themes of MoOSTs including planning, contracts, costing, execution, etc., have been the focus of most research activities, it is worth noting that the ability to successfully transfer and retain MoOSTs knowledge is still under-investigated. Effectively implementing a case study-based approach for data collection, the current study explores the harmonisation of various risk assessments (i.e., fault tree analysis and reliability block diagrams) and multi-criteria decision analysis (MCDA) tools to investigate perceived barriers to MoOSTs knowledge management and experience transfer. The case study selected for this study is a dual process line all-integrated cement manufacturing plant (the largest of such process configuration in its region). The justification for this choice of industry was driven by the volume and frequency of MoOSTs executed each year (typically 4–1 per process line), thereby providing a good opportunity to interact with industrial experts with immense experience in the management/execution of MoOSTs within their industry. A multilayered methodology was adopted for information gathering, whereby baseline knowledge from an earlier conducted systematic review of MoOSTs practices/approaches provided fundamental theoretical trends, which was then complemented by field-based data (from face-to-face interviews, focus group sessions, questionnaires, and secondary information from company MoOSTs documentation). During the analysis, fault tree analysis (FTA) and reliability block diagrams (RBDs) were simultaneously used to generate the causal relationships and criticality that exist between identified barriers, while the MCDA (in this case analytical hierarchy process) was used to identify and prioritise barriers to MoOSTs knowledge management and experience transfer, based on sensitivity analysis and consistency of approach. The primary aim of this study is to logically conceptualise core barriers/limiters to knowledge in temporary industrial project environments such as MoOSTs, as well as enhance the ability of decision-makers to prioritise learning efforts. The results obtained from analysis of data identify three major main criteria (barriers) and 23 sub-criteria ranked according to level of importance as indicated from expert opinions.

*Keywords*: industrial maintenance management; failure analysis; knowledge management; multi-criteria decision-making analysis; major overhauls-outages-shutdowns-turnarounds.

## 5.1. Introduction

The dynamic nature of new economies over the past two decades has created competitive environments among companies, compelling consolidation of existing knowledge assets as pathways to creating value [34], [208]. The most pressing needs identified by different studies on how firms can compete effectively is the ability to identify different types of knowledge existing within, utilizing these existing knowledge, and in turn developing them to create new knowledge and capabilities [53]. The need to create and add value has presented new waves of challenges for the maintenance department in continuous production and/or operational industries such as power, manufacturing, process, aerospace, defence, etc. These types of industries heavily depend on a distinct type of large scale maintenance activities performed at an instance known as, major overhauls, outages, shutdowns, and turnarounds (MoOSTs) for smooth running of physical assets [6], [209].

For instance, in oil and gas plants, MoOSTs are the largest maintenance activities in terms of criticality, cost, and time [209]. The significance of MoOSTs expenditures on maintenance organizations budgets' becomes ominous when considered that 80% of such MoOSTs related activities sometimes exceed their costs by approximately 10%–40% [113]. In an attempt to contextualize the criticality of MoOSTs, [13] reckoned that 35%–52% of industrial maintenance budgets are expended on planning and execution of MoOSTs. Similarly, MoOSTs in the energy sector is often tagged the costliest and most tedious industrial activity. This perhaps owing to the fact that virtually all sectors rely on energy to function, hence the need for routine and thorough plant improvement initiatives through extensive MoOSTs. Additionally, recent population growth trends across the globe is creating sharp disparities between energy supply and demand. In addition to capital-intensive capacity expansions, which are quite crucial, another vital means of keeping up with increasing power demand is for existing energy systems worldwide to constantly operate around their installed capacities. Based on this premise, critical maintenance interventions such as MoOSTs will need to be executed under even more stringent time and cost constraints in the immediate future, thereby making it imperative to harness all knowledge and experience to aid success.

Although there are studies within the current body of knowledge that capture knowledge management barriers in project management, the peculiarities and specific requirements of MoOSTs listed in [9], [11], dictates a need to present an approach for assessing barriers to knowledge management with emphasis on acquisition and transfer of staff experiences (tacit knowledge) specifically developed for managing MoOSTs. Consequently, there are evidences supporting arguments that favour unique approaches to sharing knowledge and experience transfer within projects, which depend heavily on social practices and patterns in organizations [52]. This is because, based on what has been learnt from different studies on managing tacit knowledge, particularly on areas concerned with surmounting the challenges of developing frameworks that can aid expression and sharing of subjective experiences, insights and intuitions of individuals, as well as groups in organizations [210].

Furthermore, existing project management based studies, [53]–[55] have focused on identifying and reviewing potential knowledge sharing barriers within organizations and project environments, which although useful in order to provide a comprehensive and structured starting point for effective audit systems, do not present a holistic approach for knowledge management and experience transfer in MoOSTs.

However, there are few studies that have recognised the need for an enhanced knowledge management system within MoOSTs supply chains [25]. The focus of most of these studies being on lagging indicators, which are mostly for the purpose of information management but as useful as these lagging indicators are in their ability to measure predetermined outputs, their ability to support prognosis and sustainable experience management are quite limited. Moreover, while reviewing the literature on methodologies adopted to address challenges of knowledge management and experience transfer in MoOSTs environments, it was observed that the use of hybrid engineering failure analysis approaches such as, fault tree analysis (FTA), reliability block diagrams (RBDs) alongside multi-criteria decision analysis (MCDA) techniques (e.g., analytical hierarchy process (AHP)) is scant. Although few references in literature exist of studies that have implemented MCDA techniques to evaluate critical qualitative and quantitative factors in MoOSTs. Take for instance, [56] examined process quality, quality of machinery, quality of project team, and output quality and [33], conducted a research on preselecting contractors based on safety criteria for MoOSTs using AHP. Perhaps [20] is one study which has highlighted possible areas in the entire MoOSTs supply chain that can benefit from learning and improvement through collective rankings and prioritisations of stakeholders requirements using the quality function deployment (QFD) tool which can be integrated into AHP. However, these articles barely identified specific barriers facing MoOSTs knowledge management and experience transfer but focused on activities that encourage information management rather than deep learning acquired through experience which is basis for this study.

Therefore, in light of these gaps in the body of knowledge, the identification and ranking of barriers to knowledge management and experience transfer in MoOSTs is pertinent, and it has also become necessary to demonstrate the effectiveness of utilising engineering failure analysis approaches alongside MCDA techniques for addressing this challenge in the context of MoOSTs. This study will follow an approach of exploring several questions which are addressed to experts through a field study:

1. What are the barriers to knowledge management and experience transfer in MoOSTs?
2. Do the identified barriers contribute equally to failure of the entire knowledge management system or could their casual effects be prioritised based on significance of impact?
3. Are these barriers specific to MoOSTs or do they equally affect other engineering projects?

The main objectives are, to identify, as well as, rank barriers to knowledge management and experience transfer based on perceptions of experts who have significant involvements in MoOSTs. The aim is to establish a road map for further work on this subject that can potentially lead to selection of appropriate solutions (alternatives) that would spur developments of knowledge management and experience transfer frameworks. This is particularly useful because, harnessing knowledge and experience domiciled within individuals in MoOSTs organizations is an important asset that can enhance the ability of a company to sustainably attain its underlying strategic business goals. Therefore, integration and application of methods such as, FTA, RBD, and AHP are demonstrated through a case study approach to assess the barriers of knowledge management and experience transfer in MoOSTs.

## 5.2. Materials and Methods

Relevant studies [211], [212] have argued that organizations can most likely learn more from failure than from success, which is perhaps due to success leaving an impression of great achievements which do not result in deep learning. Failure on the other hand produces a despondent reaction within the organization, but if properly managed, might lead to identification of probable root causes which could in turn lead to accountability.

The use of engineering failure analysis approaches to investigate probable/possible root causes of failures are quite common in literature, most notably the use of popular techniques such as fault tree analysis (FTA) and reliability block diagrams (RBDs) to model failures. A study by [58] employed these techniques (i.e., FTA and RBD) to detect the causal factors, as well as their interrelations for a chronic cement plant rotary kiln refractory brick failure, so as to provide detailed dimension of vulnerabilities in maintenance, operations, and quality practices.

While [213] and [192] also used both FTA and RBD techniques for analysing historic engineering catastrophes such as Fukushima nuclear disaster (2011), BP Texas city incident (2005), NASA's space shuttle Columbia accident (2003), Chernobyl disaster (1986), Bhopal disaster (1984), and sinking of the Titanic Ocean liner (1912). Furthermore, the integration of multi-criteria decision-making (MCDM) methods such as analytical hierarchy process (AHP) with other risk assessment techniques such as FTA and RBD to provide a hybrid solution model is also very popular in literature. According to [214], the use of a single technique has limited capacity to represent complex realities. This is in contrast with the use of MCDAs that can facilitate development of hierarchy of problems, selection of alternatives, and allocation of values, as well as preferences elicited from participants in a group [215], [216].

Demonstration of the merits of hybrid models for failure investigation within the aviation industry was also studied, using accident reports obtained from the Directorate of Accident Investigation [217]. The study [217] adequately exposed frailties within existing frameworks, particularly the decision-making facets and was adjudged to significantly contribute to recent catastrophes.

### 5.2.1. Overview of the fault tree analysis technique

FTA is a top down deductive method that translates physical systems into logical diagrams, showing how equipment failure, human error, and/or external factors can influence an event [218]. Since it was first used in the aerospace industry, it has become an increasingly popular method for people involved in reliability and safety calculations and has extended to industries such as nuclear, power, and chemical processing [219], [220]. The construction of a fault tree (FT) involves the systematic breakdown of the factors leading to an undesirable event within a system into source events, through the application of gate symbols to structure cause and effect relationships of failures [221].

The top events in the FTA are usually indications of failures of major consequences, which could endanger human lives or lead to significant economic losses. The bottom or basic events are used to determine the root causes. FTs are capable of yielding quantitative and qualitative information about a system, and are particularly useful for providing better understanding of potential causes of failures that can lead to a rethink of approaches to eliminate or reduce potential hazards within the system. However, a major limitation of this technique is that its success could be influenced by the investigation team's familiarity with the topic, thereby embedding some elements of human subjectivity [213]. Typical gate symbols used in FTA and their meanings are given in Table 5.1.

Table 5. 1 Common fault tree analysis (FTA) gate symbols and their descriptions [218]

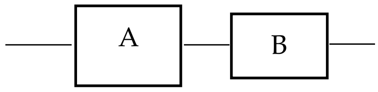
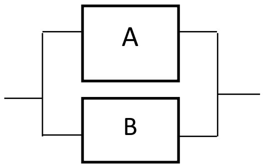
| **Fault Tree Symbol** | **Meaning** | **Description** |
|---|---|---|
|  | AND (Parallel) | Requires the occurrence of all input events for a resulting output event. |
|  | OR (Series) | Requires occurrence of any single event for a resulting output event. |
|  | Intermediate event | Resulting event of different interacting events. |
|  | Basic event | The least event that cannot be further defined. |

## 5.2.2. Overview of reliability block diagram technique

RBD is a method based on representing a system by interconnected blocks (i.e., series, parallel or combinations). The connections between individual blocks signifies the influence on the reliability of an entire system [222]. In systems' reliability analysis, a system is depicted as being in series, if it fails when one or more components fail. On the other hand, a system is depicted as parallel if only simultaneous failure of multiple components leads to system failure. RBDs are particularly concerned with different combinations of components within the system that will lead to system functionality, which is its main distinction with the FTA that solely focuses on system failure combinations [223], [224]. The overarching purpose of developing equivalent RBDs is an attempt to visualise relationships of causal factors that can lead to identification of vulnerabilities and/or resilience within a system.

Despite its usefulness, RBDs have been criticised for their overreliance on near perfect (which is often unrealistic in all circumstances, especially when dealing with unfamiliar problems) FT outputs in order to generate accurate results [192]. Detailed and clear guidelines for constructing RBDs, as well as their conversion to FTs and vice versa are available in [213], while [58] further demonstrates real-life implementations. Typical RBD symbols and their associated interpretations are provided in Table 5.2.

Table 5. 2 Typical reliability block diagram (RBD) symbols and their descriptions

| RBD Symbol | Meaning | Description |
|---|---|---|
|  | Series connection | Failure occurs when any one component fails. |
|  | Parallel connection | Failure occurs when multiple components fail simultaneously. |

## 5.2.3. Overview of analytical hierarchical process (AHP) as a multi-criteria decision analysis (MCDA) tool

Recent decades have experienced widespread applications of AHP [224] for analysing complex and dynamic problems involving multiple criteria (also denoted as multi-criteria decision analysis). Studies such as [215], [225], [226] have adequately explored the proficiency of AHP within a wide range of disciplines. In order to make a decision in an organised manner, [227] suggested the adoption of the following three principles: Decomposition, comparative judgement, and synthesis of priorities. The decomposition of the decision element, as well as its associated steps was also described in [227]. Subsequently, [228] recommended the application of a specific scale to support comparative judgements, which was also trialled and compared to other existing scales. Judgements are typically elicited qualitatively from people within a group/panel and then assigned appropriate values from the specified scale. The perceived weakness of AHP is often attributed to its reliance on the precision of the questions directed to selected decision-makers, thereby creating doubts about the consistency of results under different sets of questions, even if the investigated topic remains the same [226].

However, these criticisms have been adequately addressed by [228] whereby the ability of AHP to provide a flexible, systematic, and repeatable evaluation process that can be used for selecting optimal alternatives amidst multiple criteria has been shown [225].

During comparative judgements (also known as pairwise comparisons), a judgement matrix [229] is governed by Equation (5.1):

$$A_n = \begin{bmatrix} .. & C_1 & C_2 & .. & C_n \\ C_1 & a(1,1) & a(1,2) & .. & a(1,n) \\ C_2 & a(2,1) & a(2,2) & .. & a(2,n) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & a(n,1) & a(n,2) & .. & a(n.n) \end{bmatrix} \tag{5.1}$$

To improve consistency of judgements, reciprocals are automatically assigned to each pairwise comparison and [226] provides a clear demonstration of this approach. Upon completion of the pairwise comparison, consistency is determined by eigenvalue max λmax, whereby the consistency index (CI) is given as (λmax − n)/ (n − 1), where n is the matrix size. The test for reliability of consistency for a given reciprocal matrix is termed consistency ratio (CR) and obtained by estimating the ratio of CI to the average random consistency index (RI) given in Table 5.3. According to [229], [230], a CR lower than 10% (0.1) is classified as sufficiently consistent.

Table 5. 3 Average random consistency (RI) [229], [231].

| **Size of Matrix** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Random Consistency** | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

Table 5.4 shows the fundamental scale of absolute numbers. The final process of AHP involves synthesis and ranking of priorities which was manually demonstrated in this study and outcomes were compared to those obtained via transparent choice (an AHP software). The results from both estimations had very little variance.

Table 5. 4 Fundamental scale of absolute numbers [227]–[229].

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two activities contribute equally to the objective |
| 2 | Weak or slight | - |
| 3 | Moderate importance | Experience and judgement slightly favours one activity over another |
| 4 | Moderate plus | - |
| 5 | Strong importance | Experience and judgement strongly favours one activity over another |
| 6 | Strong plus | - |
| 7 | Very strong | An activity is favoured very strongly over another: Its dominance demonstrated in practice |
| 8 | Very, very strong | - |
| 9 | Extreme importance | The evidence favouring one activity over another is of the highest possible order of affirmation |

### 5.2.4. Group decision-making

The application of group decision-making in AHP is an integral technique for eliciting responses which are used to generate pairwise comparisons. Participants in a group make use of their experiences, as well as values on knowledge of a particular discipline to break down specific problems into a hierarchy which are then solved by step-by-step application of the AHP process [226]. Although the Delphi technique is a popular method for achieving group decision-making as it is designed as a structured group communication process that allow individuals within a group to deal with complex problems [216], but problems of dominance still persists [225]. Group sessions that consist of experts with similar goals require adequate thoughts that can be modified to suit understanding of the problem. Recommendations on expert categorisation for building representative panels in [216] and suggestions on participants selection based on modelling of a typical Delphi survey panel [232] were integrated. Furthermore, suggestions on group size (typically 9–18 participants) in order to alleviate difficulties associated with reaching consensus among experts [225] was also adopted. Hence, the group size "n" applied here was restricted to 10 participants.

### 5.2.5. Research methodology

In order to assess perceived barriers to knowledge and experience transfer in MoOSTs management, a proposal to carry out the following methodology was conceived:

- Theoretical based perspectives emerged through a previously conducted systematic literature review, to provide a broad state-of-the-art review in this discipline.
- A practice-based study was implemented to obtain responses of participants through the combination of semi-structured interviews and focus group session to employees of the case study. These covered important facets of MoOSTs (mostly extracted from the theoretical framework and internal secondary documentations domiciled at the case study).
- The group decision-making process involved identifying and selecting top level, mid-level, and lower level criteria based on values and preferences of group decision makers. Subsequently, three main top-level barriers and 23 individual basic elements were modelled using FTA. The process mimicked a modified Delphi process which involved brainstorming, streamlining, and ranking [233], but without the commonly encountered problems of group dominance, rather, hierarchy of problems and criticalities generated from FTs and RBDs were used to elicit responses (which aided the selection of values and preferences based on the linguistic AHP scale). The group was shown the problem at hand based on the initially prepared FTs. Group members were then requested to develop the hierarchy of problem, and responses involving allocation of linguistic AHP values Table 5.4. Subsequently, preferences were then ranked from highest to lowest. The consensus judgements established after choosing ‘average’ of the judgement were computed manually and through ‘Transparent Choice’. In a few instances, voting technique was adopted if the average was significantly skewed.

Table 5.5 shows the categorisation of expert skills and specific knowledge areas of participants in this specific MoOSTs case and integration of inputs from each research approach, while the entire research methodology is depicted in Figure 5.1. While Appendix D (Table A 10) provides further details of the sample sizes within each category.

Table 5. 5 Group decision panel

| Category | MoOSTs Responsibility |
|---|---|
| A | Middle to senior management staff directly involved with MoOSTs, who makes/approves decisions on overall strategies. |
| B | Supervisory staff involved with the implementation of engineering methods and/or techniques, who also has authority to make decisions during MoOSTs. |
| C | Shop floor staff experienced with handling plant assets and schematics showing working of the plant. |

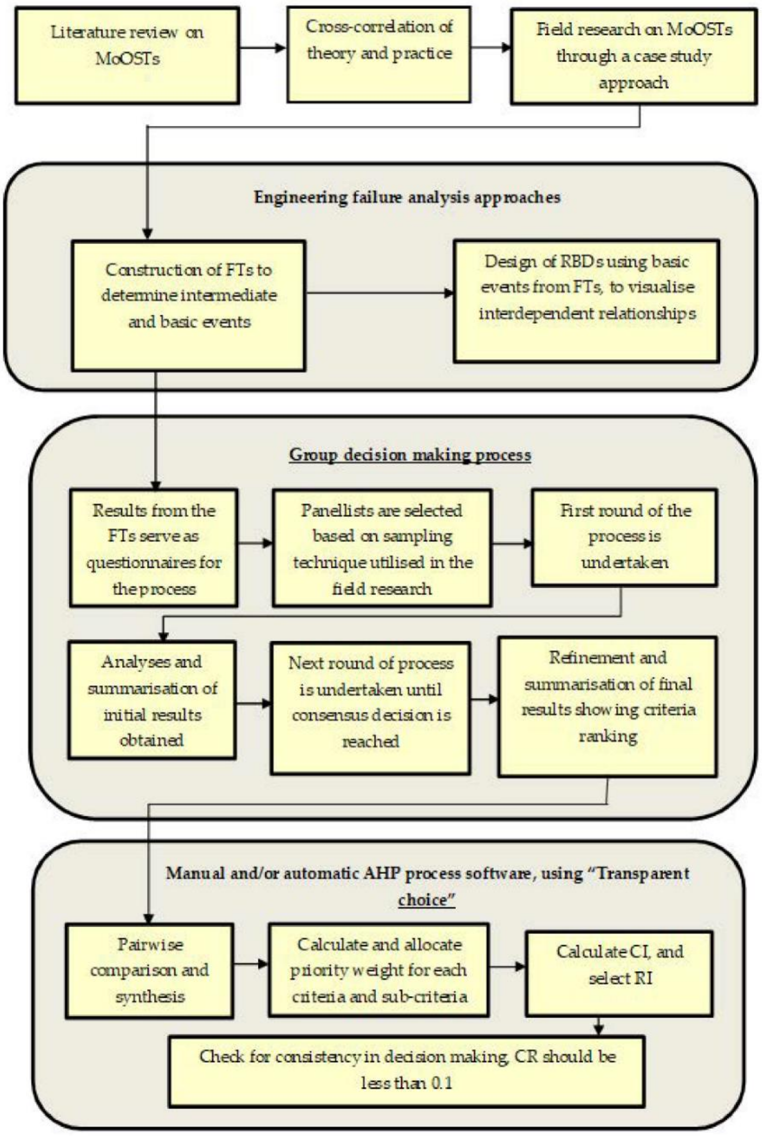



Figure 5. 1 Schematic diagram showing integration of the entire research methodology

### 5.2.6 Case study description

The case study is a cement manufacturing plant in the UK which has been tagged 'ABC' company to maintain anonymity and confidentiality. Participants were company employees, and selection criteria required their involvement in an average of 15 MoOSTs. The company operations involve a 24 h, seven days a week continuous flow processing system and transports an average of 1.45 m ton per year, with 1 m transported by rail and 450,000 by truck. Scheduled plant shutdowns for maintenance in the organization are also referred to as major overhauls. Two of such major repairs per rotary kiln production line are scheduled annually (i.e., minimum of four rotary kiln shutdowns a year since there are two rotary kilns production lines). Cement mills and raw mills shutdowns, on the other hand, are scheduled biannually. Prefabrication and preparation of long lead time items (e.g., refractory bricks, burner, and preheater castables, etc.) could take up to 18 months, and three months is dedicated for planning. A minimum of six months interval between each subsequent shutdown occurs. Execution of main activities occurs within 26–32 days for major repairs on the kiln (e.g., replacement of shell sections, kiln alignments, etc.) and 10–14 days for major repairs on the cement and raw mills. A manpower requirement typically peaks at 200–300 people, thereby amassing over 140,000 man-hours for the shutdown duration.

The justification for the selection of the cement industry as a case study was based on the premise that typical cement plants are very capital and labour intensive. Additionally, the cement industry has a very high frequency of shutdowns (at least four per year), thereby offering immense shutdown management knowledge base, especially because such shutdowns are usually executed within very short periods, making experience management very crucial.

## 5.3. Results

### 5.3.1. Application of fault tree analysis (FTA) and reliability block diagram (RBD) for assessment of barriers to knowledge management and experience transfer

According to [58], the success of FTAs is usually a function of the level of familiarity with the topic possessed by the investigation team and good practice requires integration of a brainstorming elements to its design. Apart from knowledge gained in this discipline, enhanced through review of relevant literatures, as well as data analysis obtained from the initiated semi-structured interviews, group decision-making was also an integral element to the entire process and was determined by setting up focus group sessions that comprised of experts from the organization. The strict selection criteria for participant's required significant involvement in prior MoOSTs so as to ensure familiarity with identifying the main classes of probable causes that could act as barriers to MoOSTs knowledge and experience transfer, necessary for development of relevant FTAs, as well as RBDs design.

### 5.3.2. Global FTA for assessment of barriers to knowledge management and experience transfer in MoOSTs

The application of FTA demonstrated in this study identified the top event as 'perceived barriers to knowledge management and experience transfer in MoOSTs management.' The contributions used in designing the FTA were based on theoretical findings, analysis of responses from semi structured interviews, and harmonisation of focus group decisions obtained from the case study (a cement manufacturing company) with appreciable frequency of performing MoOSTs. The three main classes of probable causes that could act as barriers to MoOSTs knowledge management and experience transfer are: Individual barriers (I), organizational barriers (O), and technological barriers (T). Figure 5.2 shows the global FTA for the three main classes of probable causes.

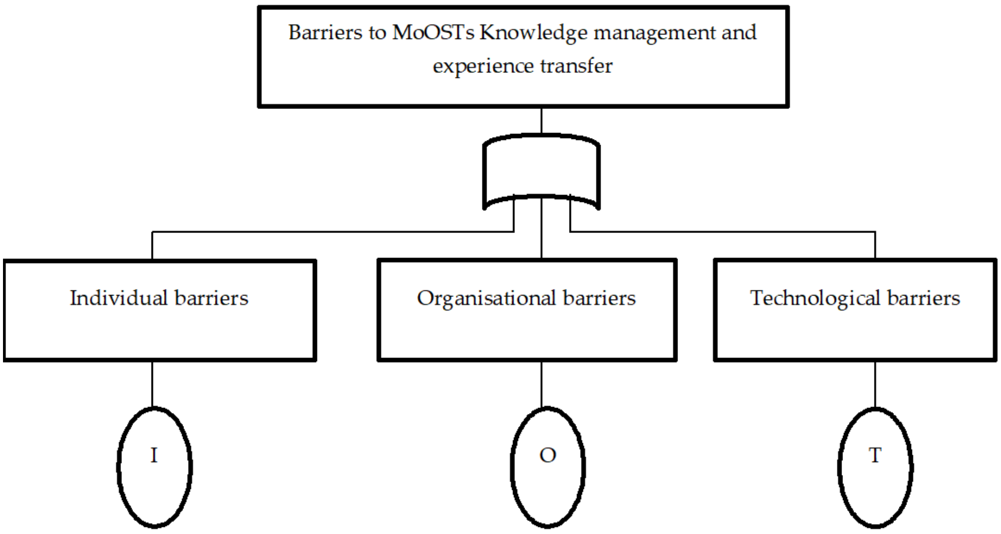



Figure 5. 2 Global fault tree analysis for main classes of probable causes

### 5.3.3. Independent FTA for probable causes due to individual barriers

Each of the main classes of identified probable causes making up the global FTA was developed independently, starting with the individual barriers. Detailed analysis in Figure 5.3 showed that two intermediate events and nine basic events contributed to the perceived barriers to knowledge management and experience transfer. Table 5.6 provides the assigned codes and description for each basic event.

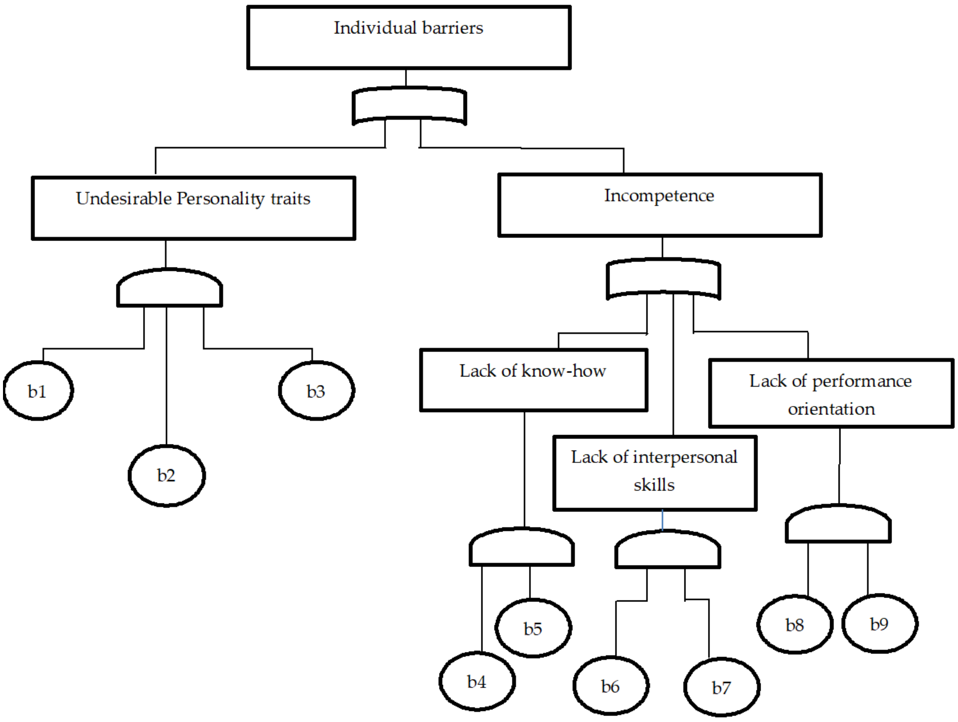



Figure 5. 3 Independent fault tree analysis for probable cause due to individual barriers (I)

Table 5. 6 Assigned codes and descriptions of individual barrier's basic events

| **Assigned Code** | **Description** |
|---|---|
| b1 | Low conscientiousness |
| b2 | Low agreeableness |
| b3 | Low openness |
| b4 | Lack of practical/technical skills |
| b5 | No awareness of strategic business orientation |
| b6 | Lack of communication skills |
| b7 | Lack of psychometric skills |
| b8 | Nonconformance to practical standards |
| b9 | Nonconformance to legal requirements |

### 5.3.4. Independent FTA for probable causes due to organizational barriers

Similarly, the FTA depicting probable causes due to organizational barriers was constructed as shown in Figure 5.4, which indicated that two intermediate events and eight basic events contributed to the perceived barriers to knowledge management and experience transfer. Table 5.7 provides the assigned codes and description for individual basic event.

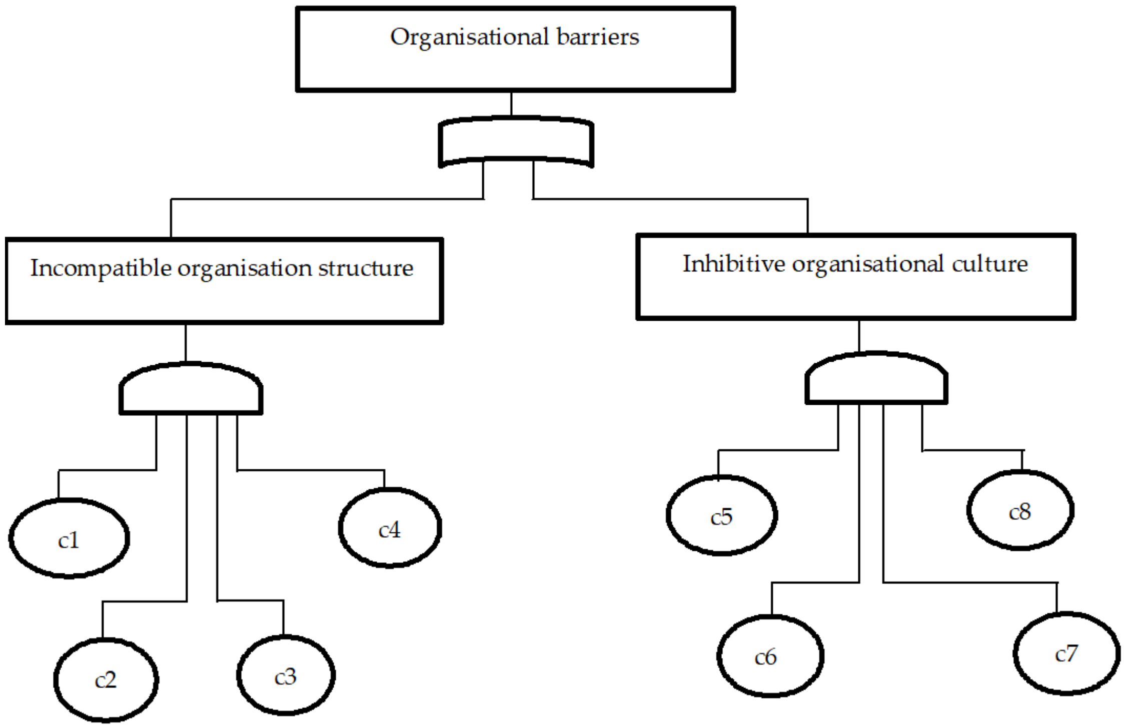



Figure 5. 4 Independent fault tree analysis for probable causes due to organizational barriers (O)

Table 5. 7 Assigned codes and descriptions for basic events under organizational barriers

| **Assigned Code** | **Description** |
|---|---|
| c1 | Limited participation in decision making |
| c2 | Chaotic environment during MoOSTs restricts sharing |
| c3 | Limited job autonomy |
| c4 | Restricted information flow |
| c5 | Lack of leadership direction in championing values encouraging sharing |
| c6 | Lack of a reward system |
| c7 | Individualism is unduly encouraged |
| c8 | Knowledge retention of experienced staff is not prioritised |

### 5.3.5. Independent FTA for probable causes due to technological barriers

The final independent FTA concerned the generation of the causal relationships between the basic events leading to technological barriers as depicted by Figure 5.5. In this case, two intermediate events and six basic events were adjudged to be most influential barriers to knowledge management and experience transfer. Table 5.8 provides the assigned codes and descriptions for individual basic event.

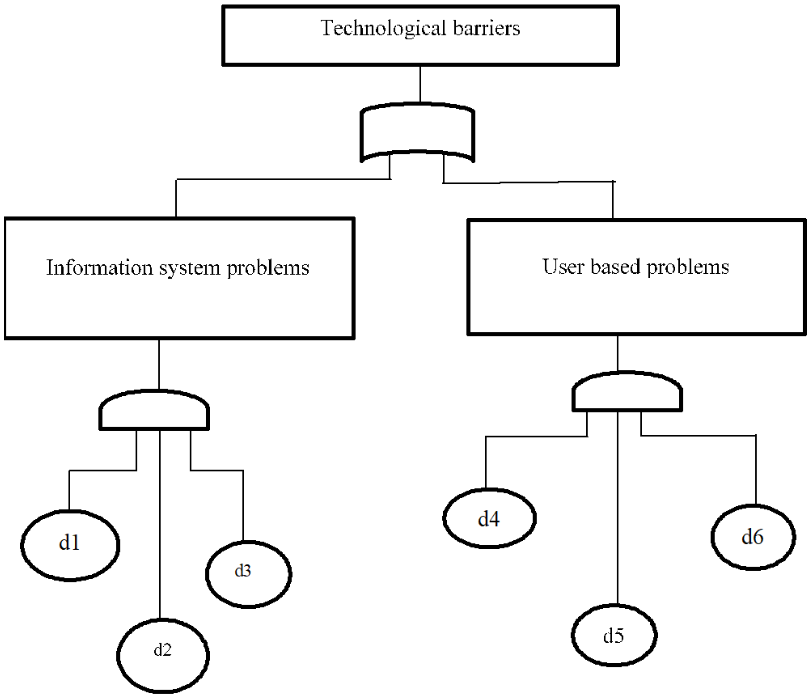



Figure 5. 5 Independent fault tree analysis for probable causes leading to technological barriers (T)

Table 5. 8 Assigned codes and descriptions for basic events that lead to technological barriers

| Assigned Code | Description |
|---|---|
| d1 | Inability to integrate with other processes |
| d2 | Lack of compatibility between diverse IT systems and processes |
| d3 | Lack of technical support |
| d4 | Lack of employees interest |
| d5 | Lack of adequate training and development |
| d6 | Unrealistic expectations of capabilities of IT systems by users |

### 5.3.6. Equivalent reliability block diagrams (RBDs)

For each of the independent FTAs [213] shown in Figure 5.3, Figure 5.4 and Figure 5.5, equivalent RBDs were constructed to aid visualisation. These are displayed in Figure 5.6, Figure 5.7 and Figure 5.8. The usefulness of RBDs is its ability to visualise the interface of failure causes through series and parallel connections. Having developed individual equivalent RBDs (Figure 5.6, Figure 5.7 and Figure 5.8), the global RBD in Figure 5.9 then integrates all equivalent RBDs so as to provide a holistic approach to visualisation. The main benefit of the application of RBDs in this case is dual.

Firstly, it allows for easy identification of points of resilience and vulnerability as such observations may prove difficult from the FTAs alone (especially when dealing with highly dynamic problems that involve human interactions). Secondly, it can also serve as a quantitative tool if historical failure probabilities are available. In this case, decision-makers can easily estimate overall system vulnerability, as well as predict failure possibilities in advance, so that adequate corrective measures can be initiated. Within all of the constructed RBDs (i.e., equivalent (Figure 5.6, Figure 5.7 and Figure 5.8) and global (Figure 5.9), there exists several series relationships between individual intermediate events, as well as their associated basic events, thereby indicating high system vulnerabilities and multiple failure causes.

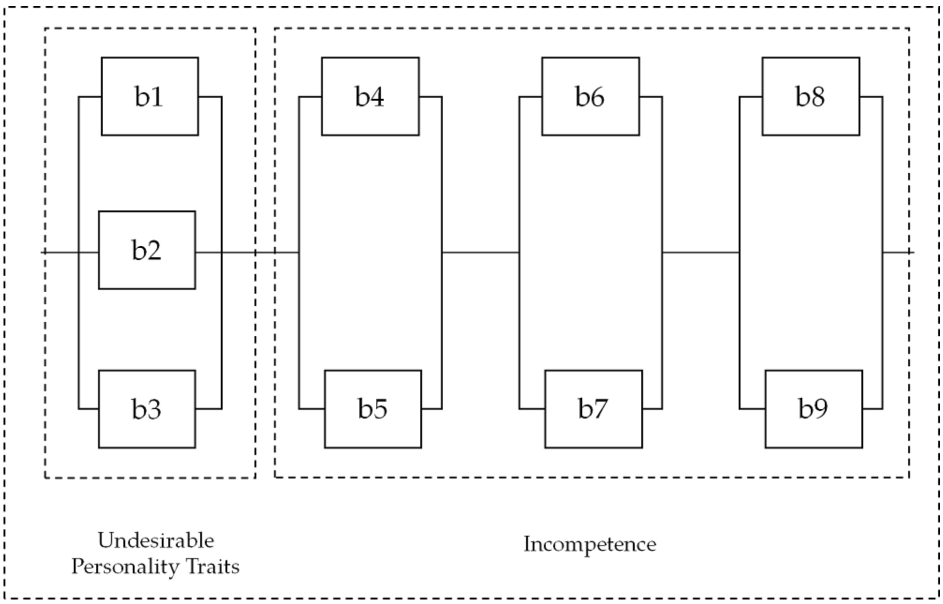


Figure 5. 6 Equivalent reliability block diagram for probable causes due to individual barriers (I)

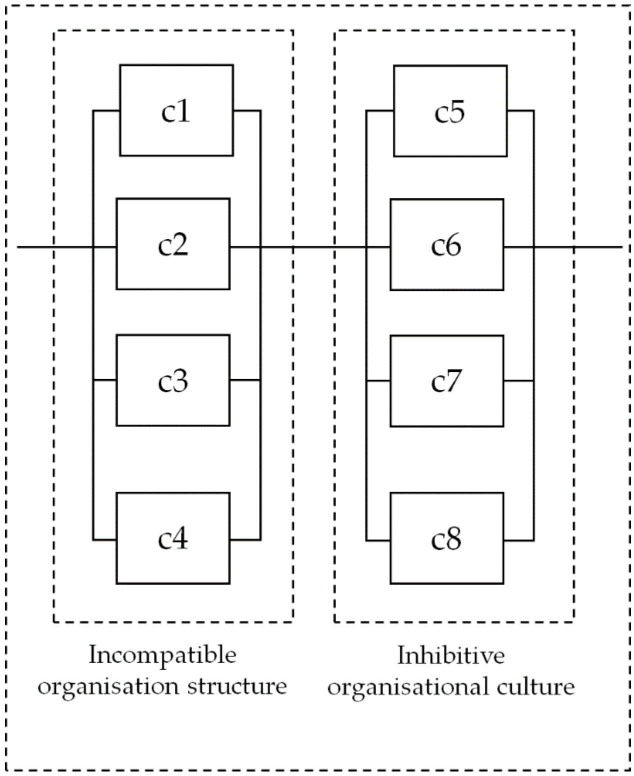



Figure 5. 7 Equivalent reliability block diagram for probable causes due to organizational barriers (O)

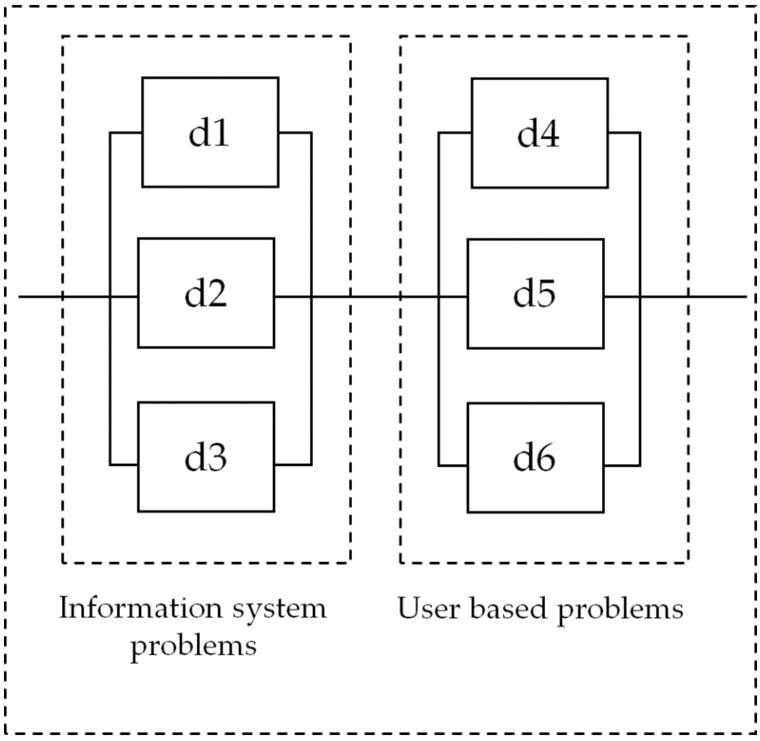



Figure 5. 8 Equivalent block diagram for probable cause due to technological barriers (T)

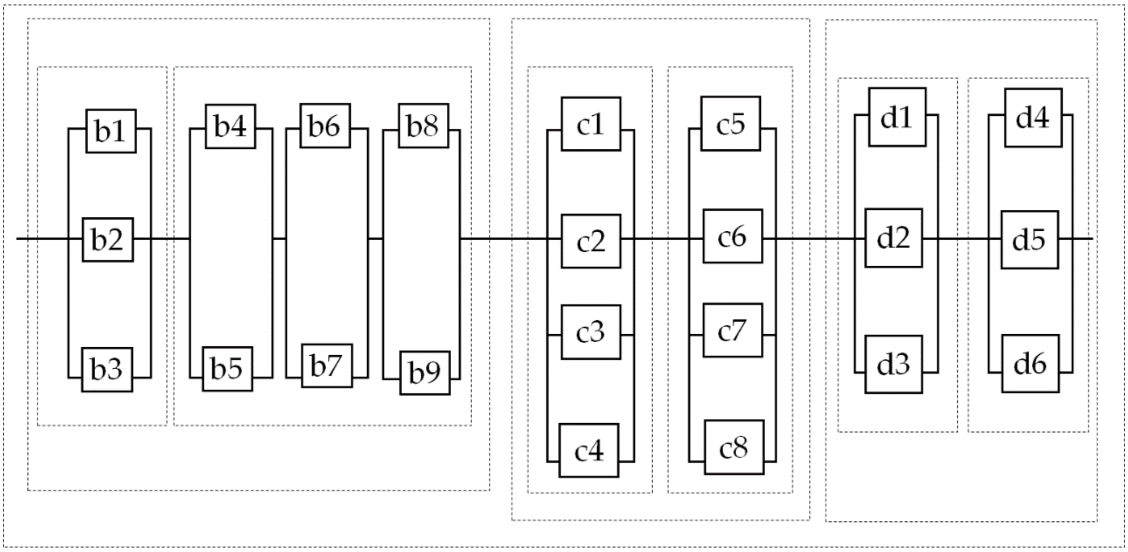



Figure 5. 9 Global reliability block diagram integrating equivalent reliability block diagrams of each resultant fault tree analysis

### 5.3.7. Application of AHP for assessment of barriers to knowledge management and experience transfer

The application of AHP in this section involves group decision-making, so as to elicit responses used to generate pairwise comparisons. The hierarchy of problems was developed as shown in Figure 5.10. Thereafter, decision makers in the group indicated their preferences and priorities for each of the main probable causes of failures, as well as ranking of basic failure events that trigger them. The results shown in Appendix (Table A5, Table A6, Table A7 and Table A8), respectively represent the outcomes of manual and automated (based on Transparent Choice AHP software) pairwise comparisons and syntheses based on the descriptions provided in [226], [227]. The aim was to rank the three main criteria (i.e., intermediate event identified from FTA in Figure 5.2) and 23 sub-criteria (basic events identified from FTAs in Figure 5.3, Figure 5.4 and Figure 5.5). The description of hierarchy elements can be found in Appendix (Table A9).

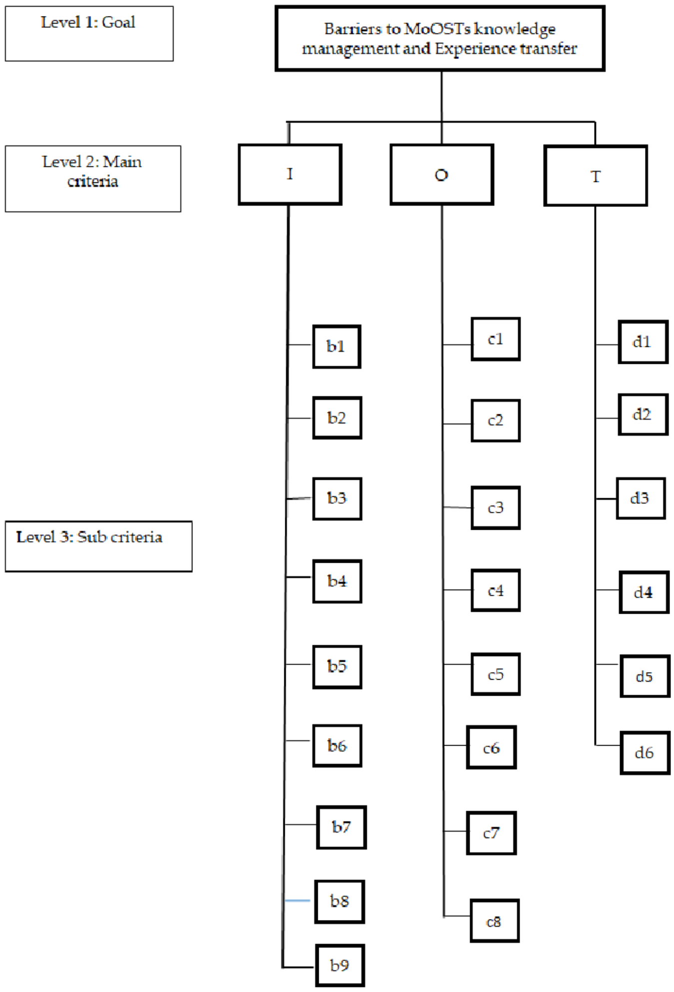



Figure 5. 10 problem hierarchy

The syntheses of pairwise comparisons are performed by division of each element of the matrix by its column total. In Table A5 for instance, to obtain the synthesised pairwise comparison matrix for the three main criteria, the value of each cell after pairwise comparison is a function of the ratio of sum of each column to the value of the cell (i.e., 1 + 3 + 1/5 which equals 4.2; subsequently cell 1.1 divided by 4.2 equals 0.24; hence the value shown in the first cell of the synthesised matrix 'I').

The priority matrix for Table A5 was obtained by estimating the ratio of the row averages (i.e., sum total of rows 'I', 'O', and 'T) to sum of the column. Similar steps were then replicated to obtain the synthesised matrix and local priorities for the sub-criteria associated with each main criterion in Table A6, Table A7 and Table A8 ( Appendix).

CR values for Table A5, Table A6, Table A7 and Table A8 (Appendix B) is less than 0.1, indicating that judgements are within acceptable limits.

Correspondingly, Transparent Choice software can automatically perform the calculations, provided correct values for the pairwise comparisons are allocated. Appendix (Table A1, Table A2, Table A3 and Table A4) shows that the results obtained from the analysis done using Transparent Choice is quite similar. The overall priorities depicted in Table 5.9 were obtained through products of the sub and main criteria.

Table 5. 9 Overall priorities ranking of barriers to knowledge management and experience transfer

| Criteria | Assigned Code | Sub-criteria Local Weight | Global Weight | Ranking |
|---|---|---|---|---|
| Individual Barriers | **I** | 0.28 | - | - |
| | b1 | 0.028 | 0.008 | 19 |
| | b2 | 0.028 | 0.008 | 19 |
| | b3 | 0.028 | 0.008 | 19 |
| | b4 | 0.259 | 0.073 | 5 |
| | b5 | 0.259 | 0.073 | 5 |
| | b6 | 0.062 | 0.017 | 13 |
| | b7 | 0.062 | 0.017 | 13 |
| | b8 | 0.156 | 0.044 | 8 |
| | b9 | 0.119 | 0.033 | 10 |
| Organizational Barriers | **O** | 0.64 | - | - |
| | c1 | 0.028 | 0.018 | 12 |
| | c2 | 0.030 | 0.019 | 10 |
| | c3 | 0.025 | 0.016 | 15 |
| | c4 | 0.286 | 0.183 | 1 |
| | c5 | 0.092 | 0.059 | 7 |
| | c6 | 0.134 | 0.086 | 4 |
| | c7 | 0.146 | 0.093 | 3 |
| | c8 | 0.258 | 0.165 | 2 |
| Technological Barriers | **T** | 0.08 | - | - |
| | d1 | 0.157 | 0.013 | 16 |
| | d2 | 0.167 | 0.013 | 16 |
| | d3 | 0.117 | 0.009 | 18 |
| | d4 | 0.068 | 0.005 | 22 |
| | d5 | 0.448 | 0.036 | 9 |
| | d6 | 0.041 | 0.003 | 23 |

## 5.4. Discussion

MoOSTs knowledge management (including acquisition, transfer, and learning) is particularly challenging due to variabilities in the frequency of the events, leading to limited growth in individual and organizational learning. Despite the enormous benefits of knowledge management to organizational growth and succession planning, organizational learning difficulties still persists in a wide range of disciplines, including MoOSTs [52]. The novel reliability-based analysis conducted here identified the main limiters in the context of individual, organization, and technology, using FTAs and RBDs. The harmonisation of FTA and RBD as visualisation techniques resulted in the identification of 23 basic events as shown in Figure 5.3, Figure 5.4 and Figure 5.5. The global FTA in Figure 5.10 highlighted significant bias towards system vulnerability (i.e., series relationships) despite the observed parallel relationships observable among the basic events of individual equivalent RBDs (i.e., Figure 5.6, Figure 5.7 and Figure 5.8).

In general, there were nine, eight, and six sub-criteria related to individual, organizational, and technological barriers as shown in Figure 5.7. The most highly ranked sub-criteria were all associated with organizational barriers especially c4, c6, c7, and c8 (Table 5.7). The next highly ranked sub-criteria were related to individual barriers which were most influenced by b4 and b5 (Table 5.6). Technological barriers were the least ranked, with lack of adequate training (d5) on newly deployed technologies being the most influential (Table 5.8). The dominance of organizational barriers adequately aligns with the findings of earlier studies [52], [53], [55] that clearly advocate the need to revisit existing practices to knowledge management within organizations. Further dissection of the intermediate events associated with organizational barriers revealed that incompatible organization structures and inhibitive organization culture as the main root causes.

Typical MoOSTs environments is characterised by interfaces between staff, contractors, and subcontractors within the client's site, which often impedes voluntary knowledge and experience dissemination. Responses gathered from the field-based focus group session attributed this tendency to hoard knowledge (especially by contractors and subcontractors) to fears of losing relevance once such expert knowledge is released.

Additionally, it is very common for MoOSTs to operate under strict time restrictions, which sometimes restricts decision-making to the top echelon of management staff, thereby inhibiting job autonomy. In the case of barriers attributed to inhibitive culture, the findings from the case has identified issues related to non-prioritisation of knowledge retention within experienced staff, unduly encouraging individualism, and a lack of reward systems. Hence, misallocation and/or misalignment of human resources and process has resulted in the emergence of organizations that lack capacity in harnessing the immense resources at their disposal.

A cursory examination of Figure 5.3 indicated that undesirable personality traits and incompetence dominated individual barriers. Drilling down into the personality traits element exposed three common factors, namely: Agreeableness, conscientiousness, and openness. All three common factors recorded similar scores which buttresses the importance of combining these traits in order to obtain desired results. In addition, [234]–[237] have claimed that personality traits have huge impacts on how individuals share work related knowledge, expertise, and contributions within an organization. Moreover, competence is indicated by having the necessary practical/technical skills along with a high awareness of strategic business orientation. However, deficiencies in any of the elements could independently lead to the undesired top-level event because only experienced staff can effectively transfer residual (tacit) knowledge. That is, if an experienced staff (defined by their virtue of long term involvement in MoOSTs) is deficient in any combination of limited interpersonal skills, (including communication skills—verbal or written), as well as having undesirable personality traits that restricts people from seeking them out for the skills they possess, (i.e., ranked low on openness, agreeableness, and contentiousness), then potential barriers for knowledge sharing increases. Consequently, if all of these desired factors are missing, less experienced or inexperienced staff would be unable to benefit, which raises the likelihood of tacit knowledge flow, which consequently results to over-reliance on explicit knowledge.

Technology also has a critical role in establishing performance of knowledge management systems, especially with respect to staff training, and integration with established processes [53][238][239][240]. While responses from identification and ranking of main criteria and sub-criteria related to this element were lowly ranked in comparison to other main criteria and sub-criteria, however, the interactions between people and technology facilitates retention and sharing of knowledge.

The two main issues highlighted were information systems problems and user-based problems. On the one hand, the top ranked sub-criterion was lack of adequate training related with the use of information systems (d5). On the other hand, inability to integrate new systems with existing legacy systems (d1) and lack of compatibility between diverse IT systems/processes (d2) were equally ranked. It is envisaged that developing the competence of users would lead to self-managed teams and facilitate acquisition and transfer of tacit knowledge.

Finally, findings from each of the techniques implemented in this study have brought to focus the usefulness of using a hybrid of techniques for problem identification, which can either generate quantitative solutions where historical failure probabilities are available or to simply generate qualitative visualisation platforms that can support conventional root causes analyses. FTAs were useful in designing the hierarchy of problems, clearly highlighting causal factors. RBDs on the other hand showed the combination of series and parallel connections within the systems, indicating fragility in combinatorial relationship, owing primarily to many series systems setups. The use of AHP to rank and prioritise the hierarchy of problems is perhaps one of the most vital pieces of the whole results because scarcity of resources informs decision-making and facilitates selection of choices. Through ranking of main criteria and sub-criteria, decision makers can design viable solutions starting with the top ranked criteria and then work their way to the bottom ranked criteria. The implementation of choices can be done in phases and decision makers can attempt to map-out long-term/short-term objectives, based on information obtained from ranking of criteria.

## 5.5. Chapter Summary

It is well acknowledged that there exist several mechanisms with the MoOSTs community of most organizations for capturing knowledge, including post-mortem meetings, pre/post-shutdown debriefing meetings, etc. As valuable as these mechanisms have proven to be over the decades, they are mainly geared towards capturing and disseminating explicit knowledge. This is perhaps owing to the ease of capturing and measuring such classes of knowledge within organizations. While this may be effective for mundane activities, the time, cost, and quality constraints associated with core MoOSTs activities make it imperative to possess substantial tacit knowledge.

Through the combination of information existing within current body of knowledge, as well as a practical case study, the present study investigated the casual relationships that exist among the main barriers to MoOSTs knowledge management and experience transfer. The study also takes into cognisance, the inability of decision-makers to confront all issues within their organization due to budget restrictions thereby necessitating the creation of mechanisms that allow for the prioritisation of the most influential factors. The most important contribution of this work includes intuitively harmonising several reliability-based (FTA and RBD) and multiple criteria decision-making (AHP) tools. This presents a practical but yet realistic model for understanding limiters to intangible performance enhancement elements of a very crucial industrial activity, MoOSTs.

Furthermore, priority ranking derived from AHP provides a road map that can direct focus of decision makers accordingly, especially when providing alternatives/solutions. This implies that holistic alternatives based on identified MoOSTs barriers to knowledge management and experience transfer can be derived and ranked appropriately. While the individual tools applied here are well-established within research and professional communities, their integration and application for solving MoOSTs knowledge management issues has never been explored. Moreover, the use of tools that are relatively familiar to the professional community is viewed as means of reducing the steepness of the learning curve that sometimes plagues the deployment of theoretical tools to the industry.

The scope of this work was limited to developing a hierarchy of problems capable of ranking and identifying the order of barriers to MoOSTs knowledge management and experience transfer, and as such has not attempted to provide solutions in terms of alternatives. While the novel harmonisation of theoretical quantitative risk assessment tools with qualitative field-based perspectives from experts can significantly enhance the ability of decision-makers to identify deficiencies in knowledge transfer mechanisms at a glance, the findings presented here can be described as being industry-specific. Despite this perceived limitation, it is envisaged that the approach presented here still offers useful contributions especially that cement manufacturing is often considered the upstream segment of one of the largest business sectors (i.e., mining and construction).

Future works are planned to encompass other key sectors (e.g., oil and gas, energy, food and beverage, etc.), as well as consider appropriate alternatives that consider the whole facet of MoOSTs in terms of tasks and associated knowledge, for the purpose of developing a knowledge management and experience transfer model specific to MoOSTs, which constitutes an essential step towards systematic but yet sustainable framework for tacit knowledge retention.

# 6 KNOWLEDGE CRITICALITY ASSESSMENT AND CODIFICATION FRAMEWORK FOR MAJOR MAINTENANCE ACTIVITIES: A CASE STUDY APPROACH

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| Paper title: | **Knowledge Criticality Assessment and Codification Framework for Major Maintenance Activities: A case Study of Cement Rotary Kiln Plant** |
| Authors: | **Lilian Iheukwumere-Esotu and Akilu Yunusa-Kaltungo** |
| Published in: | **Sustainability** |
| Volume: | **13** |
| DOI | **10.3390/su13094619** |

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|---|---|
| Paper title: | **A Multi-Attribute Knowledge Criticality framework for Ranking Major Maintenance Activities: A case Study of Cement Raw Mill Plant** |
| Authors: | **Lilian Iheukwumere-Esotu and Akilu Yunusa-Kaltungo** |
| Published in: | **Proceedings of ASME 2021 International Mechanical Engineering Congress and Exposition.** |
| Volume: | **13** |
| DOI | **10.1115/IMECE2021-72943** |



## ABSTRACT

Maintenance experts involved in managing major maintenance activities such as; Major overhauls, outages, shutdowns and turnarounds (MoOSTs) are constantly faced with uncertainties during the planning and/or execution phases, which often stretches beyond the organization's standard operating procedures and require the intervention of staff expertise. This underpins a need to complement and sustain existing efforts in managing uncertainties in MoOSTs through the transformation of knowledgeable actions generated from experts' tacit-based knowledge. However, a vital approach to achieve such

transformation is by prioritising maintenance activities during MoOSTs. Two methods for prioritising maintenance activities were adopted in this study; one involved a traditional qualitative method for task criticality assessment. The other, a quantitative method, utilised a Fuzzy inference system, mapping membership functions of two crisp inputs and output accompanied by If-Then rules specifically developed for this study. Prior information from a 5-year quantitative dataset was obtained from a case study with appreciable frequency for performing MoOSTs; in this case, a Rotary Kiln system (RKS) was utilised in demonstrating practical applicability. The selection of the two methods was informed by their perceived suitability to adequately analyse the available dataset. Results and analysis of the two methods indicated that the obtained Fuzzy criticality numbers were more sensitive and capable of examining the degree of changes to membership functions. However, the usefulness of the traditional qualitative method as a complementary approach lies in its ability to provide a baseline for informing expert opinions, which are critical in developing specific If-Then rules for the Fuzzy inference system.

*Keywords*: knowledge management; criticality assessment; major-maintenance; Fuzzy logic; task-based expertise; major-overhauls-outages-shutdowns-turnaround.

## 6.1. Introduction

Rising expectations from stakeholders have placed additional pressures on maintenance organizations worldwide, which has, in turn, necessitated better conformance with stipulated boundaries when performing major maintenance activities based on the realities of today's [167], [241] According to Kordab et al. [167], knowledge management practice and organizational learnings are significant factors to achieve sustainable organizational performance in rapidly changing business environments. Robertson [242] highlighted knowledge as a central strategic asset in developing and sustaining a competitive edge. According to Parida and Kumar [3], specific measurements of maintenance performance indices are now essential elements of strategic thinking in both service and manufacturing industries.

Consequently, emerging research areas in major maintenance activities have witnessed an increased interest in performance improvements. Major overhauls, outages, shutdowns and turnarounds, collectively denoted by the "MoOSTs" acronym here, are major types of maintenance classified as one of the most critical endeavours. This is because it offers one of the few instances whereby all elements of routine and occasional maintenance activities, including inspections (first level and specific), overhauls, repairs, and part replacements, are performed at a single instance with significant cost implications, in continuous production/operation industries [7], [10], [22].

The uniqueness of assets comprised in the bulk of activities performed during MoOSTs may lead to delays that are most evident in systems where failures are not self-revealed, especially in production critical systems, whereby running inspections are impractical [15]. Consequently, MoOSTs management is particularly burdened with overt reliance on outsourced resources, as well as constraints, such as separation of asset owners and complex accountability for asset management, which makes the measurement of asset maintenance performance and its continuous control and evaluation critical [168].

Critical issues plaguing engineering organizations are anticipated loss of specialist knowledge due to the retirement of experienced practitioners and dearth in replenishing expertise held by collective groups of individuals involved in MoOSTs [172]. In today's highly uncertain environment, the creativity of employees has been identified as the key to unlocking immense potentials within an organization [243]. However, Bell [172] reiterates that although the loss of specialist knowledge and skills presents a huge problem to engineering organizations, it also provides opportunities for knowledge acquisition, transfer and retention if the right approaches are adopted.

Prior research efforts in MoOSTs management were aimed at identifying elements perceived to be critical performance indicators, such as general information gathering, increased participation in supply chain effectiveness, improving lessons learned and sharing best practices [8]. The culmination of such research efforts has reflected in numerous ways that are not limited to the adoption of strategies in practice that emphasises large-scale data gathering and information processing (inspection records, designs, drawings, historical data and lessons learned etc.). However, because big data does not feature only large data volumes and high speed data collection but also data with complicated issues, which imposes challenges in analysis, the efficacy of current strategies is rather limited [26]. Furthermore, the continued reliance on utilising information embedded within the maintenance management system (MMS) as the most important decision-making tool for providing technical support when performing maintenance-related tasks is overstated [57][58]. This is because, as useful as these existing databases and information management systems are in identifying lagging indicators (generating audit and/or post mortem reports, as well as suggestions for measuring and storing such captured information), their ability to support prognosis and sustainable tacit knowledge management for enhanced decision-making are quite limited [59]. However, it is necessary to establish that the usefulness of large-scale information gathering can be optimised further when secondary datasets obtained from those embedded within MMS contribute towards criticality assessment by means of identifying crucial elements for subsequent knowledge acquisition and expertise transfer [244].

Therefore, research-based studies within maintenance can leverage different techniques, such as expert opinion data (based on years of knowledge acquisition), developing engineering, as well as applying mathematical relationships from prior information and past experiences on similar datasets to discern learning effects, reducing the steepness of learning curves and providing insights into maintenance activities [245]. Consequently, it is imperative to intensify research efforts towards the attainment of knowledge-based systems that aim to provide complementary solutions for prognosis and enhanced decision-making from critically assessing maintenance tasks.

Therefore, the focus of this study is to identify elements of maintenance activities during MoOSTs and prioritise them in a bid to establish criticality. This is of immense use to the maintenance organization because such criticality assessment can provide information leading to continuous improvement and learning from experience. The rest of the paper is organised as follows; Section 6.2 is a literature review on the theoretical underpinnings of the study. Section 6.3 focuses on research methodology, a brief summary of the case study and justification for its selection. Section 6.4 provides a demonstration of model applications, results and general discussion of findings. Section 6.5 is the summary and conclusion.

## 6.2. Literature Review and Study Development

Prior studies in MoOSTs have employed the use of traditional criticality assessment for risk-based equipment selection to identify equipment for shutdowns, inspection-related activities and maintenance [82], [93], [117]. Moreover, some variations of these traditional criticality assessment techniques have been applied in MoOSTs' management for decision-making. Some common depictions within existing literature include the innovative criticality index used as a tool for assessing maintenance tasks, including equipment selection in MoOSTs initiation phase [13], [116], [246]. Similarly, a risk criticality matrix for maintenance, which is applicable within cement manufacturing industries, has been demonstrated [247]. Another study by Ashok et al. [23] developed an activity assessment model to determine relationships between MoOSTs activities in order to identify non-critical activities based on the duration and divert resources to critical activities.

Most of these studies highlighted the applications of criticality assessment for MoOSTs processes and equipment selections as important methods for optimising maintenance, but detailed analyses on identifying criticality of tasks for the purpose of enhancing knowledge is scant in the body of knowledge. However, [248] critiqued traditional approaches for criticality assessments that are predominantly based on subjective expert opinions, stating that "when criticality assessments are performed using traditional qualitative criticality matrix, a suboptimal classifications tend to occur as there are no means to incorporate actual circumstances of boundary of the input ranges or at levels of linguistic data and criticality categories." Although many other methods have supplemented existing traditional criticality assessments within industrial maintenance, including multi-criteria decision-making methods to overcome the perceived challenges of this method. This is by means of subjective expert opinions that have been implemented by combining group decision-making with a popular multi-criteria decision-making approach, such as the analytical hierarchy process (AHP) [249], [250], etc.

While the usefulness of obtaining benchmarked results from expert opinions, especially when such decision-making is associated with difficulties in ranking objectives into a hierarchy, an important function of AHP cannot be overlooked, but the inherent weakness, especially in terms of uncertainty and vagueness in weight allocations, limits

its effectiveness [249]. The AHP remains popular in literature because it is a significant improvement from traditional qualitative criticality assessments that depend on the subjectivity of group decision-making as it can measure levels of inconsistencies in the judgements provided by experts. However, despite the popularity of AHP, it is often criticised for its inability to capture the subjectivity of human judgements, which is an essential part of group decision making, and it then implies that the AHP cannot be a standalone approach, but it can be strengthened by combining it with an approach that can capture subjectivity. For example, Fuzzy logic can convert verbal assessments into crisp values where necessary [251], [252]. Many differences between the traditional qualitative criticality method and distinct computational method, fuzzy logic, exist, as shown in [253], and these differences have been highlighted in Appendix.

Consequently, the application of Fuzzy logic (introduced by Zadeh in 1965) [249] can overcome the challenge of human judgement subjectivity, which is linked to imprecise reasoning in human judgement, and can provide rationality in the decision-making process. However, since Fuzzy logic is also limited as a standalone method because it cannot adequately measure the level of consistency in some datasets obtained from the judgement provided by expert opinions, it can also be supplemented with other approaches especially when setting out baselines for membership functions [251], [252]. Therefore, it is important for decision-makers to assess the type of data they seek to analyse and select combinations of effective approaches that can compensate for the weakness of others. Therefore, the use of hybrid methods is a popular method for developing criticality ranking systems [248], [254]–[256]. This study demonstrates the application of such a hybrid method; it utilises the traditional qualitative criticality method for ranking expert judgements, which serves as the baseline for setting the degree of membership functions, and the If-Then rules in the Fuzzy inference system.

## 6.3. Materials and Methods

The proposed application in this study is a hybrid model that combines quantitative and qualitative analyses to determine criticality assessment values of MoOSTs tasks. Frequency (F) parameter and consequences (C) parameter made up of three variables, namely operational reliability impact (ORI), health safety and environment impact (HSEI) and maintenance costs (MC), are considered to determine and evaluate the criticality of MoOSTs activities. To achieve this, qualitative analysis of F and C parameters as well as criticality levels are localised by an expert panel by means of the Delphi method. The Delphi technique is a popular method for achieving group decision-making, as it is designed as a structured group communication process that allows individuals within a group to deal with complex problems [216]. An integral technique for eliciting responses following the Delphi techniques for qualitative problems with many alternatives is to generate pairwise comparisons, and this can be achieved by means of the analytical hierarchy process (AHP) because different criteria can be ranked into a hierarchy of importance [215].

In this instance, since the factors of maintenance costs considered in this study is focused on labour elements and actual task execution, which comprise of non-numerical datasets, to localise such scales by an expert panel, the AHP technique by Saaty [227], [250] is first administered, for the purpose of determining normalised weights. Subsequently, MoOSTs tasks with high criticality numbers based on the criticality scale are codified. It is imperative to acknowledge that codification of critically assessed MoOSTs tasks increases the potential for harnessing tacit-based knowledge from maintenance activities and promotes the transfer and reuse of expertise partly due to distribution of work related to practical expertise, subjective experience-based insights, perspectives, intuitions, as well as beliefs among staff and outsourced resources during MoOSTs.

### 6.3.1. Traditional qualitative criticality assessment method

This method comprises of two main processes for qualitative criticality assessment of MoOSTs tasks, namely: (1) development of mathematical relationship through means of combinatorial logic of parameters and (2) practical application of the mathematical relationship for deriving criticality assessment rating system for maintenance tasks.

Proposed sequence of the method:

Consider typical maintenance activities performed on the rotary kiln system (RKS) during MoOSTs;

i. Determine parameters for criticality analysis: two main parameters, frequency and consequence (three factors related to consequence parameter);
ii. Determine weights allocation for values of each main parameter and individual factor under each parameter where necessary;
iii. Group decision-making by applying the Delphi technique is initiated to deliberate on and recommend weight allocations for values of F, deliberate on, and recommend weight allocation for values of C and assign ratings to the criticality assessment values obtained from the mathematical relationship. The baseline information for such group decision-making was dependent on data obtained from historical plant data, as well as proposed estimates based on business practices and experience for assets of the same sector and maintenance requirements. However, some factors of MC comprise of non-numerical datasets, to localise such scales by an expert panel; AHP is first administered for the purpose of determining normalised weights;
iv. Compute the assigned weight allocation of values into the mathematical relationship and determine criticality assessment values;
v. Decision mapping from expert panel to establish asset criticality levels and linguistic ratings;
vi. Demonstrate the application of the proposed model using the case example

To implement the proposed decision method, it is vital to deduce a logical procedure for carefully selecting the most relevant MoOSTs activities that would benefit from criticality assessment of task-bask-based expertise identification and codification framework. MoOSTs data embedded within the plant's CMMS that spans over a 5-year time window was utilised for the analysis. The RKS was selected because it was adjudged be to be of utmost importance in maintaining smooth-running operations of cement manufacturing [247]. Maintenance tasks for each critical sub-units under the RKS were assessed to determine criticality based on a combination of relevant factors [93]. A criticality assessment technique, applied by Crespo et al. [246], was adopted and modified to suit the specificity of this study's elements. The two main parameters considered were task frequency (F) and consequence (C). The mathematical relationship depicted in Equation (6.1) was applied to harmonise all the parameters and factors. Additionally, strict weighting protocols were implemented to yield task-based criticality assessment values ($C_{av}$) that adequately assessed maintenance tasks that fall within the premise of RKS during MoOSTs. Furthermore, a linguistic command classification system was used to assign ratings as well as multi-disciplinary requirements. It is also envisaged that this approach could foster the reduction of MoOSTs task uncertainties through incorporation into a dedicated knowledge management system.

$$C_{av} = F \times C = F \times [\text{ORI} + \text{HSEI} + \text{MC}] \quad (6.1)$$

where $C_{av}$ is criticality assessment values; F is the task frequency parameter; C is the consequence parameter; ORI is the operational reliability impact; HSEI is health, safety and environment impact; and MC is maintenance costs (including size of labour, hierarchy of labour, source of labour and task duration).

### 6.3.2. Experts' weight allocations to parameters and formulation of mathematical relationship

Effective criticality assessments are specific to individual systems: plants or business units. The criticalities of two similarly configured plants may still be different based on their operational environments, labour skill matrix or preferred maintenance strategies [255]. Typically, the criticality of certain MoOSTs tasks is decided based on predetermined objectives that are pre-set by decision-makers. An expert panel team of 10 persons was formed and assigned decision-making capabilities; these persons are representatives of different sections in the maintenance department having appreciable involvement in performing MoOSTs. The panel were presented with 5 years' worth of data obtained from the case plant and also referred to literature-based evidence of similar applications for expert judgement. The objectives of the panel were as follows.

i. Deliberate and recommend criteria and values of F based on obtained plant data.
ii. Deliberate and recommend criteria, weights and factor values of the C parameter.
iii. Establish the overall procedure for asset criticality levels and linguistic ratings.

To supplement the group decision-making exercise and reduce levels of inconsistencies in group decision-making for factors with non-numerical data, the analytical hierarchy process (AHP) was implemented to determine the assigned values for the source of labour and hierarchy of labour classifications, which are two out of four factors that are combined to yield MC. This was because, unlike the F parameter and other factors of the C parameter, where values for the mathematical relationship could be determined through consistency of judgements derived from the obtained data, source of labour and hierarchy of labour classifications were not favoured by such approach. Hence, the adoption of AHP's three principles, decomposition, comparative judgement and synthesis priorities, to elicit expert judgements and subsequent assignment of values for these two factors [227], [229], [250]. Table 6.1 shows the composition of the expert panel and their job description. Table 6.2 shows classifications of task frequency.

Table 6. 1 Relevant information of expert panel members

| Job title of panel members | Category information | Sample size (n= 10) |
|---|---|---|
| Maintenance manger | A | 1 |
| Reliability engineer | | 1 |
| Health, safety and environment manager | | 1 |
| Contracts and purchasing manager | | 1 |
| Maintenance planner | B | 1 |
| MoOSTs team lead | | 1 |
| Cost controller | | 1 |
| Document controller | | 1 |
| Shop floor technicians | C | 2 |

Table 6. 2 Classification of task frequency (F) in MoOSTs

| Frequency rating | Frequency criteria | Assigned value |
|---|---|---|
| Rare | At least once | 4 |
| Occasional | $> 1 \leq 2$ | 3 |
| Probable | 3 – 4 | 2 |
| Frequent | $> 4$ | 1 |

The logic adopted in Table 6.2 for task frequency classification differs from that used for traditional and widely established criticality assessments, owing to the high-frequency tasks being assigned the highest scores (direct proportionality) in traditional approaches. In this instance, however, the highest values were assigned to the low-frequency tasks (inverse proportionality) due to their rarity and higher probability of losing associated skillsets for such MoOSTs activities.

To determine ORI factor values, as shown in Table 6.3, the obtained values for technical support work in hours of each MoOSTs activity was utilised as a criterion for determining the level of disruption to the system. Additionally, to determine ORI and HSEI factors values, a combination of practical maintenance tools, such as FMECA (Failure Mode, Effect and Criticality Analysis) and RCM (Reliability Centred Maintenance) were applied as shown in Table 6.3.

Table 6. 3 Classification of consequence factors for ORI and HSEI

| **Impact on operational reliability (ORI)** | **Criteria** | **Assigned value** |
|---|---|---|
| Very high | Task will require more than 68.75hrs | 10 |
| High | Task can be done in 45.87 ≤ 68.75hrs | 6 |
| Medium | Task can be done in 22.9 < 45.87hrs | 4 |
| Low | Task can be done in > 0.1 < 22.99hrs | 2 |
| Very high | No affection task can be done in 0.1hrs | 1 |
| Impact on health, safety, and environment (IHSE) | Criteria | Assigned value |
| Very high | Which might be lethal/fatal and/or cause permanent environment damage | 10 |
| High | Which might cause permanent damage to health > 30 days and/or cause transient reversible damage | 6 |
| Medium | Which might cause occupational disease that is reversible in 10-30 days, and/or cause short-term environmental effects | 4 |
| Low | Which might cause poor health 3-10 days and/or cause short-term environmental effects | 2 |
| Very low | Limited discomfort 1-3 days and/or cause negligible environmental effects | 1 |

FMECA and RCM are tools utilised to recognise and evaluate potential failure of maintenance tasks and their effects, as well as identify potential actions that attempt to eliminate or reduce the chances of potential failures in assets [229], [257]. However, performing FMECA and RCM analyses could be complex and time-consuming for most operators, owing to the need for absolute understanding of the process, system, subsystem, components and their potential failure modes. As valuable and well-established as these endeavours have proven to be over the years, it is considered out of scope for this study. However, comparable levels of technical details were obtained via a field-specific questionnaire and administered using the Delphi technique. The process of expert categorisation for building representative panels, modelling of typical Delphi survey panels, group sizing and establishment of consensus judgments from choosing "averages" of judgement were detailed in a preceding study [22].

The application of group decision-making offers possibilities for deciding which alternatives are best under certain conditions and offering support in providing insights into the decision-making process by varying criterion weights and scores. Typical MoOSTs costs are often an integration of various elements of which the most prominent as depicted by [93], and they include: preparatory maintenance labour cost, duration of maintenance work, cost of technical support, cost of skilled maintenance, cost of downtime, cost of spare parts and materials, etc. Four of the most prominent cost factors peculiar to MoOSTs were then selected.
The selected costs factors are number of labours used to achieve an individual task (wi); the hierarchy of specialist labour (xi); source of labour, i.e., internal, external or combination of both (yi); duration of technical support work in hrs (zi). Table 6.4 below shows the classifications for maintenance costs.

Table 6. 4 Classification of consequences factors for maintenance cost (MC); number of labours, hierarchy of specialist labour, source of labour (internal, external or combination of both) and duration of technical support work in hrs.

| Maintenance Cost (MC) | Criteria Equation (2) | Assigned value |
|---|---|---|
| Very high | > 12.5 | 5 |
| High | 8 - 12.5 | 4 |
| Medium | 4.5 - 7.5 | 3 |
| Low | 4 | 2 |
| Very low | < 4 | 1 |
| **Number of labours criteria** | **Assigned value** | |
| > 10 | 2 | |
| 4 – 9 | 1.5 | |
| 1 -3 | 1 | |
| **Duration of technical work support in hrs.** | **Assigned value** | |
| 45.87 ≥ 68.75 | 4 | |
| 22.9 < 45.87 | 2 | |
| 0.1 < 22.9 | 1 | |
| **Hierarchy of specialist labour** | **Criteria – normalized weight from AHP** | **Assigned value** |
| Engineering/ shift manager | 0.634 | 3 |
| Supervisor | 0.26 | 2 |
| Technician | 0.11 | 1 |
| **Source of labour** | **Criteria -normalized weight from AHP** | **Assigned value** |
| External | 0.70 | 3.5 |
| Combination (External and internal) | 0.21 | 2 |
| Internal | 0.09 | 1 |

To obtain overall factor value for maintenance costs, the equation is as follows:

$$MC= \sum_{i=1}^{n} w_i + x_i + y_i + z_i \quad (6.2)$$

The outputs of Equation (6.2) were utilised in the classification system to determine MC factor values in Table 6.4. Furthermore, to achieve the assigned values of the mathematical relationship for the hierarchy of specialist labour (xi) and the source of labour, i.e., internal, external or combination of both (yi), a manual demonstration of the AHP was first administered, applying pairwise comparison and determination of consistency by eigenvalue max $\lambda_{max}$, whereby the consistency index (C1) for the two factors was 3.7% and 1.7%, respectively. According to [229], [230], a consistency ratio (CR) lower than 10% (0.1) is classified as sufficiently consistent. The entire outcomes of manual pairwise comparisons and syntheses are shown in Table 6.4 (based on the hierarchy of labour and source of labour) are and the nomenclature of codes are provided in Appendix.

In summary, criticality assessment values were determined based on the combination of all aforementioned parameters and factors. By using assigned numerical values of all parameters and factors for $C_{av}$ obtained from Equation (1), the maximum value for a MoOSTs task criticality was set at 100. The expert panel then established three levels of MoOSTs tasks criticality and criticality assessment matrix from the traditional method as shown in Table 6.5 and Table 6.6, respectively.

Table 6. 5 Expert's classification levels of MoOSTs $C_{av}$

| **$C_{av}$ Numerical range** | **Criticality level of MoOSTs task** | **Notation** |
|---|---|---|
| $C_{av} > 50$ | Extremely critical | EC |
| $25 < C_{av} < 50$ | Critical | Cr |
| $C_{av} < 25$ | Semi-critical | SC |

Table 6. 6 Qualitative criticality assessment matrix

| | | **Consequences** | | | | |
|---|---|---|---|---|---|---|
| | Descriptive term | VH | H | M | L | VL |
| **Frequency** | R | EC | EC | EC | C | C |
| | O | EC | EC | C | C | SC |
| | P | C | C | C | SC | SC |
| | F | C | SC | SC | SC | SC |

After obtaining the criticality assessment values from the traditional qualitative criticality ranking method, the next step is the Fuzzy logic demonstration.

### 6.3.3. Fuzzy logic working principles for criticality assessment

A methodology for implementing Fuzzy logic is by means of the Fuzzy inference system (FIS), which maps a given input set to an output set using Fuzzy logic. There are two popular FIS models available: the Mamdani Fuzzy model and the Sugeno Fuzzy model. Their selections largely depend on the Fuzzy reasoning and its formulations of the Fuzzy If-Then rules. To date, the Mamdani approach, developed in 1975, is very popular and has been successfully applied to a variety of industrial processes [248], [255], [258]. The Mamdani Fuzzy model is based on collections of If-Then rules. The four functional blocks that constitute the FIS described in [259] are fuzzifier, knowledge base, inference system and defuzzifier. Figure 6.1 is a representation of the FIS description adopted for this study.

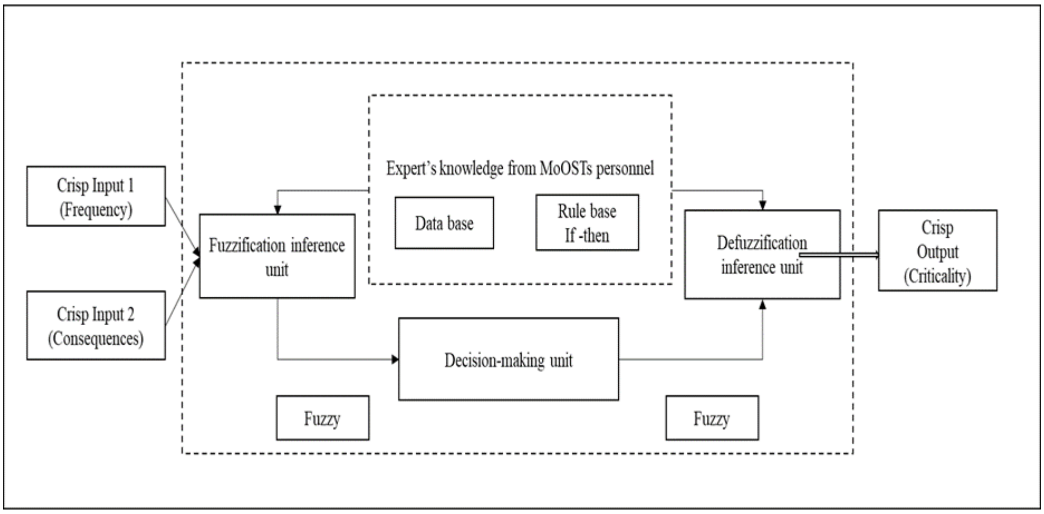


Figure 6. 1 Fuzzy criticality ranking system

Fuzzifier: In Fuzzy language, this input is called crisp input because it contains precise information about specific information about an individual parameter. The fuzzifier converts this precise quantity to the form of imprecise quantity, such as "low," "medium," "high," etc., and assigns a degree of belongingness to it. To express this mathematically in Fuzzy theory, a Fuzzy set A, in some relevant universe of discourse X, is defined by function $\mu_A(x) = [0,1]$. Thus, for any element x of universe X, membership function $\mu_A$ (x) equals the degree to which x is an element. This degree, a value between 0 and 1, represents the degree of membership element x in set A. If the degree of membership $\mu_A$ (x) is close to 1, it refers to a greater degree of belongingness of the element x to the set A. If the degree is close to 0, the degree of belongingness of x to A is small.

The membership function of the Fuzzy set refers to the coding of the membership curve, and it can be sigmoidal, triangular, trapezoidal or Gaussian etc. [260]. The triangular "trimf" and trapezoidal "trapmf" membership functions are quite popular and have been applied for many risk and criticality assessments because they are intuitively easy for decision-makers to use and calculate [255], [259], [261].

Thus, if *x* is the variable in the system, for a "trimf," a Fuzzy set A is defined by the triplet (*a*, *b*, *c*). The membership number $\mu_A$ (x) can be defined in Equation (6.3):

$$\mu_A(x) = \begin{cases} 0, x \leq a \\ \frac{x-a}{b-a}, a \leq x \leq b \\ \frac{c-x}{c-b}, b \leq x \leq c \\ 0, \ x \geq c \end{cases} \tag{6.3}$$

Where a, b, and c are real numbers and c =a=b

"Trimf" can be potentially used for representing conflicts in group decision-making because for each basic variable, *x*, "*a*" (the lowest possible value) and "*c*" (the largest possible value) can be interpreted as the minimum and maximum values of the decision-makers' judgement. The target can be a single value, or, in general, any interval in the real line of the form (*a*, *c*) that represents a range of desired values of the variables.

Likewise, if *x* is the variable in the system, for a 'trapmf', a Fuzzy set A is defined by the quadruplet (*a*, *b*, *c* and *d*). Similarly, membership number $\mu_A$ ($x_c$) can be defined as shown in Equation (6.4):

$$= \mu_A(x_c) = \begin{cases} 0, \ x \leq a \\ \frac{x-a}{b-a}, \ a \leq x \leq b \\ 1, b \leq x \leq c, \\ \frac{d-x}{d-c}, c \leq x \leq d \\ 0, \ x \geq d \end{cases} \tag{6.4}$$

For "Trapmf," the data for each variable are normalised on a scale of zero (lowest level) and one (highest level) to allow for aggregation, as well as facilitate Fuzzy computations. For each computation, each basic variable, *x*, is assigned a target, a minimum "*a*," and a maximum value "*d*." The target can be a single value or, in general, any interval in the real line of the form (*b*, *c*) in order to represent a range of desired values for the variables.

Knowledge base: This hosts both the database and rule base jointly. The database defines the membership functions of the Fuzzy sets used in Fuzzy rules, whereas the rule base contains several Fuzzy (If-Then rules) established based on expert knowledge

Inference engine/decision-making unit: This is where the decision-making unit performs inference operations; it handles how rules are combined, and/or mathematical calculus is specifically used in the analysis of a particular operation. Equations (6.5)–(6.8) provides the listings of characteristics of the Mamdani Fuzzy method and the soft computational operators employed [258], [262]

AndMethod: 'min' μA (x)=max(μA)(x), μB (x))=μA (x) VμB (x) (6.5)

OrMethod: 'max' μA (x)=max(μA)(x), μB (x))=μA (x) Λ μB (x) (6.6)

ImpMethod: 'min' Max(min μA(x), μB (x))) (6.7)

AggMethod: max{mini[μA1i(x1), μA2i(x2),…,μAsi(xs)]}, i=1,2,…,M (6.8)

*Defuzzifier*: The output generated by the interference block is always Fuzzy in nature. In real world operations, the output of the Fuzzy system needs to be crisp. The defuzzifier receives the Fuzzy input and provides real-world output (numerical values). There are many types of defuzzification methods, but centroid, also known as the centre of gravity, is the most widely used [261]. The centroid method is shown in Equation (6.9).

$$\text{Centroid method} = \frac{\int x\mu_{c}(x).\, dx}{\int \mu_{c}(x).\, dx} \quad (6.9)$$

The Mamdani FIS description used in this study is shown in Figure 6.2.

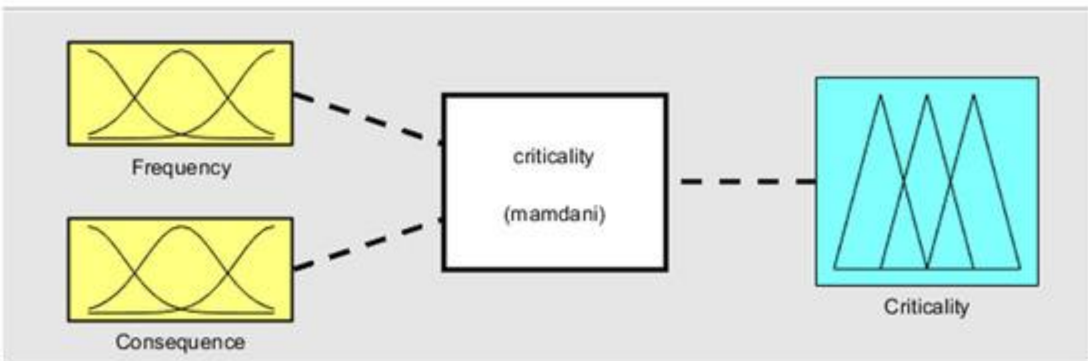


Figure 6. 2 Mamdani Fuzzy inference system

The triangular and trapezoidal membership functions were selected based on their description and computational strength. Linguistic frequency parametric terms of frequent (F), probable (P), occasional (O) and rare (R) had corresponding numerical ranges (0–4) assigned by experts. Consequence parameters were obtained from the expert assigned values for the sum of all three consequence factors (Table 6.3 and Table 6.4). Their linguistic terms of very low (VL), low (L), medium (M), high (H) and very high (VH) had corresponding numerical values (0–25). The criticality (output) was classified into three levels with linguistic terms: semi-critical (SC), critical (C) and extremely critical (EC), based on the classifications in Table 6.5 with the range of 0 to 100.

The mapping of frequency, consequences and criticality values was achieved by using Fuzzy If-Then rules of crisp inputs and outputs applied to the Fuzzy logic toolbox kit of MATLAB R2020b. A total of 20 If-Then rules were utilised in the FIS to provide the mapping. The rules are designed to follow the logic of the expert assessor derived from the qualitative criticality matrix and are outlined in Table 6.6. The parametric membership functions for inputs and output variables can be found in Table 6.7.

Table 6. 7 Parametric membership functions for two inputs variables and one output variable

| **Variable** | **Linguistic variable** | **Shape of membership function** | **Parameters** |
|---|---|---|---|
| Input 1- Frequency | Frequent | Trapezoid | [0 0 1 1.5] |
| | Probable | Triangular | [0.75 2 2.5] |
| | Occasional | Triangular | [1.5 3 3.5] |
| | Rare | Triangular | [2.5 4 4] |
| Input 2- Consequences | Very low | Trapezoid | [0 0 5 10] |
| | Low | Triangular | [5 10 15] |
| | Medium | Triangular | [10 15 20] |
| | High | Triangular | [15 20 25] |
| | Very high | Trapezoid | [20 25 30 30] |
| Output variable | Semi critical | Trapezoid | [20 25 30 30] |
| | Critical | Triangular | [25 50 70] |
| | Extremely critical | Triangular | [50 100 100] |

The 20 Fuzzy rules applied in the FIS are shown in Figure 6.3, while Figure 6.4 is the degree of membership functions for the two inputs and one output.

1. (Frequency==R) & (Consequence==VH) => (Criticality=EC) (1)
2. (Frequency==R) & (Consequence==H) => (Criticality=EC) (1)
3. (Frequency==R) & (Consequence==M) => (Criticality=EC) (1)
4. (Frequency==R) & (Consequence==L) => (Criticality=C) (1)
5. (Frequency==R) & (Consequence==VL) => (Criticality=C) (1)
6. (Frequency==O) & (Consequence==VH) => (Criticality=EC) (1)
7. (Frequency==O) & (Consequence==H) => (Criticality=EC) (1)
8. (Frequency==O) & (Consequence==M) => (Criticality=C) (1)
9. (Frequency==O) & (Consequence==L) => (Criticality=C) (1)
10. (Frequency==O) & (Consequence==VL) => (Criticality=SC) (1)
11. (Frequency==P) & (Consequence==VH) => (Criticality=C) (1)
12. (Frequency==P) & (Consequence==H) => (Criticality=C) (1)
13. (Frequency==P) & (Consequence==M) => (Criticality=C) (1)
14. (Frequency==P) & (Consequence==L) => (Criticality=SC) (1)
15. (Frequency==P) & (Consequence==VL) => (Criticality=SC) (1)
16. (Frequency==F) & (Consequence==VH) => (Criticality=C) (1)
17. (Frequency==F) & (Consequence==H) => (Criticality=SC) (1)
18. (Frequency==F) & (Consequence==M) => (Criticality=SC) (1)
19. (Frequency==F) & (Consequence==L) => (Criticality=SC) (1)
20. (Frequency==F) & (Consequence==VL) => (Criticality=SC) (1)

Figure 6. 3 Extract of the formulated rules

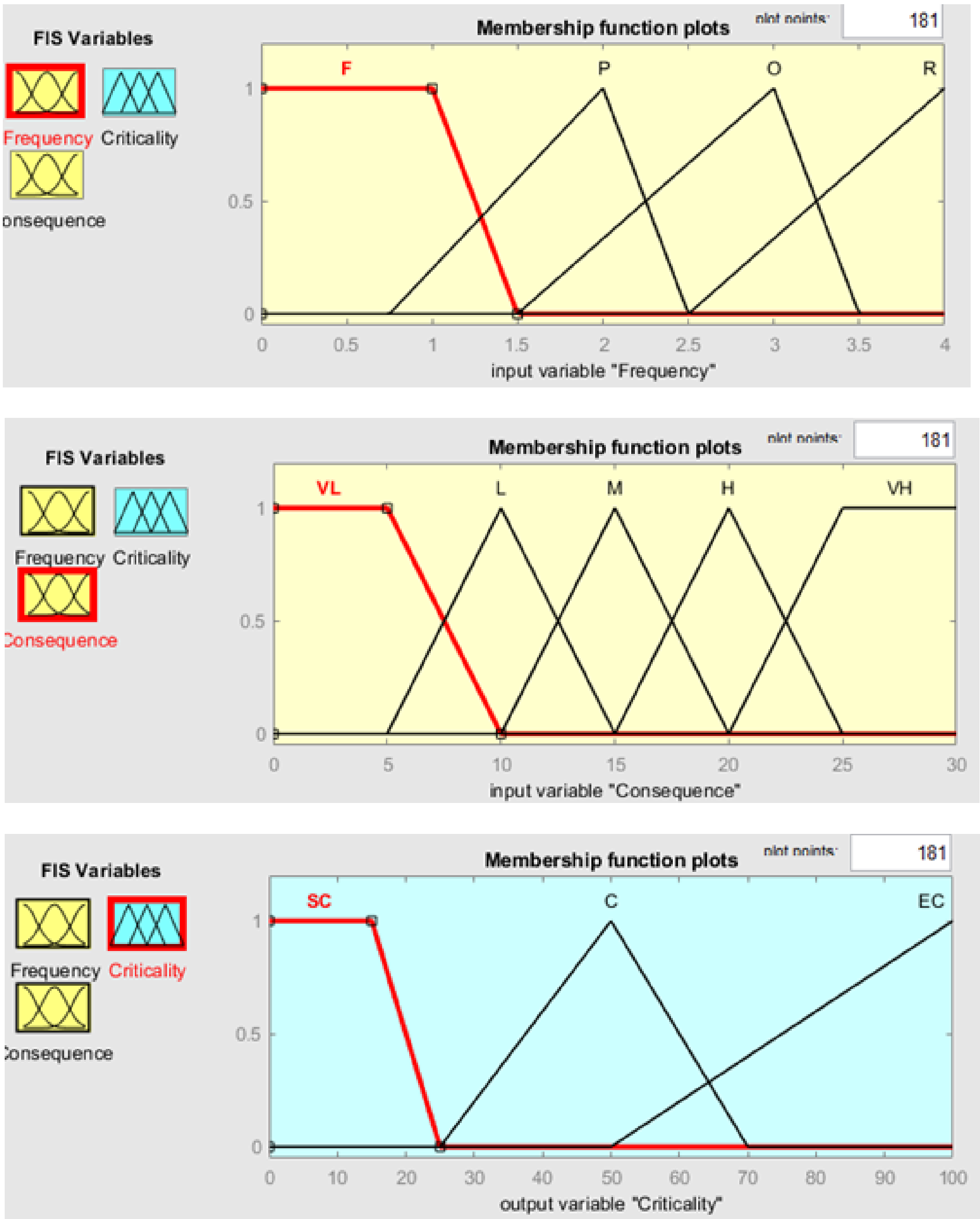


Figure 6. 4 Fuzzy membership function plots for frequency, consequences and criticality

The introduction of fuzziness is vital for facilitating the analysis of inputs (i.e., ranges of estimated frequency and consequences values) at the boundaries in the process of criticality assessment-related decision-making. This enables optimal criticality analysis results by introducing fuzziness to the ranges of each input/output value as well as the corresponding membership function values.

The final output of the system, fuzzy criticality index (FCI) [254], is displayed in the mathematical relationship in Equation (6.10):

$$\text{FCI} = \frac{\sum_{i=1}^{N} k_{i\,Criticality_i/N}}{\sum_{i=1}^{N} k_i} \tag{6.10}$$

Where,

N and

$K_i$ respectively represent number of consequences and weight factor for each consequence;

*Criticality*$_i$ is then equivalent to-calculated Fuzzy criticality value for each consequence attribute.

The resulting output envelopes for two Fuzzy inputs, frequency and consequences as well as one Fuzzy output criticality is displayed in Figure 6.5. High value of criticality is obtained for any high value of frequency, consequences or combinations of both. Conversely, low value of criticality is obtained for low values of frequency and consequences combinations.

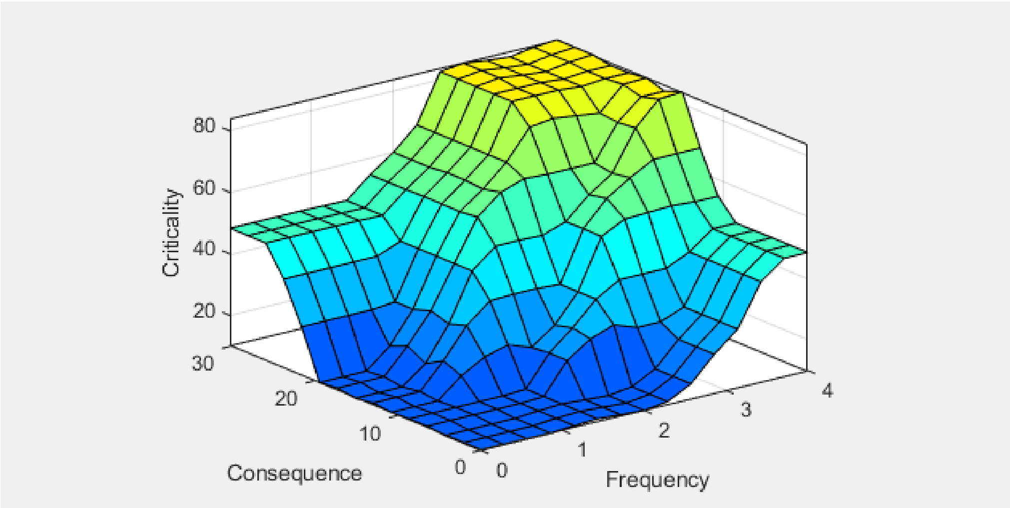


Figure 6. 5 Output risk surface envelop (Mamdani) for two Fuzzy inputs: frequency and consequences

An examination of the plot of criticalities' surface over the possible combinations of the input variables (Frequency and Consequences) shows consistency of the rule base used for the criticality assessment. Furthermore, Figure 5 reveals no evidence of abrupt changes in the output variable (criticality) for small changes to the input variables range.

A rule view and an example calculation of criticality value for a MoOSTs task is shown in Figure 6.6. The calculation has been performed for a MoOSTs task with Frequency of 2 and Consequence of 14. The Criticality value estimated by the FIS is 41.5 and the corresponding linguistic value is EC (using the MFs in Figure 4). Comparison of criticality values obtained from the traditional criticality assessment and Fuzzy criticality output was performed after recording each numerical output and linguistic value against individual MoOSTs task.

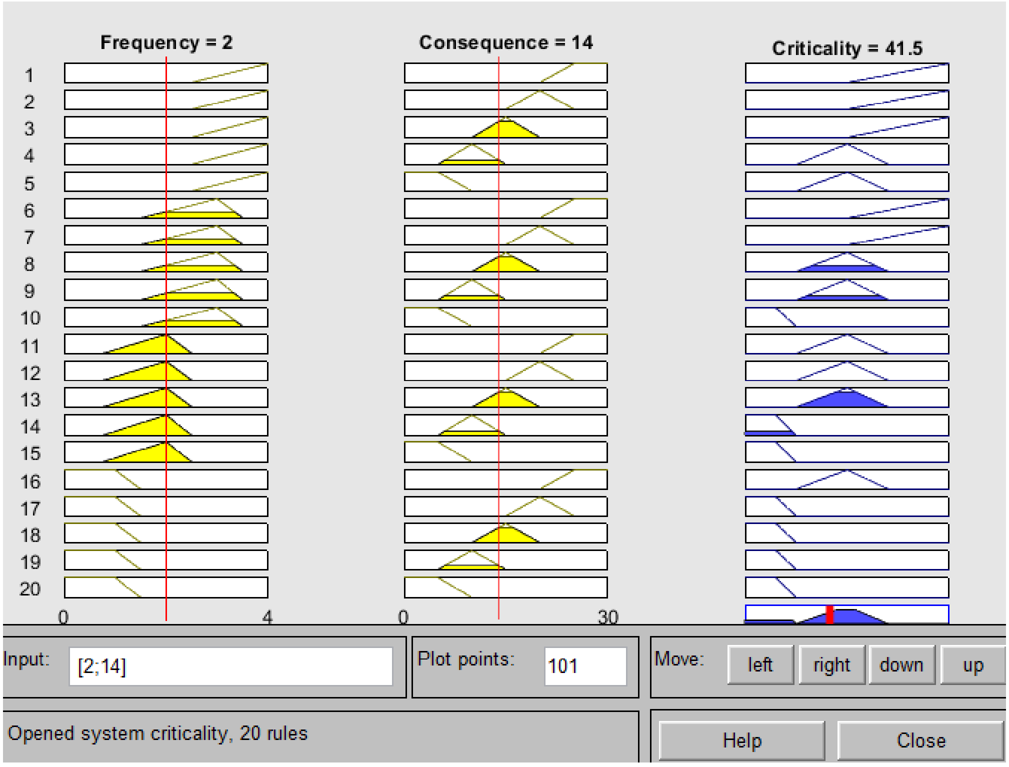


Figure 6. 6 Rule view and calculation of criticality

### 6.3.4. Practical consideration using a case example

Having established the criticality values from the traditional criticality assessment method and Fuzzy criticality ranking system this portion of the study will aim to demonstrate the practicality of earlier postulations using real-life MoOSTs data. The case example is a cement manufacturing plant with appreciable MoOSTs frequencies, (typically two cycles per year per RKS). Justification for selecting the cement industry is because it provided a good balance between capital intensiveness and high MoOSTs frequencies. The cement manufacturing process is characterised by large, complex and closely connected physical industrial assets (PIAs), especially the RKS. According to Yunusa-Kaltungo et al [58] a significant number of process plants, including cement manufacturing, depend heavily on RKS for achievement of their manufacturing objectives. In a comprehensive description of a typical RKS provided by [58], [263], RKS was described as a calcinatory device that facilitated chemical or physical transformation by subjecting materials (mainly limestone, alumina, iron ore and silica) to extremely high temperatures (also known as pyro-processing) for production of clinker (main ingredient for cement manufacturing). The critical function of the RKS ensures its associated performances in continuous production plant operations is achieved by performing MoOSTs.

## 6.4. Results and Discussion

In total, 325 tasks were obtained from the 5-year MoOSTs tasks lists. Based on their Fuzzy criticality numbers, 105 of these tasks were classified as either extremely critical or critical, while the remaining 220 were classified as semi-critical. Based on the criticality numbers following implementation of the traditional qualitative method, 96 tasks were classified as extremely critical and critical, while 229 were classified as semi-critical. Six similar MoOSTs tasks were classified as extremely critical based on both Fuzzy and traditional criticality number ranges.

The numbers of MoOSTs tasks assigned linguistic levels of EC and C were 8.5% higher (a difference of 9 tasks) based on their Fuzzy criticality numbers (105 tasks) compared to those allocated similar linguistic levels of EC and C based on the traditional criticality approach (96 tasks). Moreover, further analysis of these nine tasks reveals that some of these tasks had high-frequency numbers (this study applies an inverse logic for describing task frequency owing to the rarity of these tasks). The difference in results could be attributed to the approach adopted by the two methods; for instance, Fuzzy logic takes into account imprecision often associated with the qualitative ranking of frequency and consequences data.

Therefore, because the combinations of these 9 tasks revealed either a high frequency, low consequences and/or low frequency, high consequences as well as exceeded the boundaries of semi-criticality based on Fuzzy criticality numbers, the total number of MoOSTs tasks selected for considerations were 105 in total. Table 6.8 shows the comparison between the values derived from the traditional and fuzzy logic method.

Table 6. 8 Comparison of traditional and Fuzzy criticality numbers to MoOSTs tasks

| **Allocation of traditional criticality numbers to MoOSTs tasks** | | | |
|---|---|---|---|
| Criticality number | No of MoOSTs task | Criticality level | Total |
| 28 | 3 | C | 89 critical MoOSTs task |
| 30 | 10 | C | |
| 32 | 70 | C | |
| 36 | 1 | C | |
| 40 | 5 | C | |
| 56 | 7 | EC | 7 extremely critical MoOSTs task |
| **Allocation of Fuzzy criticality numbers to MoOSTs tasks** | | | |
| Criticality number | No of MoOSTs task | Criticality level | Total |
| 30 | 4 | C | 98 critical MoOSTs task |
| 35.9 | 6 | C | |
| 41.5 | 1 | C | |
| 48 - 48.3 | 87 | C | |
| 75.4 | 7 | EC | 7 extremely critical MoOSTs task |

Based on these comparative analyses, Fuzzy attributes assisted in overcoming data uncertainty, which allowed the analysis to obtain Fuzzy values that were more precise in the ranking and classification of criticality. These values and their inputs provide extensive information for making first-hand decisions on the management of uncertainty. At a glance, MoOSTs tasks that are rarely performed can be identified; this is important because the possibility of missing out on critical skills associated with such tasks might be underestimated. The logic of inverse proportionality adopted for assigning values to MoOSTs tasks frequency has yielded an outcome that makes provisions for tasks that might be termed as non-critical based on their rarity of occurrences when using traditional task frequency assessments. Unlike other traditional approaches to assessing criticality in maintenance that concentrate on failure frequencies in order to identify “bad actors” among asset bases, a reoccurring challenge with MoOSTs is often the inability to predict and prepare for uncertainty due to unknown occurrences of unidentified tasks in the work schedule.

Likewise, it is possible to identify the maintenance cost from a combination of labour hierarchy, source of labour, number of labour requirements and task duration for performing an individual MoOSTs task. Just like most operational projects, MoOSTs are usually time-intensive because industrial plants are incurring heavy downtime costs in addition to spares and labour costs. Additionally, the large number of labour requirements, which exceed normal online routine maintenance and overt reliance on outsourced labours, can significantly increase MoOSTs costs if there are schedule overruns. This makes it imperative to identify all factors that contribute to the mathematical relationship of $C_{av}$ and establish a mechanism for predicting future endeavours, a vital element of knowledge management. Additional information that can be obtained from Table 6.6 is the combination of multi-disciplinary requirements to perform individual MoOSTs tasks, the hierarchy of the disciplines, and their source (internal, external or combination of both). In fact, it is believed that previous studies on MoOSTs have dedicated little interest to quantifying the level of importance for unquantifiable factors, such as the hierarchy of labour and source of labour. Hence, the approach adopted by the expert panel, by hierarchizing these two factors and allocating judgements of importance using AHP.

Furthermore, by linking ORI to task duration, consequences of failure from not performing MoOSTs tasks to achieve pre-determined outcomes is analysed thoroughly because tasks, which require longer durations for completion of maintenance activities, would cause longer disruptions and delay the plant from coming on-stream. For instance, a major criterion for performing MoOSTs is to maintain desired operational and production levels. Consequently, equipped with such holistic parametric information on factors that contribute to criticality, it is possible for schedulers, planners and safety experts etc., to predict the workflow pattern, identify bottlenecks and effectively plan to reduce accidents and hazards during MoOSTs.

Table 6.9 is a review of the data containing 105 selected maintenance activities, which provides numerical values of F, C and $C_{av}$ for the traditional method as well as Fuzzy criticality numbers and multidisciplinary requirements.

Table 6. 9 Traditional and fuzzy criticality numbers of MoOSTs task

| No. | Breakdown of MoOSTs Tasks | F | C | Cav no | Fuzzy no | Cav level | Labour discipline |
|---|---|---|---|---|---|---|---|
| 1 | Amendment of leakage at the burner pipe due to fine coal pressuring at air pipe | 3 | 8 | 24 | 35.9 | C | Mechanical fitter and welder |
| 2 | Anchoring of burner pipe exposed portion | 4 | 8 | 32 | 48.1 | C | Mechanical fitter and welder |
| 3 | Assembling of crusher rotor onto new shaft | 4 | 8 | 32 | 48.1 | C | Mechanical fitter and welder |
| 4 | Back filter bottom screw No.1 - 10 drive chains cleaning | 4 | 7 | 28 | 48.1 | C | Mechanical fitter |
| 5 | Capping of cracked shell portion (Inside of the kiln) | 4 | 14 | 56 | 75.4 | EC | Mechanical fitter |
| 6 | Capping of cracked shell portion (outside of the kiln) | 4 | 14 | 56 | 75.4 | EC | Mechanical fitter |
| 7 | Casting of stage 4 riser duct area | 4 | 14 | 56 | 75.4 | EC | Mechanical casting |
| 8 | Connections of main drive motor left and right hand side rotor cables | 4 | 8 | 32 | 48.1 | C | Automation and electrical |
| 9 | Connections of main drive cooling fan motor power cable | 4 | 8 | 32 | 48.1 | C | Automation and electrical |
| 10 | Connections of main drive motor 3.3KV power cables | 4 | 8 | 32 | 48.1 | C | Automation and electrical |
| 11 | Connections of main drive motor control cables | 4 | 8 | 32 | 48.1 | C | Automation and electrical |
| 12 | Connections of main drive tacho cables | 4 | 8 | 32 | 48.1 | C | Automation and electrical |
| 13 | Cut off lining plate out of inspection door @ stage 4 | 4 | 10 | 40 | 48.3 | C | Mechanical fitter |
| 14 | Cutting of new holes (6off) for the blaster stainless steel pipes | 4 | 8 | 32 | 48.1 | C | Mechanical welder |
| 15 | Cutting of platforms channels, plate & hand rails pipes @ DA17 Dampers areas | 4 | 14 | 56 | 75.4 | EC | Fabricator and welder |
| 16 | Cutting of stainless steel pipe (6") | 4 | 8 | 32 | 48.1 | C | Mechanical fitter |
| 17 | Dismantling of burner pipe oil gun jacket tube | 4 | 8 | 32 | 48.1 | C | Mechanical fitter |
| 18 | Dismantling of canter-lever scaffold at preheater stage 4 | 4 | 8 | 32 | 48.1 | C | Scaffolding |
| 19 | Dismantling of scaffold @ Gepol fan inlet & outlet duct expansion joint area | 4 | 8 | 32 | 48.1 | C | Scaffolding |
| 20 | Dismantling of scaffold @ LIW hopper internal | 4 | 8 | 32 | 48.1 | C | Scaffolding |
| 21 | Dismantling of scaffold @ LIW plug valve area | 4 | 8 | 32 | 48.1 | C | Scaffolding |
| 22 | Dismantling of scaffolding at backend up-riser area | 4 | 8 | 32 | 48.1 | C | Scaffolding |
| 23 | Dismantling of the backend blaster ((8off) | 4 | 8 | 32 | 48.1 | C | Mechanical fitter |
| 24 | Erect scaffolding @ Niro inlet & outlet duct inspection door areas | 2 | 14 | 28 | 41.5 | C | Scaffolding |
| 25 | Extraction gate power cylinder servicing 4off | 4 | 8 | 32 | 48.1 | C | Electrical |
| 26 | Extraction gate power cylinder removed to workshop 4off | 4 | 8 | 32 | 48.1 | C | Electrical |
| 27 | Filling & hard-facing of clinker crusher hammers (old ones) | 3 | 10 | 30 | 48.1 | C | Mechanical welder |
| 28 | Fix and tighten main drive DE top/bottom covers | 4 | 8 | 32 | 48.1 | C | Mechanical technician |
| 29 | Fix and tighten main drive NDE top/bottom covers | 4 | 8 | 32 | 48.1 | C | Mechanical technician |
| 30 | Fix back roofing support frame vertical and horizontal | 4 | 8 | 32 | 48.1 | C | Mechanical |
| 31 | Form-work | 4 | 8 | 32 | 48.1 | C | Mechanical |
| 32 | Free and service all cyclone flaps. | 4 | 8 | 32 | 48.1 | C | Mechanical fitter |
| 33 | General house and conveying of all scrap metals/pipes | 4 | 7 | 28 | 48.1 | C | Fabricator and welder |
| 34 | Gepol fan lubrication flow switch serving and test | 4 | 8 | 32 | 48.1 | C | Automation and electrical |
| 35 | Gepol fan motor cooling unit servicing | 4 | 8 | 32 | 48.1 | C | Automation and electrical |

| Nos. | Breakdown of MoOSTs activities | F | C | Cav no | Fuzzy no | Cav level | Labour discipline |
|---|---|---|---|---|---|---|---|
| 36 | Inspection of Niro screw journals & hanger bearings | 4 | 8 | 32 | 48.1 | C | Mechanical inspection |
| 37 | Inspection of preheater cyclone top | 4 | 8 | 32 | 48.1 | C | Mechanical inspection |
| 38 | Inspection of preheater stage 4 wall bricks | 4 | 8 | 32 | 48.1 | C | Production/Operations |
| 39 | Inspection of stage 1, 2,3 & 4 Wall linings / hanging material | 4 | 8 | 32 | 48.3 | C | Production/Operations |
| 40 | Install air-lensing holes at preheater cyclone flap areas | 4 | 8 | 32 | 48.1 | C | Mechanical fitter |
| 41 | Backend Gas Analyser | 2 | 12 | 24 | 30 | C | Instrumentation |
| 42 | Bolts and align main drive motor with coupling | 4 | 8 | 32 | 48.3 | C | Automation and electrical |
| 43 | Bottom screws top & bottom covers seal ropes to be replaced | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 44 | Casting of backend inlet segment plate | 4 | 10 | 40 | 48.3 | C | Mechanical casting |
| 43 | Casting of backend inlet trays (4 off) | 4 | 10 | 40 | 48.3 | C | Mechanical casting |
| 46 | Cleaning of the girth gear teeth | 4 | 9 | 36 | 48.3 | C | Mechanical fitter |
| 47 | Clinker crusher internal & external inspection / wear rate measurement | 3 | 10 | 30 | 48.3 | C | Mechanical inspection |
| 48 | Clinker crusher old hammers to be removed | 4 | 10 | 40 | 48.3 | C | Mechanical fitter and welder |
| 49 | Clinker crusher top cover to be boxed up | 3 | 10 | 30 | 48.3 | C | Mechanical fitter |
| 50 | Convey and Fix L.I.W LHS & RHS plug valve compartment unit | 4 | 8 | 32 | 48.1 | C | Electrical |
| 51 | Convey and fix to position L.I.W LHS & RHS plug valve compartment | 4 | 8 | 32 | 48.1 | C | Electrical |
| 52 | Cooler 1 replacement of 10 bad mild steel lifters, 10 cast lifters & 2 slotted | 4 | 8 | 32 | 48.1 | C | Mechanical fitter and welder |
| 53 | Cooler 1 replacement of 3 cast lifters | 3 | 8 | 24 | 35.9 | C | Mechanical fitter and welder |
| 54 | Cooler 1 replacement of 6 worn cone breakers, 10 cast lifters & 9 slotted | 3 | 8 | 24 | 35.9 | C | Mechanical fitter and welder |
| 55 | Cooler 2 replacement of 5 straight edge mild steel lifters, 10 cast lifters & | 3 | 8 | 24 | 35.9 | C | Mechanical fitter and welder |
| 56 | Cooler 2 replacement of 6 slotted hub lifters | 4 | 8 | 32 | 35.9 | C | Mechanical fitter and welder |
| 57 | Couple back / alignment of kiln main drive motor coupling | 4 | 8 | 32 | 48.3 | C | Mechanical |
| 58 | Couple back kiln girth gear pinion coupling | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 59 | Crusher rotor back to site / assembled | 4 | 8 | 32 | 48.3 | C | Mechanical fitter and welder |
| 60 | Cyclone 1 - 4 thermocouple probe servicing in the workshop | 4 | 8 | 32 | 48.3 | C | Instrumentation |
| 61 | Cyclone 1 -4 thermocouple probe to disconnect and remove to workshop | 4 | 8 | 32 | 48.3 | C | Instrumentation |
| 62 | Cyclone 1- 4 thermocouple probe to fix and connect back | 4 | 8 | 32 | 48.3 | C | Electrical |
| 63 | Cyclone 4 bottom flange leakage | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 64 | Cyclone 4 gas outlet expansion joint loose bolt. | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 65 | Erect scaffold / installation of tarpaulin @ station 1 - 3 for cracks welding work | 4 | 8 | 32 | 48.1 | C | Scaffolding |
| 66 | Erect scaffold / installation of tarpaulin @ station 2 for kiln shell cracks welding wo | 3 | 10 | 30 | 48.3 | C | Scaffolding |
| 67 | Erect scaffold @ backend power cylinder area | 3 | 10 | 30 | 48.3 | C | Scaffolding |
| 68 | Erect scaffold @ Gepol fan inlet & outlet duct expansion joint area | 3 | 10 | 30 | 48.3 | C | Scaffolding |
| 69 | Erect scaffold Gepol fan damper bearings area | 4 | 8 | 32 | 48.3 | C | Scaffolding |
| 70 | Erect scaffold @ girth gear area | 4 | 8 | 32 | 48.3 | C | Scaffolding |

| Nos. | Breakdown of MoOSTs activities | F | C | Cav | Fuzzy no | Cav level | Labour discipline |
|---|---|---|---|---|---|---|---|
| 71 | Erect scaffold Gepol fan damper power cylinder area | 4 | 8 | 32 | 48.3 | C | Scaffolding |
| 72 | Erection of mini scaffold for removal of damper power cylinder | 3 | 10 | 30 | 48.3 | C | Scaffolding |
| 73 | Erection of scaffold (canter-lever) at preheater state 4 internal | 3 | 10 | 30 | 48.3 | C | Scaffolding |
| 74 | Erection of scaffold / blanking at kiln backend internal | 4 | 8 | 32 | 48.1 | C | Scaffolding |
| 75 | Filling / Machining of clinker crusher rotor shaft bearing seat | 4 | 14 | 56 | 75.4 | EC | Mechanical fitter and welder |
| 76 | Fix back clinker crusher drive belt & guard | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 77 | Girth gear heat shield bolts retightening / replacement of heat shields | 4 | 14 | 56 | 75.4 | EC | Mechanical |
| 78 | Goudging of cracked shell at station 2 | 2 | 12 | 24 | 30 | C | Expert gouder |
| 79 | Goudging of cracked shell from inside of the kiln | 2 | 12 | 24 | 30 | C | Expert gouder |
| 80 | Gouging / grinding of station 1- 3 cracked tyre pads | 4 | 8 | 32 | 48.1 | C | Mechanical steel work |
| 81 | Greasing of girth gear pinion coupling | 4 | 8 | 32 | 48.1 | C | Method lubrication |
| 82 | Greasing of station 1& 2 thruster block | 4 | 8 | 32 | 48.1 | C | Method lubrication |
| 83 | Grinding of the girth gear mushroomed teeth | 2 | 12 | 24 | 30 | C | Mechanical fitter |
| 84 | Hard-facing of clinker crusher rotor and casing liners / patching of punctured | 3 | 10 | 30 | 48.3 | C | Mechanical fitter and welder |
| 85 | Hydraulic unit lube tank oil to be drain and tank to be clean | 4 | 8 | 32 | 48.1 | C | Mechanical fitter |
| 86 | Inspect & record clearance of bag filter fan bearings (DE & NDE) | 4 | 8 | 32 | 48.3 | C | Mechanical inspection |
| 87 | Inspect Gepol fan outlet duct expansion joint canvas (need scaffolding). | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 88 | Inspection / cleaning of air chamber | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 89 | Inspection / replacement of damage diaphragms | 4 | 8 | 32 | 48.3 | C | Mechanical fitter |
| 90 | Inspection / validation of preheater stage 4 canter-lever scaffold | 4 | 8 | 32 | 48.3 | C | Pyro-processing |
| 91 | Inspection / validation of scaffold | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 92 | Inspection / validation of scaffold @ fan damper power cylinder area | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 93 | Inspection / validation of scaffold @ girth gear area | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 94 | Inspection / validation of scaffold @ LIW plug valve area | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 95 | Inspection / validation of scaffold @ LIW screw area | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 96 | Inspection / validation of scaffold @ Niro chamber Internal | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 97 | Inspection / validation of scaffold @ Niro inlet & outlet duct inspection door | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 98 | Inspection / validation of scaffold + platform | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 99 | Inspection / validation of scaffold at station 1 & 2 | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 100 | Inspection /lidation of backend scaffold & blank | 4 | 8 | 32 | 48.3 | C | Safety inspection |
| 101 | Inspection of bag filter fan base vibration isolator | 4 | 8 | 32 | 48.3 | C | Mechanical inspection |
| 102 | Installation of backend floating rings segments (12off) | 4 | 10 | 40 | 48.3 | C | Mechanical fitter and welder |
| 103 | Kiln Turn with No.1 - 9 cooler @ TDC | 4 | 14 | 56 | 75.4 | EC | Production/Operations |
| 104 | Re-build platform No.1 - 9 elbow area | 3 | 8 | 24 | 35.9 | C | Scaffolding |
| 105 | Ultra-Sonic crack detection test of station 1 - 4 right roller shafts | 3 | 10 | 30 | 48.3 | C | Ultra sonic crack detection |

### 6.4.1. MoOSTs activities coding system

It is imperative to codify knowledge associated with a MoOSTs task owing to their rarity, which in turn enhances organizational knowledge preservation, talent, management and succession planning. The codification sequence adopted relevant distinct maintenance terminologies from [263]. For instance, maintenance task levels by categorisation (Level 1 to 5) referred to in this study are as follows;

- Level 1 is characterised by simple actions carried out with minimal training;
- Level 2 is characterised by basic actions carried out by qualified personnel's using detailed procedures;
- Level 3 is characterised by complex actions carried out by technical personnel's using detailed procedures;
- Level 4 is characterised by actions which imply know-how of a technique carried out by specialised technical personnel and;
- Level 5 is characterised by actions, which imply knowledge held by the manufacturer or a specialised company with industrial logistics support equipment.

The codification framework established in this study is shown in Figure 6.7.

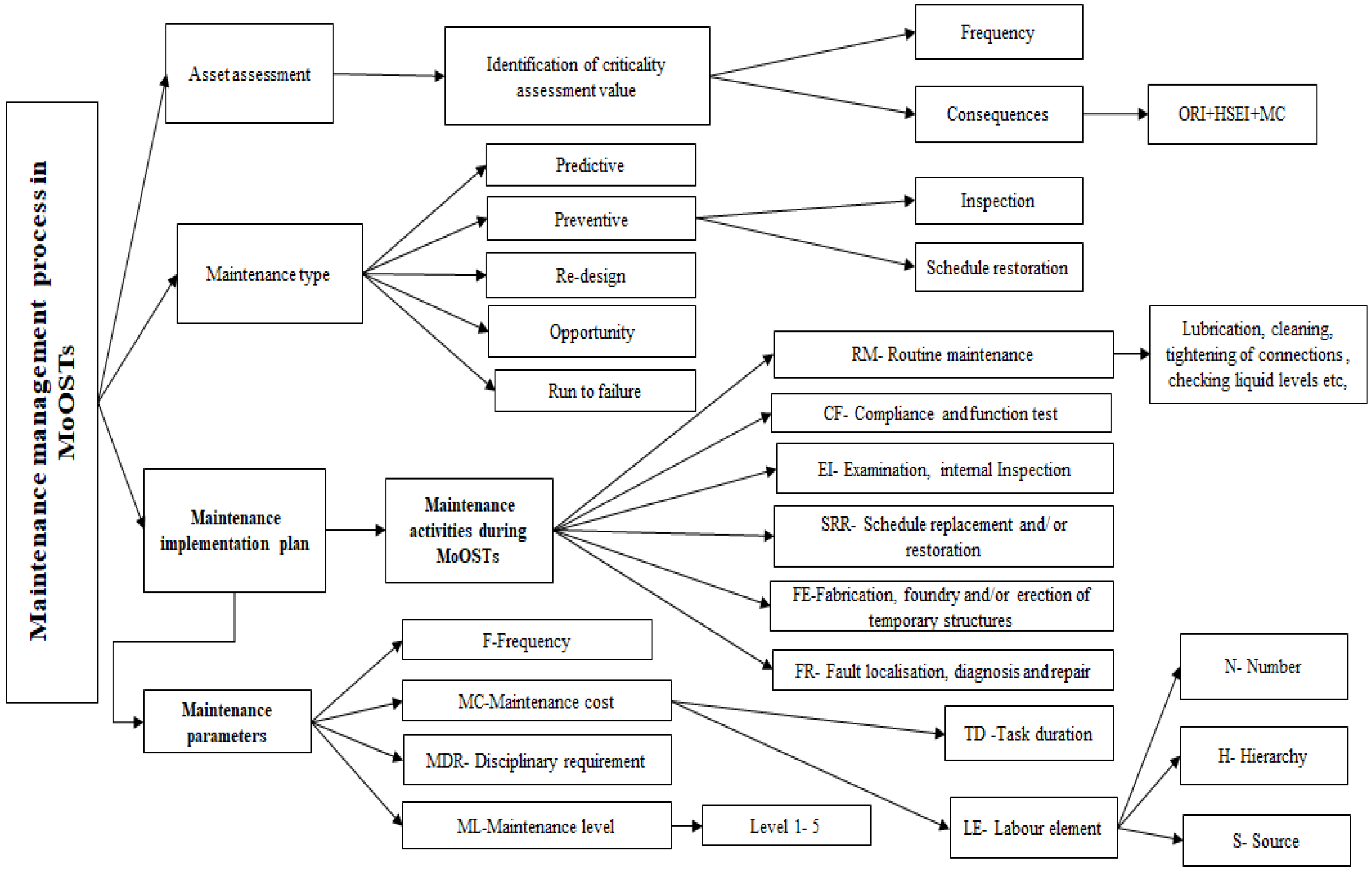


Figure 6. 7 Codification process of MoOSTs activities

An illustration utilising the codification process of Figure 6.7 is demonstrated for an extremely critical (EC) MoOSTs task activity identified from Table 6.9: Casting of stage 4 riser duct.

FE–F1- N5- H/T –S/E-TD/24.4-Mech.—L 3

FE—Fabrication, foundry, and erection of temporary structures.

F1—frequency is once within five years period

N5—number of labours is five

H/T—hierarchy of labour skill is technician

S/E—source of labour value is external

TD/24.4—task duration would require 24.4 h

Mech.—disciplinary requirement is Mechanical

L 3—maintenance level of activity is level 3

The maintenance level is a useful piece of information because it can provide valuable insights into the types of maintenance knowledge (explicit and tacit) that a person performing a maintenance task (knowledge holder) may be able to capture.

## 6.5. Chapter Summary

This study has applied a combination of the traditional qualitative criticality method and Fuzzy logic system for assessing the criticality of a MoOSTs task. The decision-making process to obtain parametric numerical ranges for both methods was provided by experts in cement manufacturing processes. Unlike the traditional method that makes use of a qualitative criticality matrix, the Fuzzy method generates a three-dimensional surface envelope diagram output for the computation of criticality values and examines the degree of changes to membership functions. Furthermore, although the total number of rules utilised for constructing the FIS, 20 rules in total, corresponds to the rows and columns of the qualitative criticality matrix, it is a more improved method because it allows the ranking of criticality alternatives based on a unified measure. Based on a comparison of the results from both methods, it can be ascertained that Fuzzy attributes assisted in overcoming data uncertainty, which allowed the analysis to obtain Fuzzy values that were more precise in the ranking and classification of criticality.

Practical application of the two methods using a case example has led to the identification and codification of critical maintenance activities performed during MoOSTs. The detailed procedures for converting large amounts of data into information that are reusable. Thus, an important element of knowledge transfer and management was depicted. Furthermore, because maintenance objectives are achieved by prioritising many competing variables, a multi-criteria decision approach that combines a quantitative method (Fuzzy logic) and a qualitative method (expert opinions), as well as historical data, was deemed suitable for assessing task criticality.

A unique contribution of this research is to demonstrate how practical assessments of MoOSTs tasks criticality and codification systems can be utilised as inputs for developing suitable web-based knowledge management, acquisition and transfer framework that would complement existing industry-based solutions.

Traditional approaches of criticality assessments in MoOSTs, as well as other maintenance endeavours, are usually focused on assessing failure modes and criticality of assets and systems utilised in operations but not on actual tasks. Hence, there is vast knowledge on predicting asset failures and prognosis but not enough on assessing individual maintenance activities and processes for performing maintenance. Through this research, valuable insights on identifying critical MoOSTs tasks through a combination of the mathematical relationships of specific parameters and factors that are unique to MoOSTs and contribute to an overall execution of the task was demonstrated. The imprecise reasoning of decision-makers involved in setting boundaries/classifications and levels was smoothed by means of a Fuzzy logic system. Valuable insights of contributing parameters to uncertainties in MoOSTs were obtained; for instance, task frequency could provide decision-makers with crucial information about the task with remote possibilities of occurrence, thereby reducing uncertainties associated with performing such rare MoOSTs tasks in future.

Furthermore, an understanding of the average labour size is quite crucial for workload smoothening and labour management. Information about the manpower composition of MoOSTs organization is useful for planning the communication channels via which information and experience can be adequately captured. Therefore, labour size analysis as a factor under the consequence parameter is relevant to this study and analysed as such in Table 6.4 and Table 6.6. The codification strategies implemented in this study enhances the acquisition and subsequent transfer of tacit knowledge. This is because tacit knowledge is rooted in an individual's actions, experiences as well as emotions. Identifying who the knowledge holder is (discipline requirements) and adequate information on the tasks they are required to perform can be instrumental in facilitating the capture of expertise embedded within the minds of experts, based on their historical involvements with MoOSTs. The classification of MoOSTs knowledge made possible by the codification strategy can potentially be used to develop a web-based platform, a means by which future knowledge can be automatically captured. The scope of this work was limited to developing a criticality ranking of maintenance activities by combining two main maintenance parameters, frequency, and consequence during MoOSTs activities using a high frequency shutdown case study, cement-manufacturing plant.

However, it would be useful to examine the dynamics existing between high-frequency and low-frequency tasks in different industries, where the execution of MoOSTs sometimes takes up to three to five years intervals, and other factors such as where accessibility is low. Despite this perceived limitation, it is envisaged that the approach presented here still offers useful contributions, especially because cement manufacturing is often considered the upstream segment of one of the largest business sectors (i.e., mining and construction). Future works are planned to undertake further planned studies from other industries with much lower frequency tasks to compare the robustness of the approach.

# 7 DEVELOPMENT OF AN INTERACTIVE WEB-BASED KNOWLEDGE MANAGEMENT PLATFORM FOR MAJOR MAINTENANCE ACTIVITIES: CASE STUDY OF CEMENT MANUFACTURING SYSTEMS.

**Reformatted Version of this paper:**

Paper title: **Development of an Interactive Web-Based Knowledge Management Platform for Major Maintenance Activities: Case Study of Cement Manufacturing Systems.**

Authors: **Lilian Iheukwumere-Esotu and Akilu Yunusa-kaltungo**

Submitted to: **Journal of Production Planning and Control**

## ABSTRACT

The expectations of organizations within industries that perform MoOSTs when adopting knowledge management (KM) as part of their organizational process is to improve the ability to execute their core business functions in the process of capturing as well as retaining expert knowledge. However, existing literature is limited in MoOSTs-specific knowledge management systems (KMS) that can assist with experience capturing, collation and transfer. This is partly due to the challenges associated with the ability to design, implement and test the efficacy of such KMS in practice, owing to many intricately identified knowledge barriers within MoOSTs. In this study, through a cement manufacturing process case study, a proposal depicting a typical KM process within MoOSTs is presented along with an early stage interactive web-based KMS for MoOSTs. The developed KMS is termed MoOSTs knowledge platform (MoOSTsKP). The MoOSTsKP was evaluated by experts for its fluidity, resilience, and adaptability to different MoOSTs organizations, which are crucial elements for integration into existing MoOSTs information technology (IT) systems. The MoOSTsKP is identified with having many benefits including, prioritization of MoOSTs activities based on an in-built criticality assessment model, which enables MoOSTs experts to instantly identify priority

knowledge classes and in turn rationalise the workload associated with knowledge capture and reuse. Based on expert opinions, it is envisaged that the proposed MoOSTsKP would contribute immensely towards the alleviation of challenges associated with incessant loss of vital expertise.

*Keywords*: Expertise; Knowledge management platform; major overhauls; outages; shutdowns; turnarounds; knowledge management platform.

## 7.1. Introduction

Knowledge management (KM) is critical for organizations seeking to remain relevant and achieve their desired goals within current dynamic business environments [36]. The maintenance and production functions often form the heart of most industrial operations but the institutionalisation of adequate control mechanisms would never be possible without KM. In today's knowledge-based economy, maintenance organizations can not underestimate the importance of effective KM, because the two fields of knowledge and maintenance are key to obtaining competitive advantage [32], [34]. Major overhauls, outages, shutdowns and outages (MoOSTs), are vital maintenance endeavours within technology intensive industries such as petrochemical plants, oil and natural gas refineries, cement plants, chemical plants, electric generating plants, among others [16]. The need to effectively manage MoOSTs based on recent technology is crucial because, predictive and prescriptive maintenance of production systems are assessed to be some of the most important application areas of industrial analytics within the next three years [29]. However, requirements for MoOSTs is unprecedented because it is characterised by complexities and intricate elements including; large number of workforce, voluminous tasks to be accomplished, narrow window of opportunity for execution and uncertainties [16], [25].

Industry 4.0 has revolutionized industrial processes through the integration of information and communication technologies (ICTs) to facilitate the handling of large amounts of data, as well as their transfer and interpretation, because previous means for storing information are restrictive for handling large data, owning to interconnectivities that exist between the global systems of organizations [59], [188]. This rapid advancement of ICTs as well as integration of maintenance process within knowledge management 4.0

framework implies that, most organizations are racing against time to develop and retain the required competencies [30], [31]. In practice, competency challenges are dire because human operators are key resources within MoOSTs organizations, since such workers are aware of specific technological processes [32], [33]. Furthermore, knowledge (especially tacit knowledge) is considered one of the main intangible assets within MoOSTs organizations, owning to its profound impacts on MoOSTs safety, work quality, process control and cost-effectiveness. However, MoOSTs organizations are still challenged by the approach to implement for adopting representative knowledge management systems (KMS), especially with regards to the ability to identify, categorize, represent, store and reuse important knowledge types [40]. This is because there are different types of knowledge but organizations are predisposed to KMS suitable for managing explicit knowledge. However, tacit knowledge which consists of personal relationships, practical experiences and shared values has been universally described as the most complex knowledge type to implement, due to difficulties associated with identifying, categorising, capturing and reusing being under emphasised [40].

An important task for any KMS within MoOSTs is to identify the different sources of knowledge because MoOSTs specific knowledge comes from many different sources, with the majority originating from contractors, subcontractors and regulators that are considered external to the organization [264]. This implies that the ability to capture the knowledge from external sources who are heavily involved in MoOSTs within an organization is at risk. [38]. Managing knowledge often proves challenging because the knowledge possessed by an individual is personal to them, often the greater part of that knowledge is tacit based and when that individual leave, such valuable knowledge, skills and experiences are lost [38], [39]. Notwithstanding the KM aspect of MoOSTs (especially the capture and transfer of tacit knowledge ) is a narrowly understood and explored area within MoOSTs discipline, owing to fundamental difficulties associated with capturing engineering knowledge from people that are based on temporary activities [40].

As such, very limited studies are available on tacit knowledge capture and experience transfer frameworks within MoOSTs, which further strengthens the need for the development of mechanisms that would ease the process of knowledge capture and transfer during MoOSTs.

The overarching aim of this paper is to discuss as well as practically demonstrate the implantation of a KMS for a typical MoOSTs-intensive industry termed as a “MoOSTs knowledge platform” (MoOSTsKP) and it’s validation by industry experts. Prior to this, the paper discusses the difference between MoOSTs and engineering, procurement and construction (EPC) projects to put forward reasons for the need of a formalized KMS specific to MoOSTs. Furthermore, trends and limitations of existing knowledge activities and technology utilized in project-based activities are also discussed to reinforce the need for the study direction. The research philosophy on which the platform is built especially the integration of a criticality assessment element for MoOSTs activities, based on pre-defined parameters is also presented. This crucial pre-assessment element eases the identification of the most critical MoOSTs activities, which often serves as a precursor to critical knowledge elements. Considering that MoOSTs are as applied as they are theoretical, a focus group discussion session was held with maintenance experts from the industry to validate the approaches proposed in this study, especially the structure and functionality of the MoOSTsKP.

## 7.2. Literature Review

The review of literatures presented in this section, is the basis upon which the theoretical underpinning of this study is developed from. It begins with efforts that clearly distinguishes MoOSTs from EPC projects, and the need for specific KM strategies to accommodate pertinent requirements for both phenomenon. KM processes, KM technological applications as well as KM trends within MoOSTs are some other relevant topics discussed under this section.

### 7.2.1 Distinguishing MoOSTs from engineering, procurement and construction (EPC) projects

Although professionals within industries where MoOSTs are prevalent often have an understanding of what they are, albeit, there are misconceptions about the differences between MoOSTs and typical EPC projects. MoOSTs have inherent multi-facetted dimensions comprising of three broad elements of engineering, business, and management [11], [14]. MoOSTs is characterised by large organizations, with greater dependencies on internal and external multidisciplinary workforce due to large volume of activities to be undertaken within short time frames. Typically MoOSTs setting often depict arrays of interrelated activities that are executed at the same time, within workspaces and at different levels of the plant [16]. This in turn leads to increased possibilities of uncertainties due to emergent jobs, accidents, human errors, and scope variations which further compounds and makes KM challenging. Furthermore, these difference are far more conspicuous during the execution phase of MoOSTs, owing to the inherent risks associated with the discovery of unplanned/emergent activities and the significantly diminished error margins [7].

However, the execution phase provides immense opportunity for MoOSTs organizations to capture knowledge and foster expertise, due to the enormity of in-house staff and contract workers performing large-scale as well as complex maintenance activities at an instance [13]. MoOSTs activities within each phase generates "big data" which is about large volume of data that require new ways to process them, which is an integral part of KM for both MoOSTs and typical EPC projects. According to [265], traditional databases often used within MoOSTs and EPCs cannot adequately manage the challenges related to collecting, storing, processing or analysing big data sets in real-time. Although [266] has described how big data can be utilised for potentially evaluating projects. Unfortunately, issues related to MoOSTs KM are not limited to but include, heavy workload; lack of an encompassing web based knowledge platform; unavailability of a systematic way to implement KM; and the lack of dedicated time and/or resources for knowledge capture [22], [264], [267]. There is no doubt that typical MoOSTs organizations are often considered to be labour and knowledge– intensive, due to the volume of activities they perform and information they possess [206]. However, studies have emphasised the need to enhance the smartness of KM, especially tacit knowledge through investments in information technology systems.

### 7.2.2. Knowledge management processes and technology

A typical knowledge management processes comprises of knowledge identification, creation/acquisition, storage/retention, transfer and utilization respectively [182]. Knowledge identification refers to what type of knowledge is available, who the knowledge holder is, and why the knowledge is relevant. Knowledge identification is aligned with creation/acquisition. For instance, [268] stated that in project environments it was often difficult to delineate between knowledge identification and creation/acquisition due to how they are interchanged. However, [182] stated that knowledge identification is more aligned with existing knowledge, while knowledge creation seeks new knowledge. Knowledge storage/retention involves the activities of documenting and codifying knowledge that has been identified in the organization in order to stem the loss of knowledge that might arise as a result of infrequent use of knowledge, staff retirement and/or departures [268]. Knowledge transfer refers to the measures and procedures for transferring and sharing knowledge. Bell [172] states that knowledge transfer techniques can be broadly categorised as either 'capture' or 'share'. Lastly, knowledge utilization refers to the procedures of applying knowledge identification to create value.

The importance of knowledge transfer is most relevant perhaps in specific industries that depend on project related activities that are capital-intensive such as MoOSTs which makes it imperative to initiate live as well as post execution capture of critical knowledge-based activities [206]. The high importance of knowledge transfer in MoOSTs can be attributed to many reasons such as, high staff turnover and reassignment of people after projects which leads to insufficient capture and evaluation of knowledge in post project evaluations [269]. Therefore, there is a need to focus on the two elements of KM activities, "capture" and "transfer" as well as type of MoOSTs knowledge in this case expertise (tacit knowledge). 'Capture' can be expressed as a means of acquiring know-how in such a way that it can be reused [206]. Conversely, knowledge 'sharing' is described by [172] to include, means by which people or group of people share their know-how in an organization. Know-how can be referred to as procedural or tacit knowledge, which is most associated with a type of knowledge that is rooted in experiences and actions.

Tacit knowledge can be broadly categorised into two classes- cognitive (mental nodes, beliefs and viewpoints) and technical, which relates to know-how, craft and skill in specific contexts [270]–[272]. Knowledge capture techniques commonly used in other project based industries include, before action reviews, peer assists, mentoring, post project reviews, communities of practices, forum and training [60] and post mortem reporting as a major strategy for capturing knowledge in MoOSTs [25].

Conversely knowledge transfer technology include, groupware, documentation of knowledge, expert directory, and customised knowledge-based systems [62], [169]. Knowledge acquisition is one of the major challenges of the KMS development, this is due to difficulties associated with acquiring the knowledge of experts and the representation of this knowledge in the most appropriate and applicable form [273]. Therefore, it is imperative to investigate how knowledge activities are implemented, limitations of existing KMS and possible mitigations of such limitations [274].

### 7.2.3. Trends and limitations of existing knowledge management systems

In project management, KM is essentially concerned with reusing existing knowledge and creating new knowledge [267]. To achieve this, a KMS that can facilitate organizational learning, competence building through lessons learned from previous projects as well as historical organizational information are well established [267]. However, the limitations of commonly used data and information management approaches that exist in construction projects while configured to facilitate data transfer, do not effectively handle big data or enable real time collaborations between users [62]. Most importantly, these information management approaches are not well developed to capture and process the intrinsic value of expert knowledge, thus do not proffer solutions to existing KM challenges within the industry.

According to [62], the failures of KM solutions within industries involved in projects could be due to lack of the mechanisms, processes, more specifically databases that provide formal structure and/or strategic systems for knowledge transfer. This is perhaps why increasing numbers of recent studies on information management are exploring emerging real-time interfaces such as those offered by cyber-physical systems (CPS). In the literature, CPS are described as systems that can measure and process large information up to the level that makes it usable for the end users [29], [189], [190]. The development of a CPS structure capable of implementing big data predictive analytics for transformation of data to information and then to knowledgeable action such as those advocated by internet of things (IOT), cloud computing, and immersive technologies (including virtual, augmented and mixed realities), to improve decision-making is one of the many challenges facing MoOSTs organizations [30], [189], [191].

In the quest for solutions [60] had presented a methodology for the live capture and reuse of project knowledge in construction industry which comprised of a web-based KMS, an integrated work-flow system and a project knowledge manager as administrator, so as to enable real-time capturing of knowledge from ongoing construction projects. In another study [275] presented a study that focused on generating lessons learned information in the object elements provided in a building information model (BIM) within the development of a proposed knowledge management of building maintenance (KMoBM) framework with three distinct modules (case browsing, case retrieving, and case module retention) that were used to achieve the predefined requirements. However, most of the KMS within existing literature were developed to mostly manage explicit knowledge, which is far less complex to handle when compared to tacit knowledge [61].

To bridge the gap, [40] presented a study that focused on a new tacit knowledge technique called Manufacturing tAcit Knowledge Motion Sequence Elicitation (MAKMOSE) to explore the uses of motion sequence to trace the routes that workers and robots make when performing complex manufacturing activities. Similarly, [274] paper presented a technical mapping and tacit knowledge elicitation, in the form of production rules for use in manufacturing processes, which was referred to as Methodology for Acquisition of Tacit Knowledge (MACTAK) whereby two KMS were constructed. Another study by [264] was a conceptual framework to formalise the knowledge capturing process within construction companies to develop a web-based system, knowledge platform for contractors (KPfC), which mainly facilitated knowledge capture and reuse. Recently, [276] developed a knowledge-based management system (KBMS) designed to forecast duration and productivity of construction operations data from historical projects data. While studies on the development and management of KMS for EPC projects have immensely progressed beyond what is obtainable in MoOSTs, significant gaps still exists.

Some of the gap highlighted by [267] were, that while studies in construction focused on developing effective KM processes [60], [269] there was scarcity of studies on appropriate KM tools and techniques [277] to effectively deliver encompassing KM solutions. In addition, the lack of consideration of specific barriers for implementing KM within projects and how they can be overcome implies the work done so far do not offer options for implementing effective KM solutions within MoOSTs [264]. In response, it implies that although there are well documented KMS and KM technologies for capturing knowledge and reuse in construction projects, the gaps mentioned as well as the need for a specific KMS for MoOSTs given its inherent characteristics and differences from EPC projects would not permit adoption of existing EPC projects KMS without substantial reframing efforts.

Thus, the contribution of this study to the body of knowledge is the development of an integrated web-based platform for managing knowledge in MoOSTs. The integrated web based knowledge platform is developed with many objectives, chiefly to foster knowledge retention so as to overcome the usual issues of time constraints that often limit knowledge capture due to chaotic MoOSTs environment; and to enable integration with other existing MoOSTs management IT systems. Hence, the proposed MoOSTsKP is simplified, concise, and cheap, it can be readily deployed and accessed with hand held or desktop systems without necessarily creating additional workload. This is because a reoccurring barrier with the implementation and operation of KMS in general, is the additional costs of setting up a new KMS. A KMS that significantly increases the workload of the knowledge users would lead to ineffectiveness [60].

To significantly reduce this workload, a mechanism for assessing the criticality of MoOSTs activities was incorporated. Once the critical activities are identified and ranked, the crucial elements are then captured and preloaded to simplify the active capture of relevant MoOSTs knowledge. The long-term strategy for the MoOSTs KMS is for use in planning and decision-making processes by MoOSTs professionals. Knowledge extracted for reuse in every MoOSTs event may be utilised in the planning process to reduce the impact of uncertainty which would in turn guide the decision-making process of professionals.

## 7.3. Architecture of the Proposed MoOSTs Knowledge Platform Architecture

The proposed platform “MoOSTs Knowledge Platform” (MoOSTsKP) comprises of four important sections- the MoOSTs information library, the knowledge case retention template for capturing the details of specific MoOSTs activities, knowledge capture template and knowledge approval template. These sections are accessible through an interactive web-based and user friendly interface that can be readily configured on different platforms, including web-based and desktop applications. The appropriateness of web-based technology for this study was established based on extensive literature, particularly owning to its significant reduced costs and immense flexibility [32], [61], [267]. For instance, installation and local data management costs are minimal, as well as the retrieval of data irrespective of user's geographical location and device type. Figure 7.1 depicts the Homepage of the proposed MoOSTsKP.

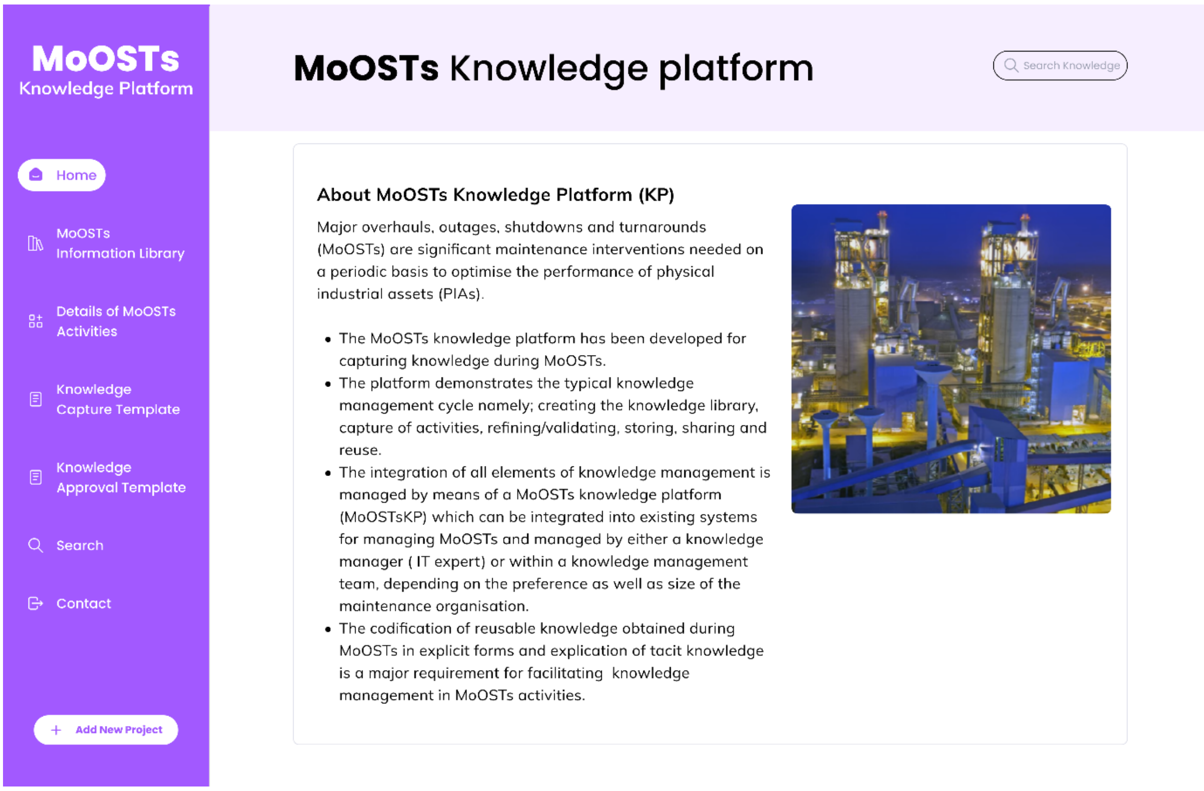


Figure 7. 1 Homepage of the proposed MoOSTsKP

The MoOSTsKP has been developed to facilitate knowledge capture and transfer during MoOSTs. There are six elements within the MoOSTsKP that holistically integrate all elements of the KM process, namely; creating the knowledge library, capture of activities, refining/approval, storing, sharing and reuse. It is suggested that the platform can be managed by either a MoOSTs knowledge manager (MoOSTsKM), well versed with ICT or within a MoOSTs knowledge management team (MoOSTsKMT), depending on the preference as well as size of the maintenance organization. The configuration of the platform process covers the following;

i. The knowledge bank containing preloaded critical MoOSTs activities and relevant parameters;
ii. The source of knowledge (“knowledge holders”);
iii. The interval at which knowledge holders should enter new knowledge into the platform;
iv. The selected knowledge approver;
v. The Knowledge approval process; and
vi. The knowledge acceptance requirements and maintenance.

The overall outlook of the process flow of activities within the MoOSTsKP is shown in Figure 7.2

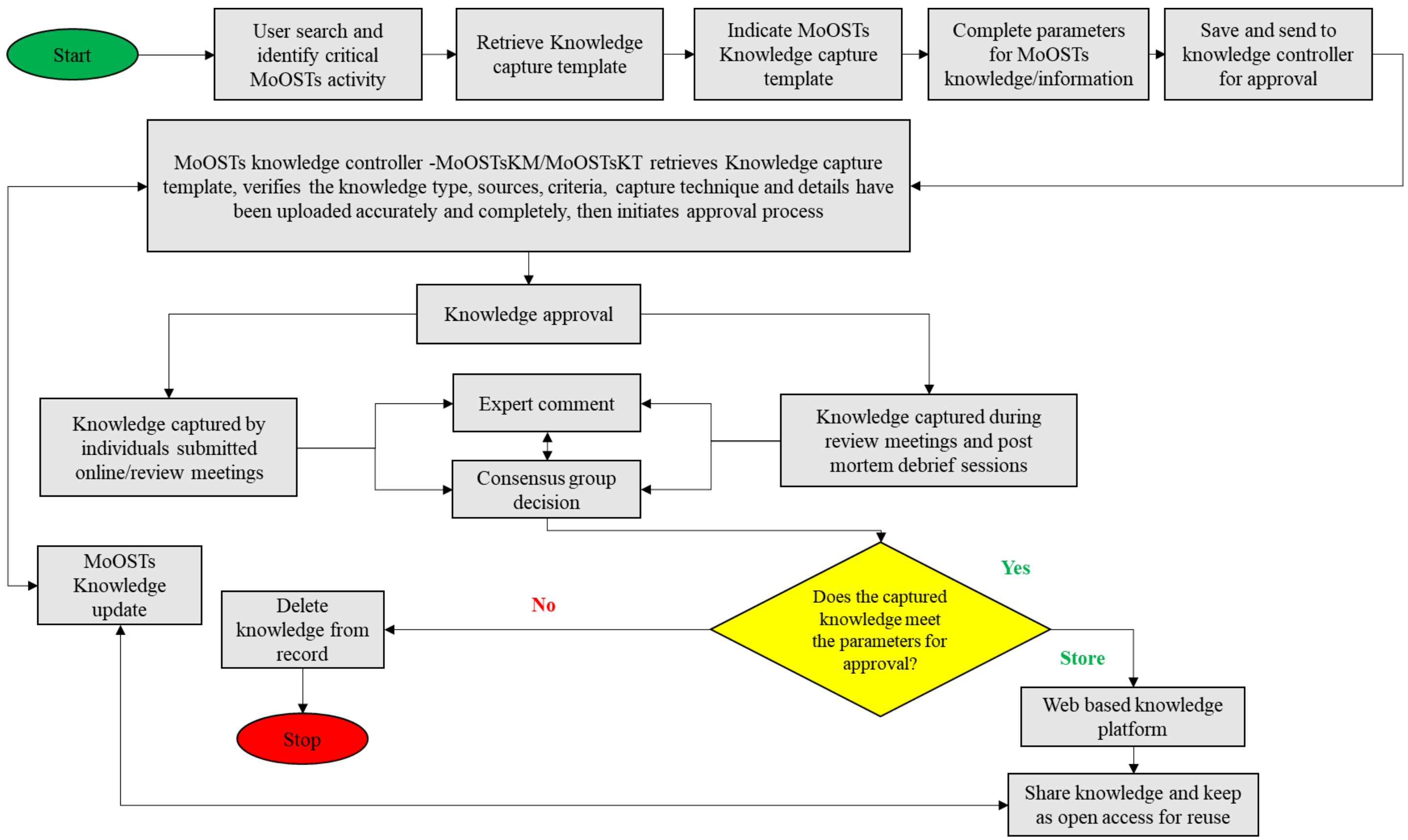


Figure 7. 2 Overall outlook of the process flow of activities within the MoOSTsKP

### 7.3.1. Philosophy for identifying critical MoOSTs activities

The prioritisation of maintenance activities based on the well-established criticality assessment procedure has proven to be for vital decision-making [82], [93], [117]. A mathematical relationship shown in Eqn. (7.1) to determine the criticality of MoOSTs activities and enable assignment of linguistic description ranging from extremely critical (EC), critical (Cr) and semi critical (SC) was developed in [21]. Within the MoOSTsKP, the critically assessed MoOSTs tasks are either pre-populated in the knowledge case retention template or developed using same logic.

$$C_{av} = F \times C = F \times [ORI + HSEI + MC] \tag{7.1}$$

Where $C_{av}$ is criticality assessment values; F is task frequency parameter; C is consequence; ORI is operational reliability impact; HSEI is health, safety and environment impact; and MC is maintenance costs (including size of labour, hierarchy of labour, source of labour and task duration).

The rationale for integrating the MoOSTs activities criticality assessment model obtained by means of a mathematical relationship is to overcome the hesitancy associated with the implementation of prior KMS. Therefore, the current arrangement identifies the most critical MoOSTs activities, so that relevant information that can assist capture are preloaded into the platform, thereby reducing workload. In the event of emergent and/or discovery activities, (which is a common occurrence in MoOSTs) [8] the MoOSTsKP allows users to input the relevant details required to generate a task criticality value and linguistic description, it is within the remit of its users to then decide if they want to proceed with the knowledge capture of that particular task

### 7.3.2. MoOSTs information library

The details of the parameters used to develop the criticality assessment model obtained through the mathematical relationship are contained within the MoOSTs information library template. Furthermore, the MoOSTs information library contains the knowledge case description for each MoOSTs activity and it is divided into category one and category two parameter respectively. The MoOSTs information library is shown in Figure 7.3.

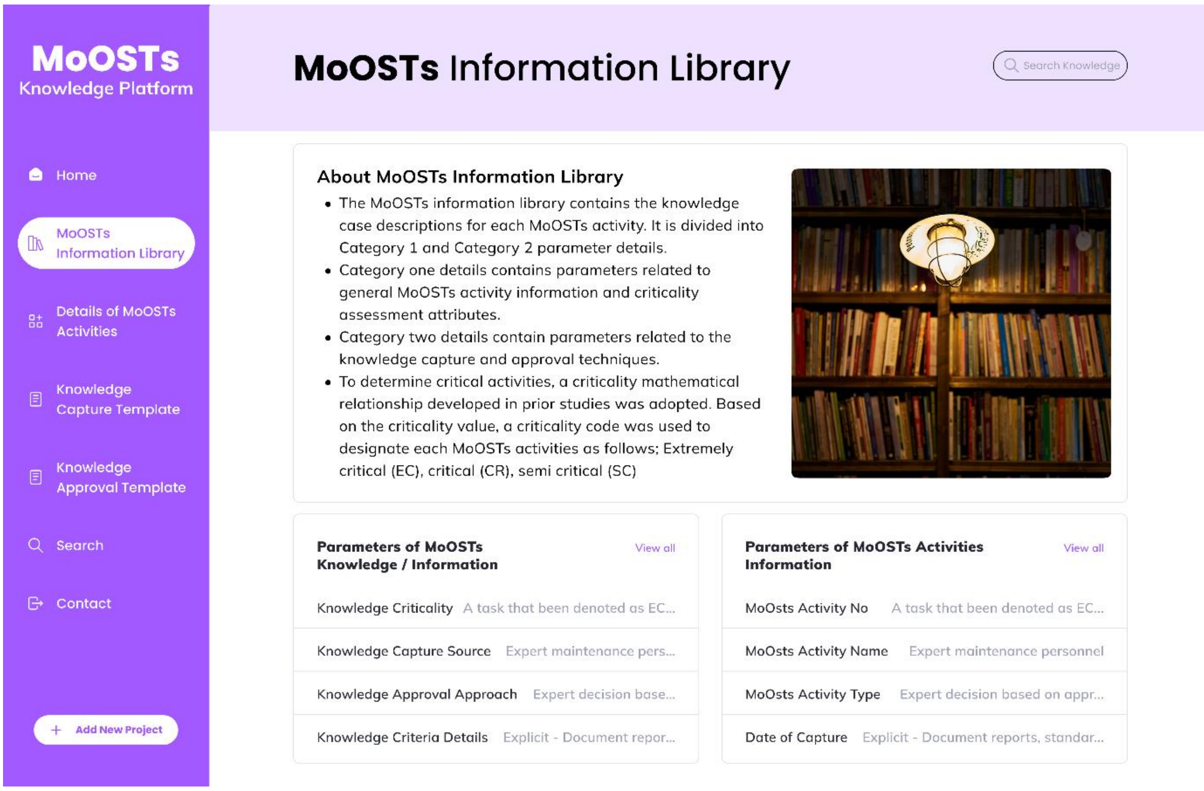


Figure 7. 3 Image of the MoOSTs information library

The MoOSTs attributes contained within category one, as shown in Figure 7.4 include the following elements, MoOSTs activity/work order number, activity/work order name, consequence value, frequency value, number of specialist labour used to perform a task, duration of technical work order hrs for executing an individual MoOSTs activity, source of labour, criticality value and linguistic descriptions related to general MoOSTs activity attributes that informed the development of the mathematical relationship for criticality assessment.

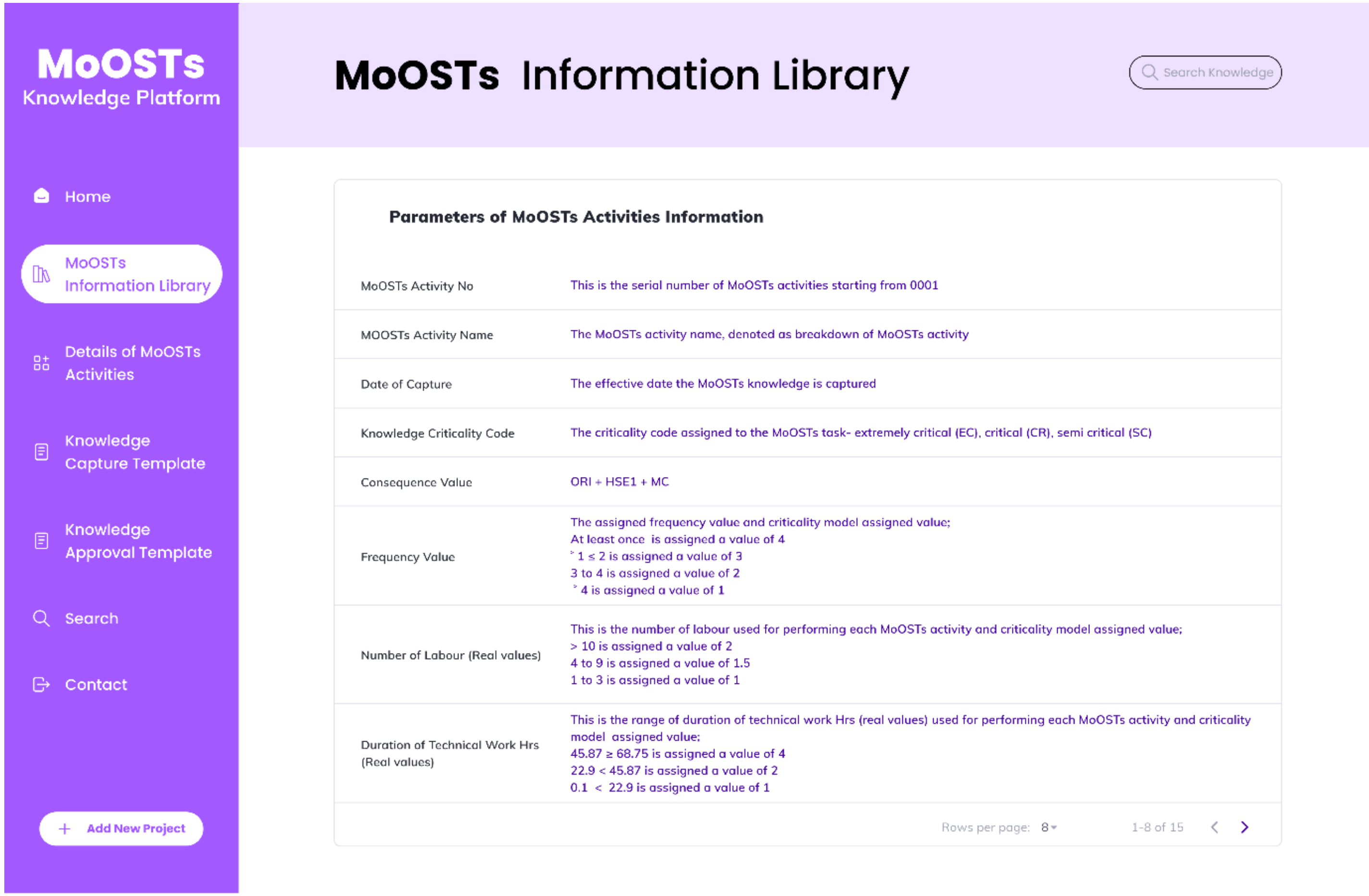


Figure 7. 4 Details of MoOSTs activities for criticality analysis under category one

The list of attributes contained within category two as shown in Figure 7.5, they are related to specific KM attributes. This list contains the descriptions of the knowledge criticality rankings (from high to low), knowledge type in this case (either tacit or explicit), knowledge capture source (which could be from these three sources; live capture from professionals executing the MoOSTs activity, during debrief sessions upon termination of the MoOSTs cycle or during daily meetings when MoOSTs is ongoing), knowledge criteria details (mostly related to the required capture information based on knowledge type), knowledge approval approach (which could be either by an individual expert or consensus decision from a group), knowledge capture technique (for instance, protocol analysis, critical decision list etc.,), knowledge value (to ascertain a score on a Likert scale from 1 to 5 based on 3 elements of knowledge value) and final approval decision (this could be either an approve or reject).

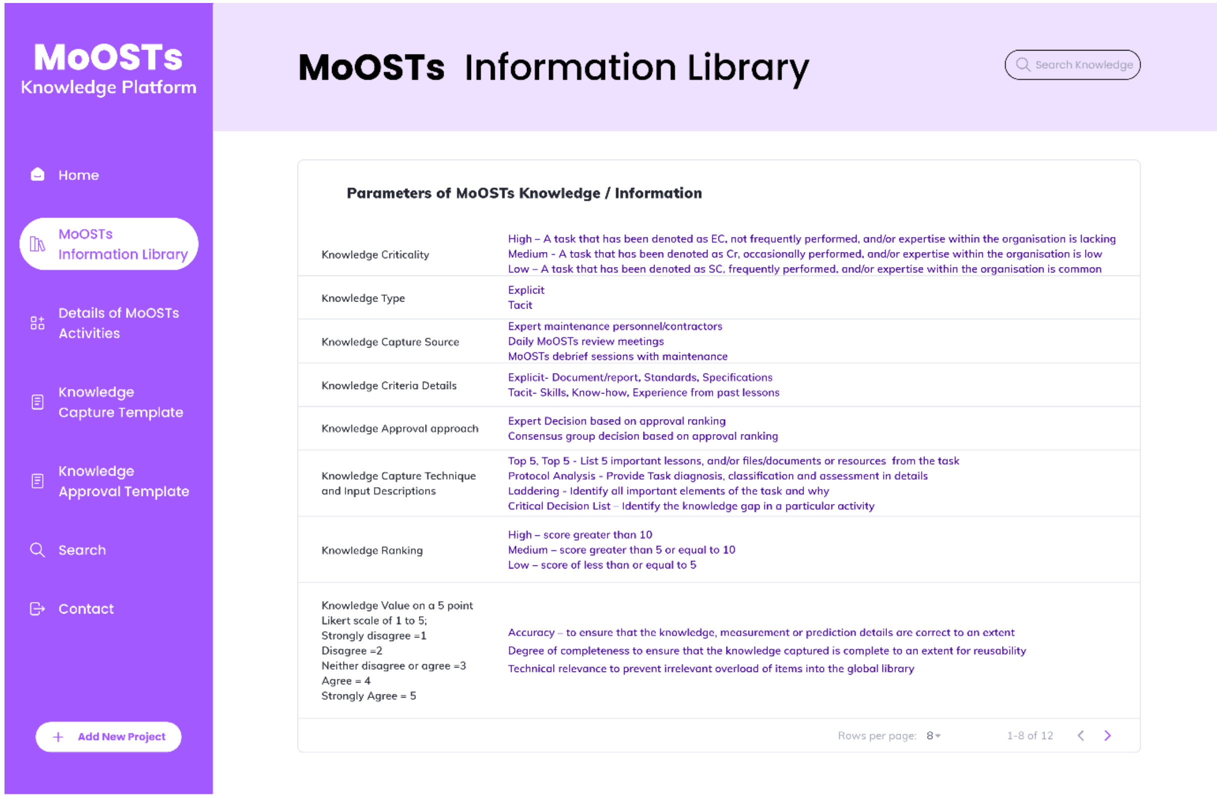


Figure 7. 5 Descriptions of KM attributes considered for each MoOSTs activity under category two

In order to foster better visualisations of the operation of the proposed MoOSTsKP, the subsequent section provides a practical description of its development based on information from the MoOSTs activities of the most vital station of a cement manufacturing process - rotary kiln system (RKS).

## 7.4. Practical Demonstration of the Development Case study of Building an Interactive Web-based MoOSTs Knowledge Management Platform for a Cement Manufacturing Plant

The case example is a cement manufacturing process with appreciable MoOSTs frequencies, (typically two cycles per year per process line). The emphasis of this practical demonstration is the rotary kiln process stage, due to its criticality to the entire cement manufacturing process. The justification for selecting the cement industry is based on the premise that it provides a good balance between capital-intensiveness and high MoOSTs frequencies, thereby allowing for the generation of spates of MoOSTs activities and their corresponding knowledge. The cement manufacturing process is characterised by large, complex and closely connected physical industrial assets (PIAs), especially the RKS. According to [58], a significant number of process plants, including cement manufacturing, depend heavily on RKS for achievement of their manufacturing objectives. In a comprehensive description of a typical RKS provided by [58], [192], RKS was described as a calcinatory device that facilitated chemical and/or physical transformation by subjecting materials (mainly limestone, alumina, iron ore and silica) to extremely high temperatures (also known as pyro-processing) for production of clinker (main ingredient for cement manufacturing). The critical function of the RKS necessitates its continuous operations (i.e. 24 hours a day and 7 days a week) for the entire life span of the refractory bricks that lines its internals (usually 180 days for the burning zone), after which its stopped for routine ensures MoOSTs activities.

### 7.4.1. The process for creating critical MoOSTs activities based on the work order

The process starts with uploading critical MoOSTs tasks and their parameters into the MoOSTs information library (i.e MoOSTs activities that have been classified as either EC OR C as criticality classifications of either extremely critical (EC) or critical (Cr). The detailed description of the methods adopted for the criticality ranking of MoOSTs tasks are already detailed in an earlier study by [21]. It is vital to note that not all critical MoOSTs tasks will be contained in the MoOSTs information library. Therefore, another crucial element within the MoOSTsKP is the "Add New project" function, which allows the knowledge controller (MoOSTsKM and/or MoOSTsKMT) to initiate the process of developing the MoOSTs activity requirements for emergent activities, as well as uploading such to the MoOSTsKP.

The requisite information and knowledge that are embedded within the MoOSTs information library are as follows:

a. Brief information on MoOSTs activities – These include a brief description of the MoOSTs activity performed; criticality score and/or code; start and completion dates; task frequency; number of labour used to achieve an individual task; hierarchy of specialised labour; source of labour (internal, external or combination); duration of technical support work in hours; and date by which knowledge is captured (which is included to address knowledge obsolescence); and
b. Health, safety and environment related information provided for performing MoOSTs activities. These might be related to information regarding the removal or dismantling of installed plant and equipment (e.g., any special arrangements for lifting such equipment), as well as assigned criticality values.

Figure 7.6 depicts the practical demonstration of generating critical MoOSTs activities based on the information contained within the MoOSTs activity /work order.

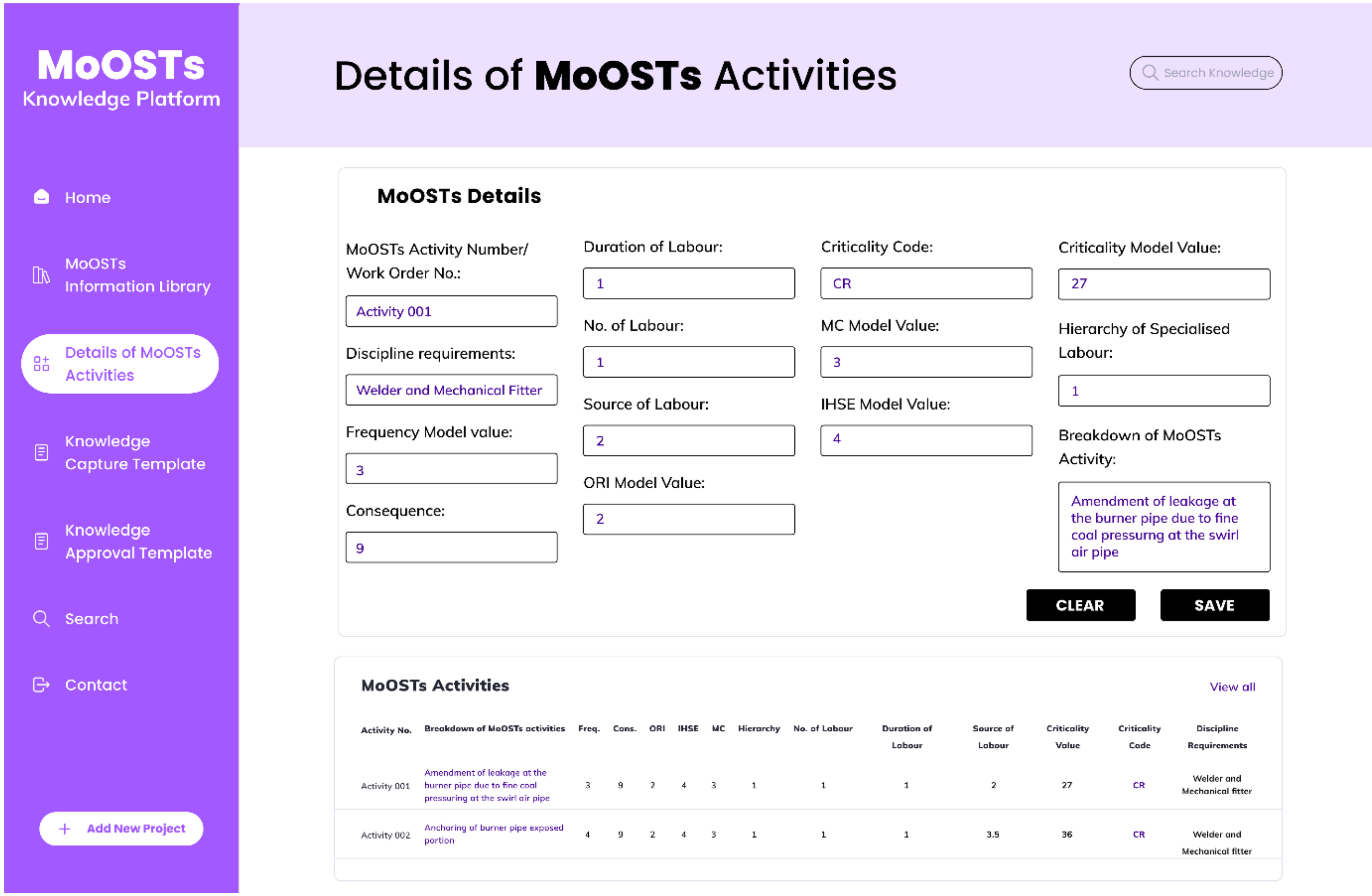


Figure 7. 6 Template for generating critical MoOSTs activities based on information contained within the work order

### 7.4.2. MoOSTs knowledge capture and collection

The knowledge capture and retention section of the platform, includes the manual retention of newly identified critical MoOSTs activities (knowledge cases) before the capture of relevant knowledge elements. The platform allow users to fill the template for creating and updating critical MoOSTs activities. For existing critical MoOSTs activities users retrieve directly stored knowledge cases with respect to individual MoOSTs activity that have been pre-uploaded. Subsequently, the knowledge capture template is then filled to create new knowledge case, which is then saved and sent for the necessary approval.
Upon creating the knowledge bank of critical MoOSTs activities, the subsequent stage is the capture and/ or collection, which can occur in three ways namely;

a. By expert maintenance personnel/contractor, a prompt at agreed intervals to specific personnel's to capture knowledge that they ascertain to be critical based on the MoOSTs activity criticality assessment value/code;
b. During the daily/weekly review meetings, critical activities which have been pre-embedded in the MoOSTsKP and or identified from newly discovered/emergent activities are also captured; and
c. Finally, capture can be undertaken during debrief sessions after completion of MoOSTs, which is typically when such capture exercises occur in traditional MoOSTs settings.

The knowledge capture and retention process within the MoOSTsKP is shown in Figure 7.7.

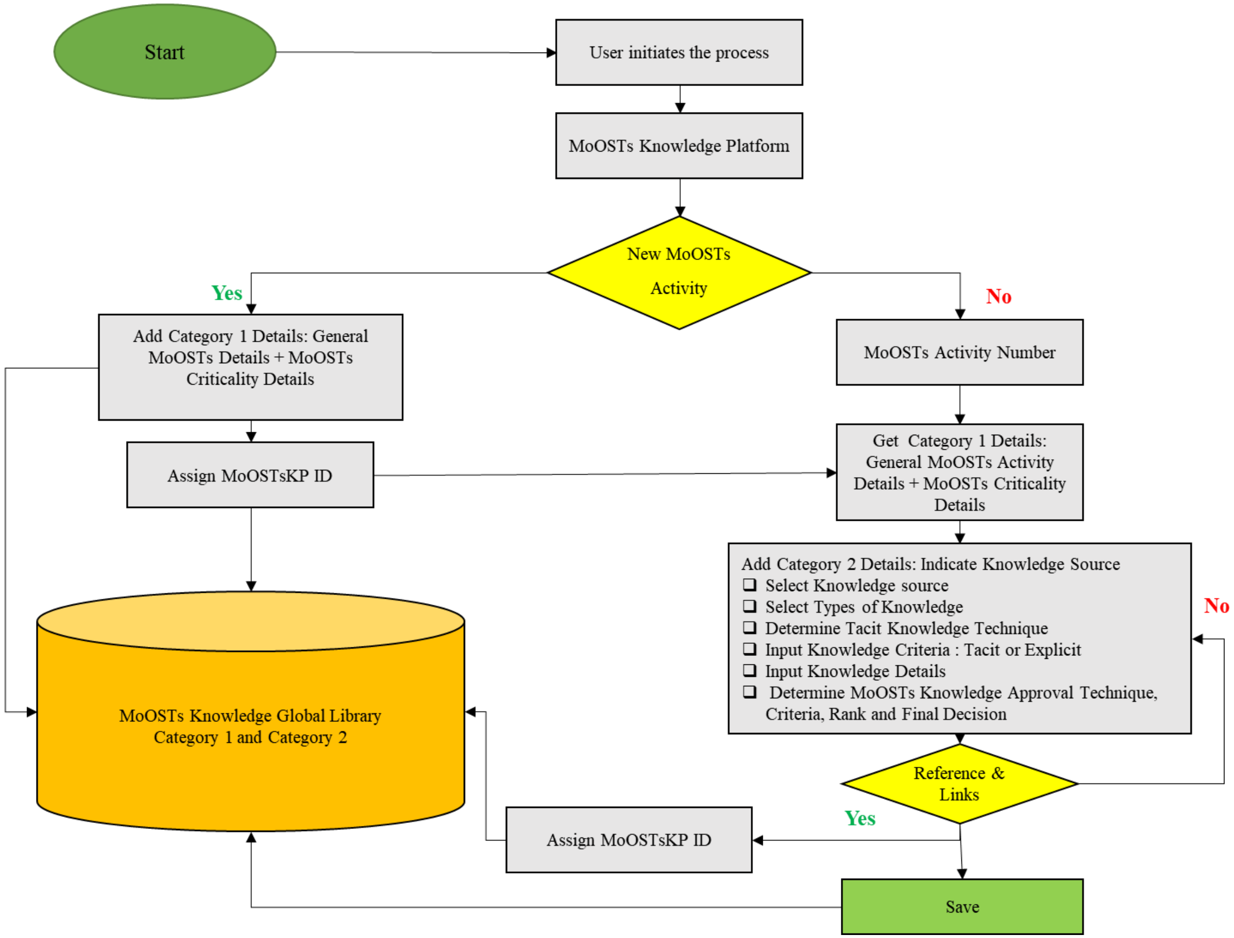


Figure 7. 7 Knowledge capture and retention process flow within the MoOSTsKP

The knowledge capture template contains requisite information and knowledge that needs to be captured from experienced practitioners (mainly maintenance staff and contractors) during and/or after MoOSTs to improve the learning process within the organization as follows:

a. The breakdown of MoOSTs activities and MoOSTs activity/Work order Number;
b. The date the knowledge was captured;
c. The knowledge sources, i.e was it captured by an expert maintenance personnel/contractor, captured from daily/weekly MoOSTs review meetings or captured from debrief sessions after completion of MoOSTs;
d. Type of knowledge captured i.e tacit or explicit. The type of tacit knowledge that can be captured would include, skills, process records, know-how, problem-solution, expert suggestions and innovation etc;
e. The knowledge capture technique used to support tacit knowledge capture by individuals within a group including, by means of critical decision template, protocol analysis, laddering, and semi structured interview template etc. On the other hand, explicit knowledge can be captured by uploading documents, reports, standards, specifications etc;
f. Short description of the knowledge captured and why it is deemed significant; and
g. Attachments and other evidences that can supplement knowledge entry.

The function of the template in Figure 7.8 is mainly to capture information and knowledge from any of the three knowledge sources highlighted during MoOSTs. Some of the details would already be pre-populated, including the MoOSTs activity details and MoOSTs criticality parameters. When an expert is assigned a task, the task code would indicate if it is a critical task and once the task is selected, the pre-populated information would automatically appear. However, in the event, of an unplanned and/or emergent work, the expert would alert the MoOSTsKM/MoOSTsKT in order to develop the knowledge capture template and then upload such into the MoOSTsKP so it can be retrieved during a MoOSTs activity execution.

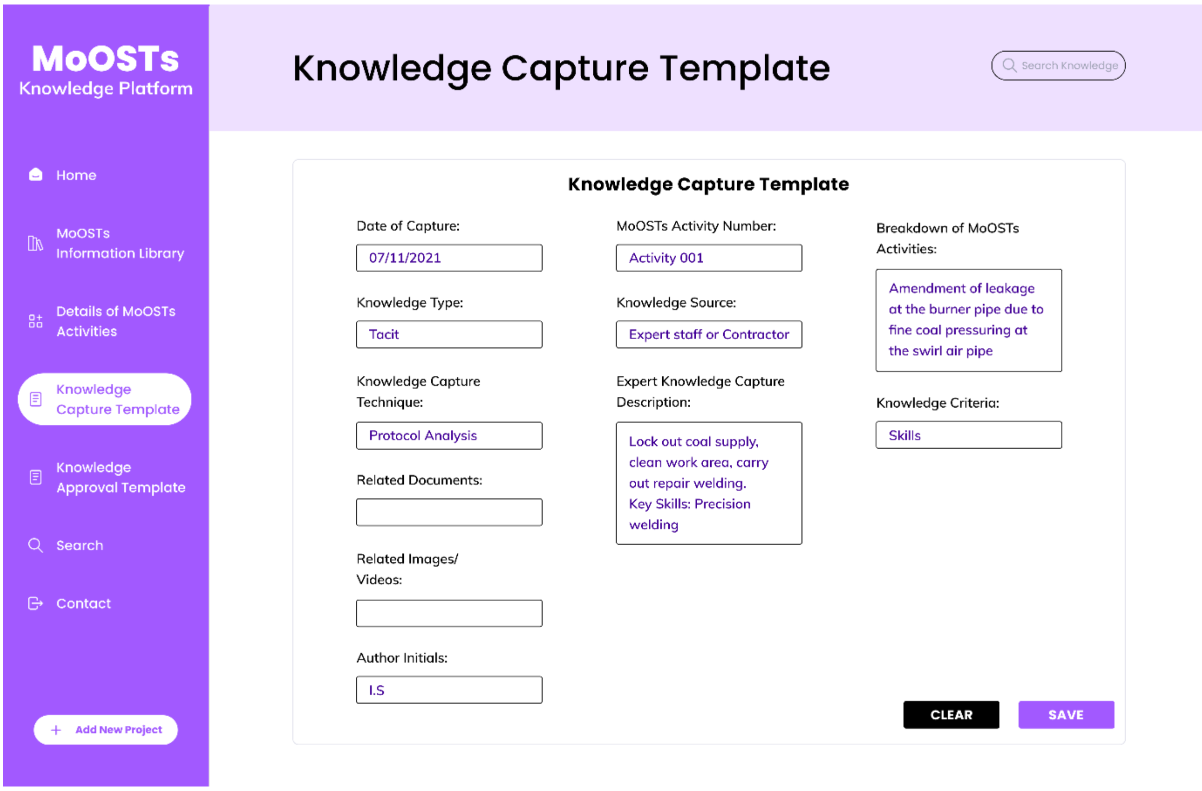


Figure 7. 8 Knowledge capture template for MoOSTs activities within the MoOSTsKP

Alternatively, unplanned and/or emergent work as well as routine activities which have been pre planned and deemed critical can be captured either during the MoOSTs daily/weekly review meetings depending on the peculiarities and level of details required. Further details on already captured MoOSTs activities can be added to existing documents during debrief sessions or post-mortem. The type of knowledge to be captured (i.e explicit, tacit or both) should be selected from the drop down menu. Following this should be the criteria of MoOSTs knowledge, which is also pre-populated as well as the relevant criteria selected. For instance for tacit knowledge the criteria of knowledge would include; skillsets, experience and technical know how. On the other hand, explicit knowledge criteria would include a relevant standard, code, regulatory requirement, equipment performance, basis for preliminary maintenance actions etc. Other relevant documents including reference drawings/diagrams can be uploaded via the reference and links section. Although the focus of the study is to capture tacit knowledge and codify it as depicted by the emphasis of the case example, it should however be noted that the ability to capture explicit knowledge is well within the premise of the proposed MoOSTsKP.

The tacit knowledge technique option within the template is designed in such a way that other validated tacit knowledge capturing within existing are applied [172]. Some of the critical consideration are as follows;

a. Top 5, Top 5 – List 5 important lessons, and/or files/documents or resources from the task
b. Protocol analysis – Provide task diagnosis, classification and assessment in details;
c. Laddering – Identify all important elements of the task and why; and
d. Critical decision list- Focus on a specific activity and identify the knowledge gap.

The next sequence after completing the capture of MoOSTs knowledge is the knowledge verification and approval process described in section 7.4.3.

### 7.4.3. MoOSTs Knowledge verification and approval process

The learning experiences captured either during and/or after MoOSTs are submitted for verification to ensure accuracy, completeness and ascertain the degree of technical relevancy by either an individual and/or group of people within the MoOSTs team. The dedicated staff or group assigned to this task could be either a MoOSTsKM or MoOSTsKT (including an IT expert if required) who then verifies and validates the knowledge that has been captured, sometimes vaguely. Potential add-on activities that may require initiation include digitization of any information received verbally in addition to the completed template, edit information (i.e add or delete details, comments and notes), prior to classifying all received knowledge and information accordingly. The subsequent action after the knowledge obtained from the three capture groups identified is to initiate approval. However, knowledge captured during MoOSTs review meetings and post mortem debrief sessions can be validated and improved upon concurrently during capture, unlike those captured by maintenance personnel/contractors.

The approval process involves assessments of knowledge against three parameters including, accuracy (i.e. all the knowledge being captured is credible and that the source can be identified); technical relevance; and completeness (i.e. all important sections of the document have been captured by the expert, to determine how well another user can use the information embedded in the knowledge profile to make informed decisions on future MoOSTs activities). Based on these parameters, a high, medium and low ranking system is adopted through either of the following means;

a. Consensus group decision based: an average of responses for or against can be determined; or
b. Expert comment.

Figure 7.9 depicts the knowledge approval process embedded within the MoOSTsKP.

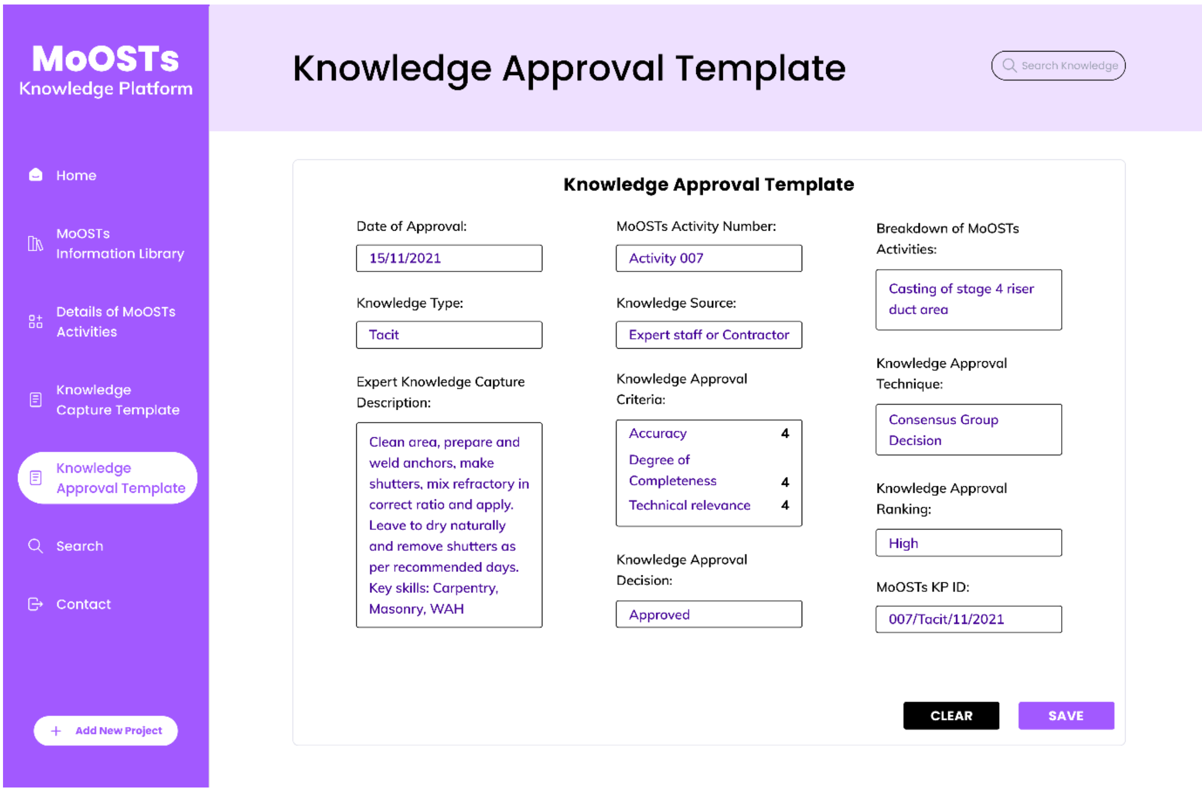


Figure 7. 9 Knowledge approval process embedded within the MoOSTsKP

If the knowledge captured does not meet the parameters for approval, such will be rejected automatically and deleted or in rare circumstances they sent back to the knowledge holder for more information or clarification. Alternatively, if it does meet the parameters, it is approved and then stored in based on a unique ID to distinguish features as well as provide a link different knowledge cases.

### 7.4.4. Store and manage knowledge in the MoOSTsKP

Once the captured knowledge has been verified and approved, the next step involves storage for future reuse. Based on the notion, accurate storage usually ensure easy retrieval and reuse, the approved knowledge is then stored in a simplified and reasonable format within the knowledge repository of the MoOSTsKP so as to ease organization wide access. The different sub-sections within the MoOSTsKP are clearly delineated before it is stored. In addition, appropriate review and reviewers details are included for easy tracking. Figure 7.10 shows the output of knowledge stored within the MoOSTsKP as well as the opportunity to modify/update or delete existing entries.


Figure 7. 10 Sample of Knowledge stored within the MoOSTSKP

### 7.4.5. Dissemination and reuse of knowledge

The final stage of the knowledge management process is making the knowledge available to relevant stakeholders in a useful format. Accessibility to the knowledge within the MoOSTsKP is immediate once knowledge is deposited, approved and uploaded. A notification through the intranet, E-Mail and other digital sources alerts the relevant users. The MoOSTsKP is equipped with an important feature which allows users to view all the MoOSTs activities that have been loaded into it and other functions such as, delineating these activities across different time period exist. Further partitions can be found within the MoOSTsKP for instance, if the user is only interested in obtaining information on individual MoOSTs activities, the search function key could be utilised to obtain details such as, criticality score and/or code, start and completion dates, task frequency, size of labours used to achieve task, hierarchy of specialised labour, source of labour (internal, external or combination), and duration of technical support work (hours) for executing the MoOSTs activity.

Alternatively, a user maybe interested in identifying possible learning events and situations that could enhance their understanding of knowledge types (i.e. tacit and/or explicit) that can be reused from certain MoOSTS activities. In such circumstances, what the user needs to do is to select the MoOSTs activity and identify which type of knowledge has been uploaded and then process the information for that particular activity.

### 7.4.6. Overarching purpose of the MoOSTsKP

Some of the many advantages to the development of a MoOSTsKP include:

i. Enabling the capture of learning events by identifying critical MoOSTs activities and providing accurate, complete and relevant descriptions through a procedural approach which minimises the loss of MoOSTs related knowledge;
ii. Improving real time communication and collaboration between the various MoOSTs stakeholders;
iii. Assisting the standardisation of tacit knowledge requirements for continuous learning, owing to the ability of the knowledge capture template to codify experiences obtained from learning events;

iv. Cultivating systematic knowledge sharing within teams as well as formalised roles of knowledge holders; and

v. Improving the representativeness of MoOSTs predicted outcomes by allowing transfer of learning experiences from one MoOSTs cycle to another.

## 7.5. Validation of MoOSTs Platform

It was necessary to obtain the perception of maintenance professionals within industries where MoOSTs are practised in order to validate the MoOSTsKP. It has been stated in the literature that studies within MoOSTs would benefit from integrating a blend of theory and practice to effectively implement any solutions on KM [278]. This section describes the research approach adopted to validate the proposed MoOSTsKP. A panel of maintenance professionals with significant involvement with MoOSTs was assembled to provide feedback on their general perception of the platform after demonstration of its capabilities.

### 7.5.1. Justification for the selection of a focus group research method

Traditionally, qualitative research methods are used under two broad circumstances. Firstly, qualitative research methods have been employed in many studies where the aim is to obtain an understanding of the "why(s)" behind peoples′ behaviours or actions [279]. Therefore, qualitative research can provide an outlet for a researcher to obtain an in-depth understanding of the underlying causes behind various human behaviours. Secondly, qualitative research methods are also employed when the aim of the study is to obtain better understanding of a particular topic from the perspective of different participants in order to develop a conclusion that can be drawn from a larger, generalizable sample [280]. Since the aim of this study is to demonstrate the applicability of the MoOSTsKP in providing appropriate KM solutions to varying MoOSTs activities across different industries, as well as obtain a group's perception of the proposed knowledge platform, the focus group research method was selected as the means to obtain primary data. In this study, participants were required to formulate their answers to the structured questions posed to them with the aim of obtaining their perceptions on four vital aspects of the Knowledge platform [281]. Previous studies have demonstrated the proficiency of Delphi technique for managing group decision-making, due to its ability to elicit responses [232].

The Delphi technique is designed as a structured group communication process that allows individuals within a group to deal with complex problems. Participants in a group make use of their experiences, as well as values on knowledge of a particular discipline to make critical and well-informed decisions, feedback and/or recommendations. Recommendations on expert categorization for building representative panels in [282] and suggestions on participants selection based on modelling of a typical Delphi survey panel were integrated [232]. Furthermore, suggestions on group size (typically 9-18 participants) in order to alleviate difficulties associated with reaching consensus among experts [216] was also adopted. Hence, the group size "n" applied here was restricted to nine participants.

### 7.5.2. Selection of study participants

The focus group consisted of industry professionals from across the Nigerian cement industry, since this was the origin of case example used to develop the knowledge platform. Although the current case example is based on a cement manufacturing process, mainly due to the high frequency of MoOSTs within the industry, however, it should be noted the approach adopted is rather generic and can be conveniently implemented for other industries. The selection of participants in the group were selected based on a number of factors that were identified in a study by [278]. Prior to the focus group formation, a short survey was sent to a number of professionals within the organization to ascertain their availability and suitability. Their responses informed the selection process. The selection of participants were based on many factors including, participant's involvement with MoOSTs, (i.e. how many years of MoOSTs experiences or number of MoOSTs, at least five years' worth of experience and/or five involvements in MoOSTs cycles was deemed adequate), experience of project management, familiarity with ERP systems (e.g. SAP, Maximo, Ellipse etc.), involvement with knowledge capture, etc. The job classes of participants in the focus group and number within each class are shown in Table 7.1.

Table 7. 1 Characteristics of interview participants involved in the focus group within each job class

| Industry | Category and Job Class | Number |
|---|---|---|
| Manufacturing-cement | D- Maintenance manager, Project coordinator, Training and Knowledge manager | 3 |
| | E- Maintenance supervisor (Mechanical), Maintenance planner/scheduler | 4 |
| | F- Methods inspection technician, Instrumentation technician | 2 |
| Total | | 9 |

### 7.5.3. Data collection process

The focus group session was conducted virtually via MS Teams platform. Each round lasted about 60 minutes and there were three rounds altogether. Prior to the first meeting, the link to MoOSTsKP was sent to all participants to interact with the platform as well as identify areas in which they required further clarifications. The link to the MoOSTKP was pre-populated with five–year's MoOSTs data for the RKS (pyro-processing) line. The identified knowledge holders within the group were asked to capture relevant expert knowledge based on the identified MoOSTs activities. During the focus group sessions, the team was asked to assess the captured knowledge and either approve or reject based on the set criteria.

Prior to the commencement of the actual data collection process, participants were collectively briefed on the requirements of the study as well as given through explanations on the attributes of individual modules within the MoOSTsKP. The first round of the data collection process entailed validation and ranking of assessment criteria. Ten of the most prevalent parameters used for ranking the efficacy maintenance management systems (MMS) and related tools were extracted from within existing literature [193], [283], [284]. These ten parameters include - collaboration and extent usability of the MoOSTsKP (C1), consistent infrastructure (C2), structure and layout i.e contextual representation of knowledge (C3), level of infrastructure technology (C4), ability to build new knowledge (C5), degree of effectiveness for capturing relevant information (C6), ease of integration with other structure (C7), cost of setting up the platform (C8), cost of running the platform (C9), storage capacity (C10). Earlier studies [283] have used similar approach for assessing the usefulness of IT tools based on predetermined KMS indicators.

Similarly, [284] gave an overview of factors that a KMS should integrate to achieve the development of KM in any field. Based on the study by [193] it is positioned that the layout of a KMS is an important criteria, because when presented in an appropriate format, engineers are better able to understand the system's operations, prepare identical ones, as well as add new functions if needed. However, [264] stated that the criteria for evaluating the efficacy of any KMS would obviously require careful selection of a coordinated strategy based on organizational needs and strategies to achieve potential benefits of KM.

Based on these premises, the experts were asked to rank all ten assessment criteria in order of importance based on a Likert scale of 1-5, with 1 depicting least relevant and 5 most relevant (a score of 3 meant somewhat relevant). Details of the scores for individual assessment criteria against each participant for all the rounds can be found in Appendix. The submitted scores at the end of each round were then showed to all participants prior to the commencement of subsequent rounds so as to enable participants adjust their scores if need. This activity was repeated over 3 rounds and once a satisfactory cut-off point was achieved, the eventual selections of the parameters that scored an average of 4 and above were then identified for further discussions. Further details on the fundamentals of focus group discussion technique and the associated ranking procedures are also described in [62]. Four out of the Ten initial assessment criteria met this requirement. In the third session, based on the four agreed criteria, the participants were asked to provide feedback on their perceptions. These four criteria are as follows;

1. C1- Extent of usability of the MoOSTsKP;
2. C3-Structure and layout of the MoOSTs Knowledge capture and approval template;
3. C6-Degree of effectiveness of the MoOSTsKP with capturing relevant MoOSTs information; and
4. C7-Ease of implementation with existing technology in the industry

The most prominent responses received from the focus group sessions based on the agreed criteria are shown in Table 7.2

Table 7. 2 Feedback template on the four criteria set to evaluate the MoOSTsKP

| S/N | Assessment Criteria | Comments | Improvements and suggestions |
|---|---|---|---|
| 1 | C1 | *"It appears to be intuitive and is not overly cluttered with unimportant information fields. This is crucial to ensure participants are engaged and not distracted."*<br><br>*"Every system should be easy to use depending on the level of exposure (training & probably duration of use).. Well I feel to a certain degree it is rather easy to use and or navigate."* | *"Connection to SAP and other CMMS."*<br><br>*"Virtual trainings may be +/-50% effective in introducing systems like this but I feel more physical guides and practical handlings will be more effective during implementation."* |
| 2 | C3 | *"UI/UX is friendly, most used buttons are visible."*<br><br>*"It's simple, it's almost explicit enough to system users in general. I liked the outlook of the template version. Aesthetics are pretty cool and easy on the eyes too."*<br><br>*"Captures relevant knowledge and approval criteria for captured knowledge is technical in depth."*<br><br>*"The layout of the webpage could do with small improvements."* | *"The platform should be easy to load when on other site."*<br><br>*"Observed a few acronyms that maybe need to be clarified or explained (details of MoOSTs activities) Maybe a 'legend', a 'read-only hover note' or something that could shed a little bit of light or clarity on key fields or criteria to be populated may be introduced."*<br><br>*"To improve the user experience, I suggest, the Home button should be renamed About."* |
| 3 | C6 | *"The interaction with the criticality module makes it a go to platform, most especially for the maintenance team."*<br><br>*"All systems basically feed off inputs (GI/GO),, I think this can be effectively covered if key users input the right kind of data. This should determine the degree of effectiveness of the tool/platform.."*<br><br>*"Highly effective, can empower a newbie to deliver to performance on first attempt."* | *"If possible criticality analysis should be triggered from the platform based on the data inputted by plant team."*<br><br>"*Question: Are all fields mandatory? Indicators marking key fields for selection may be added. Possibly to avoid missing out on info for final calculation criteria."* |

| S/N | Assessment Criteria | Comments | Improvements and suggestions |
|---|---|---|---|
| 4 | C7 | *"There is much room for further development here. The functionality to capture data is present but there is an apparent gap in terms of how the data will be mapped to a CMMS/ERP tool"* | *"To improve integration with existing company systems, the following should be considered: - explicit knowledge typically contained in standard operating procedures (SOPs)can "attach" to tasks that are performed on generic asset class. To enable this, a non-mandatory field for asset class neds to be included in the capture form. The tasks could then be selected (from a dropdown) when raising a work order against generic asset class."* |
| | | *"It's a digital age and of course every bit of technology brought in to improve our systems and knowledge base is most always welcome. Just like every other integrated system/software I think this can or will easily be implemented alongside our current systems."* | *"As long as there is no drag in the system when in use, field personnel will find it useful."* |

The feedback from the experts were vital for improving the functionalities of the MoOSTsKP. Most of the suggestions proposed during the feedback sessions were minor and did not entail extensive modifications. Hence, they were immediately implemented. However, those that required extensive modifications to the existing architectural framework formed part of future work that can be easily implemented during real-life commissioning. Examples of feedback from the experts include:

i. "explicit knowledge, typically contained in SOPs, can 'attach' to tasks that are performed on generic asset classes/types. To enable this, a non-mandatory field for asset class/types needs to be included in the capture form. The tasks could then be selected (from a dropdown or lookup) when raising a work order against generic asset class/types"
ii. "tacit knowledge can 'attach' to tasks that are performed on specific assets because it contains local information that relate to the operational context. To enable this, a non-mandatory field for asset ID needs to be included in the capture form. The

tasks could then be selected (from a dropdown or lookup) when raising a work order against specific assets"

iii. "it would be more appropriate for the knowledge manager to be a maintenance systems engineer rather than an IT expert. The systems engineer will have expert knowledge of maintenance practices and a working knowledge of IT systems. It is important that the bias of this role is towards asset management and not IT"

iv. "the knowledge manager is responsible for entering the explicit and tacit knowledge into the relevant maintenance tasks"

v. "there is potential to link the MoOSTs knowledge base to failure modes of assets. Depending on the CMMS/ERP configuration, a prompt could provide the option (from a dropdown or lookup) to generate a task when a failure mode is assigned to a work order. The task can contain knowledge extracted from the MoOSTs knowledge base."

Overall, comments and feedback from MoOSTs experts were positive, which further emphasised the potentials of the proposed MoOSTsKP to alleviate the current practical challenges associated with MoOSTs KM.

## 7.6. Chapter Summary

MoOSTs are universally recognised as some of the most labour and capital intensive industrial endeavours, which rely heavily on team experience for success on all fronts. Existing knowledge management approaches are solely inclined towards EPCs, which are not characterised by the same level of complexity and uncertainty. Based on these premises, the current study demonstrated several crucial benefits and potentials for industrial deployment. Firstly, critical MoOSTs activities and their associated knowledge elements can be captured as soon as they occur. Hence, they can be submitted into the interactive web-based MoOSTsKP, thereby enhancing the ability to promptly approve or reject specific knowledge elements during relevant MoOSTs meetings. Besides enhancing instantaneous capturing of critical MoOSTs activities, the platform also enables MoOSTs managers to easily identify critical manpower, which is vital for succession planning and talent management. Secondly, the compatibility of the platform with most of the prevalent computerised maintenance management systems (CMMS) would ease existing data compliance and management challenges. In addition to easing data management, it is quite common for large establishments to own a chain of operations with similar configurations at multiple locations, which would require very similar MoOSTs. The web-based functionality of the MoOSTsKP ensures accessibility to MoOSTs experience and knowledge information lodged by multiple stakeholders, irrespective of their geographical locations.

The development of the platform entailed integrating several well-known maintenance concepts such as job and risk prioritisation. It is envisaged that the familiarity of most industry experts with these concepts would reduce the steepness of the learning curve during deployment, since similar concepts are often used for ranking failure modes of assets. To achieve this, multiple years of MoOSTs data was acquired from the pyro-processing stage of a cement plant, due the high frequency of MoOSTs within this industry. The proficiency of the platform for capturing representative MoOSTs tacit knowledge was examined through a focus group exercise with industry professionals, based on 4 crucial attributes – usability; structure and layout; representativeness of MoOSTs knowledge captured; and ease of integration with existing CMMS. The feedback from the experts were generally positive and further emphasised the need to deploy such platforms in the near future. In some instances, experts suggested some modifications to certain functionalities within the MoOSTsKP but these were mostly minor and did not entail extensive modifications. Hence, such modifications were immediately implemented. However, in the rare instances whereby suggested modifications required extensive changes to existing architectural framework, such formed part of future work that can be easily implemented during real-life commissioning.

The current study is limited by the fact that the MoOSTs data, knowledge and industry experts consulted are all from the cement industry, even though this decision was justified by the high frequency of MoOSTs within this industry and the generic nature of the core engineering tasks performed. It would be useful for future studies to repeat similar research exercises based on case studies from other high-risk industries such as power, transport, and oil & gas.

# 8 CONCLUSION AND IMPLICATIONS FOR RESEARCH AND PRACTICE

## 8.1 Introduction

In this conclusion chapter, the main findings of the thesis are summarised and their implications for theory and practice are presented. The chapter also discusses the limitations of the entire study and recommendations for future work.

## 8.2. Synthesis of Findings

At the beginning of this study in Chapter 1, the aims of the thesis was to design and comprehensively evaluate mechanisms for knowledge management and experience transfer in major maintenance activities with emphasis on MoOSTs activities, so that the loss of knowledge and expertise in this discipline can be significantly minimised. Its objectives were as follows:

i. **Research Objective 1:** To conduct a SLR which comprehensively identifies trends, gaps and limitations in MoOSTs research on the basis of its complexities, to establish an overall picture of research methods, demographic information and selections of appropriate principles governing its successful management; and to identify the challenges in MoOSTs that are specific to knowledge management.

ii. **Research Objective 2:** To conduct a comparative study across diverse industries involved in MoOSTs activities to obtain the perspectives of practitioners on the knowledge management challenges which are identified in real-world practices during MoOSTs, to validate the findings generated from the prior SLR;

iii. **Research Objective 3:** To develop a generic approach by combining engineering failure analysis tools and multi-criteria decision-making (MCDM) techniques that can be adapted to different case-based models within practice capable of identifying and ranking barriers to knowledge management and experience transfer based on the perceptions of experts who have significant involvements in MoOSTs, to enable the selection of appropriate solutions specific to the individually identified and ranked knowledge barrier;

iv. **Research Objective 4:** To develop a generic approach by utilising qualitative criticality analysis approach and fuzzy logic,  that can be adapted to different case-based models within practice capable of identifying crucial attributes of maintenance activities during MoOSTs in order to prioritise them with the aim being to establish maintenance task criticality;

v. **Research Objective 5:** To design and evaluate the implantation of a generic approach that can be adapted to different case-based models within practice in the form of an interactive web-based knowledge management platform developed specifically for MoOSTs, to foster knowledge management as well as minimise loss of expertise.

In order to achieve these aims and objectives, this study was conducted in five phases: the first phase was the SLR involving the review of secondary data and development of theoretical framework to present an overview of the knowledge trends and identify challenges in MoOSTs. In total 122 articles were reviewed.

The second phase was a mixed method approach involving the use of primary data (i.e. administration of survey and interviews) to obtain the perspectives of experts on the extent of alignment between theory and practice based on the issues identified from the SLR. Prior to the main study, a pilot investigation with 15 participants was conducted to provide sufficient methodological evidences about the design, planning and justification which was used to develop questionnaires as well as interview questions.. The main study in the second phase, involved the administration of surveys to industry professionals across five industries, as well as interviews. In total, 49 professionals completed the surveys, while 44 professionals were interviewed.

The third phase of the study was also a mixed method research that utilised focus group interviews (qualitative approach) to obtain the perspectives of professionals on their assessment of barriers to knowledge management and experience transfer in MoOSTs. Data analysis of the obtained responses was undertaken by integrating engineering failure analysis statistical tools and multi-criteria decision-making analysis techniques (Quantitative approach) to quantify the responses of panel members.

The fourth phase of the research involved a mixed method approach to obtain the criticality assessment values of MoOSTs activities. This was following the integration of traditional qualitative approach to obtain primary data using a focus group interview, as well as secondary data (collation of historical plant data- 5 years' worth). Data analysis was achieved through the refinement/standardisation of the qualitative data using a quantitative approach (fuzzy logic).

The fifth and final phase, was the culmination of the research efforts in the prior four phases, which involved the design of a knowledge management platform termed "MoOSTsKP" and its validation by professionals in the industry using focus group interviews to obtain responses.

### 8.2.1. Research objective 1

This study (Chapter 2- Part 2) suggests that based on the analysis of a wide range of databases for MoOSTs-related articles, that there were glaring underrepresentation of concise literature review articles for managing MoOSTs compared to other strands of industrial operations. The very few literature review articles in this discipline were limited in their scope, because the information triangulation performed in them were too streamlined to a particular industry and theme, thereby leaving significant knowledge gaps with regards to key facets. Hence the need for the SLR in this study which provided information on the critical examinations to quantify the adequacy of current research in fulfilling the practical needs for the management of MoOSTs. Secondly, the SLR in this study was useful for identifying common trends of studies, author's inclinations, standard approaches towards the overall management of MoOSTs as it relates to each phase and distinct themes, in order to provide a holistic view of the state of affairs in this discipline. Furthermore, the SLR in this study acknowledged the universal recognition of the usefulness of experience as a key element of successful MoOSTs implementation, which none of the existing studies considered as a tool for knowledge transfer and retention, but rather focused on lagging indicators that are often easy to measure.

### 8.2.2. Research objective 2

This study (Chapter 4) suggest that, because MoOSTs is an applied discipline, significant human endeavours are required in its planning and management, which makes it pertinent to examine and obtain the perspectives of experienced MoOSTs practitioners. The study first examined the extent of alignment between findings from literature as it relates to the challenges encountered during MoOSTs, as well as probe their underlying causes in practice. Subsequently, to show how relevant the findings from this study would be in providing a baseline for establishing a proposal for capturing MoOSTs knowledge and the transfer of experience. The study approach involved analysis of demography information as well as specific MoOSTs related questions. Based on the results from the study, nine challenges were identified as critical themes, six of which were associated with managing knowledge. The study identified not only known constraints from literature but also their underlying causes based on the perspective of practitioners involved in multiple MoOSTs, which is crucial for developing sustainable mitigation strategies. A unique contribution of this research was the mapping of demographic information such as industry, country, job class, years of experience, MoOSTs organization size, frequency for performing MoOSTs, etc., to responses obtained from participants, which has not been shown in literature prior to now. The importance of such rigorous efforts in the research design, is crucial for enabling the adoption of holistic approaches to eliminating the underlying causes of challenges encountered in MoOSTs, based on first hand reporting of people involved. In addition, the relevance of such first-hand analyses of responses obtained from this study; serve as baseline for the introduction of the proposal to adequately manage knowledge management issues in this discipline

### 8.2.3. Research Objective 3

This study (Chapter 5) established that through the combination of information identified within the current body of knowledge, as well as a practical case study, it was possible to investigate the casual relationships that exist among the main barriers to MoOSTs knowledge management and experience transfer. The study also takes into cognisance, the inability of decision-makers to confront all issues within their organization due to budget restrictions thereby necessitating the creation of mechanisms that allow for the prioritisation of the most influential factors. The most important contribution of this work includes intuitively harmonising several reliability-based (FTA and RBD) and multiple criteria decision-making (AHP) tools. This presents a practical but yet realistic model for understanding limiters to intangible performance enhancement elements of a very crucial industrial activity, MoOSTs.

Furthermore, priority ranking derived from AHP provides a road map that can direct focus of decision makers accordingly, especially when providing alternatives/solutions. This implies that holistic alternatives based on identified MoOSTs barriers to knowledge management and experience transfer can be derived and ranked appropriately. While the individual tools applied here are well-established within research and professional communities, their integration and application for solving MoOSTs knowledge management issues has never been explored. Moreover, the use of tools that are relatively familiar to the professional community is viewed as means of reducing the steepness of the learning curve that sometimes plagues the deployment of theoretical tools to the industry.

### 8.2.4. Research objective 4

This study (Chapter 6) proposed that through the combination of a traditional qualitative criticality method and quantitative Fuzzy logic system for assessing the criticality of MoOSTs tasks, the decision-making process to obtain parametric numerical ranges for both methods can be provided by experts in cement manufacturing processes. The combination of the two approaches was to improve the reliability of results and offset any perceived weaknesses of either of the two methods. For instance, unlike the traditional method that makes use of a qualitative criticality matrix, the Fuzzy method generates a three-dimensional surface envelope diagram output for the computation of criticality values and examines the degree of changes to membership functions. Furthermore, the practical application of the two methods using a case example led to the identification and codification of critical maintenance activities performed during MoOSTs. The detailed procedures for converting large amounts of data into information that are reusable, an important element of knowledge management process.

A unique contribution of this research was to demonstrate how practical assessments of MoOSTs tasks criticality and codification systems can be utilised as inputs for developing a suitable web-based knowledge management platform that could complement existing industry-based solutions. This is because, although there is vast knowledge on predicting asset failures and prognosis but not enough on assessing individual maintenance activities and processes for performing maintenance. The codification strategies implemented in this study enhances the acquisition and subsequent transfer of tacit knowledge. This is because tacit knowledge is rooted in an individual's actions, experiences as well as emotions. Identifying who the knowledge holder is (discipline requirements) and adequate information on the tasks they are required to perform can be instrumental in facilitating the capture of expertise embedded within the minds of experts, based on their historical involvements with MoOSTs.

### 8.2.5. Research Objective 5

This study (Chapter 7) proposed the design, implementation and evaluation of an early model web-based knowledge management and experience transfer platform for the capture of learning activities and experiences during and after MoOSTs. This is a significant improvement from what is currently available in practice. Although, several studies advocate for continuous learning in MoOSTs, but their approaches depend largely on post evaluation reporting performed upon completion of MoOSTs cycles which are captured in KMS which do not encourage its use among professionals. However, following the approach demonstrated in this study, critical MoOSTs activities and their associated knowledge are captured as soon as they occur, they can be submitted in the interactive web based MoOSTsKP and the knowledge approved or rejected immediately during Meetings and reviews by team of selected experts.

The significant activities demonstrated with the MoOSTsKP are many they include, firstly, pre-selection of MoOSTs activities and subsequent upload, this ensures that only tasks which are deemed critical based on the criticality ranking criteria are analysed. The reason for this approach is to ensure that knowledge and expertise captured are at manageable levels, which can be treated within the tight timelines of typical MoOSTs. In addition, should there be discoverable work which were hitherto unplanned for in the schedule of activities (a common occurrence in MoOSTs), such activities can be added, uploaded and treated accordingly without excessively increasing the workload for those tasked with knowledge transfer. Also, the pre-uploading of critical MoOSTs activities, as well as pre-population of possible knowledge details and outcomes ensures that the knowledge approval activities packages are deliberated on immediately and easily.

Besides enhancing instantaneous capturing of critical MoOSTs activities, the platform also enables MoOSTs managers to easily identify critical manpower, which is vital for succession planning and talent management. Also, the compatibility of the platform with most of the prevalent computerised maintenance management systems (CMMS) would ease existing data compliance and management challenges. In addition to easing data management, it is quite common for large establishments to own a chain of operations with similar configurations at multiple locations, which would require very similar MoOSTs. The web-based functionality of the MoOSTsKP ensures accessibility to MoOSTs experience and knowledge information lodged by multiple stakeholders, irrespective of their geographical locations.

## 8.3. Implications for Theory and Practice

The research offers four original contributions to theory and practice. First, it provides empirical evidence of the extent of alignment between findings obtained from literature based on the identified knowledge management challenges in MoOSTs as well as underlying causes in practice, in order to establish the knowledge management challenges specifically related to MoOSTs within practice. The second contribution of this research proposes an approach for identifying and ranking barriers to knowledge management and experience transfer in MoOSTs, to ensure that only the most relevant solutions to each identified barrier is developed, this was achieved by adopting reliability engineering and multi criteria decision-making techniques respectively. The third contribution, was developing a framework for identifying critical attributes of MoOSTs activities in the form of a hybrid MoOSTs activity criticality assessment that combines quantitative criticality analysis as well as a technique for representing uncertain information generated from qualitative analysis to establish the most critical MoOSTs activities that would benefit from the knowledge management and experience transfer platform. Finally, a research-based approach for designing and evaluating an interactive web-based knowledge platform for capturing and sharing knowledge and experience during MoOSTs, proposed as a potential solution for overcoming the challenges of uncertainty in the management of MoOSTs was discussed.

The design and evaluation of an interactive web-based knowledge platform for a MoOSTs intensive industry termed as a "MoOSTs knowledge platform" (MoOSTsKP) is one of its kind. The integrated web-based knowledge management platform shown in this thesis is designed to manage both tacit and explicit knowledge during MoOSTs. The MoOSTsKP have been developed with many objectives namely; to identify critical maintenance activities that support capture and retaining of specialist knowledge possessed by experienced professionals; and to overcome real-time knowledge capture limiters especially time restriction and temporary project environment, which MoOSTs fall under.

The research philosophy on which the knowledge platform in this thesis is built on, enables the integration of MoOSTs criticality assessed parameters for identification of critical MoOSTs activities as well as the steps to building the knowledge platform aimed at overcoming the identified barriers to the KMS proposal. Validation of this early stage development of the MoOSTsKP was achieved by means of expert opinions, with provision for feedbacks and recommendations to improve the platform.

## 8.4. Limitations and Recommendations for Future Research

This study may be the first and only existing study that designed and evaluated a knowledge management and experience transfer specific to MoOSTs complexity levels and elements, with in built considerations for MoOSTs activities criticality analysis. Both the data and methodological approaches as well as combination of theoretical underpinnings and practice -based approach applied, enhanced the comprehensiveness of the findings. Nevertheless, as in all studies, this research has limitations. These limitations were discussed in each of the results chapters (i.e Chapters 4, 5, 6, 7). These limitations are compiled in this section, and several recommendations for future research are proposed accordingly.

The first limitation was stated in Chapter 4, based on the study to determine the extent of alignment between theoretical findings from the SLR and the case study approach as it relates to the challenges in knowledge management that were specific to MoOSTs. In this study, the scope of work was limited to include analysis of data based on specific gaps identified from a prior SLR and questions asked in the interviews were directly relevant to the study aim of aligning practice with research. Another SLR might discover additional qualitative findings which will need to be elucidated in future empirical studies with the view of obtaining other practitioners' perspectives. In addition, the qualitative research method is often criticised for not usually being generalizable, because the conditions in which it is conducted can often not be replicated. However, this is not a hindrance or limitation to the research, but it is rather a feature that can be overcome by establishing common values of transparency during data collection, analysis and interpretation of results. It is the opinion of the authors that the research direction, discussions and outcomes from this study are very relevant in examining pertinent issues raised by research and practice in the study of knowledge management and experience transfer in MoOSTs.

The second limitation was stated in Chapter 5, based on the study to assess and rank the barriers to knowledge management and experience transfer within MoOSTs. The scope of this work was limited to developing a hierarchy of problems capable of ranking and identifying the order of barriers to MoOSTs knowledge management and experience transfer, and as such has not attempted to provide solutions in terms of alternatives. While the novel harmonisation of theoretical quantitative risk assessment tools with qualitative field-based perspectives from experts can significantly enhance the ability of decision-makers to identify deficiencies in knowledge transfer mechanisms at a glance, the findings presented here can be described as being industry-specific. Despite this perceived limitation, it is envisaged that the approach presented here still offers useful contributions especially that cement manufacturing is often considered the upstream segment of one of the largest business sectors (i.e., mining and construction).

Recommendations for future works is proposed, to encompass other key sectors (e.g., oil and gas, energy, food and beverage, etc.), as well as consider appropriate alternatives that consider the whole facet of MoOSTs in terms of tasks and associated knowledge. This is for developing a knowledge management and experience transfer model specific to MoOSTs, which constitutes an essential step towards systematic but yet sustainable framework for tacit knowledge retention.

The third limitation was stated in Chapter 6, based on the study to critically assess maintenance activities during MoOSTs, to identify and prioritise the most critical activities that would benefit from knowledge capture and experience transfer. The scope of this work was limited to developing a criticality ranking of maintenance activities by combining two main maintenance parameters, frequency, and consequence during MoOSTs activities using a high frequency shutdown case study, cement-manufacturing plant. However, it would be useful to examine the dynamics existing between high-frequency and low-frequency tasks in different industries, where the execution of MoOSTs sometimes takes up to three to five years intervals, and other factors such as where accessibility is low. Despite this perceived limitation, it is envisaged that the approach presented here still offers useful contributions, especially because cement manufacturing is often considered the upstream segment of one of the largest business sectors (i.e., mining and construction). Future works could be planned to undertake further planned studies from other industries with much lower frequency tasks to compare the robustness of the approach.

The fourth limitation was stated in Chapter 7, based on the study to design, implement and evaluate a knowledge platform specific to MoOSTs activities. This research demonstrates knowledge capture techniques for the capture of knowledge and experience of critical MoOSTs activities following a case example of an RKS in cement manufacturing plant. The information presented are particularly skewed towards the data obtained from a particular cement plant which formed the basis of the criticality assessment. It is important to state that some of the criticality assessment criteria depicted in this study might not be suitable for another industry or even plant. However, the architectural framework of the proposed MoOSTsKP was designed with the ability for modification to suit the requirements of various industrial processes. Furthermore, the platform demonstrated in this study is still in its early development and further iterations are needed to standardise the information presented as well as test its suitability and integration with other plant ICTs.

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# APPENDICES

## Permission to Submit Thesis in Journal Format

MANCHESTER
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The University of Manchester

**Faculty of Engineering & Physical Sciences**
**PERMISSION TO SUBMIT A THESIS IN JOURNAL FORMAT**
Postgraduate Research Degrees

**To be completed ONLY where a candidate intends to submit a PhD or MPhil thesis in alternative format.** See section seven of the *Presentation of Theses Policy* for full guidance on alternative format theses.

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| **Research Degree Title:** | PhD MANAGEMENT OF PROJECTS |

**This is to confirm that the above named has been granted the permission to submit a PhD or MPhil thesis in the alternative format approved under the appropriate regulation, including sections which are in a format suitable for submission for publication or dissemination.**

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|---|---|
| **Supervisor's Name (PLEASE PRINT):** | Dr Akilu Yunusa-Kaltungo |
| **Supervisor's Signature:** | |
| **School / Division:** | |
| **Date of Thesis Submission:** | DECEMBER 2021 |
| **Approval of School PG Committee (signature):** | |
| **Print name:** | Dr Andrea Bottacin Busolin (Deputy Head of PGR) |

## Authors’ Contribution to Thesis

Table 1 Author’s Contribution to the Thesis

| | | | **Contributing Authors** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Lilian Iheukwumere-Esotu** | | | | | | | | **Akilu Yunusa-Kaltungo** | | | | | | | |
| **Publication Title** | **Publication Type** | **Thesis Chapter** | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 |
| A Systematic Analysis of Research Based Evidences of Major Overhauls, Outages, Shutdowns, Turnarounds (MoOSTs) Management | Conference article | 2-Part 2* | x | x | X | X | x | x | | | | X | x | | | | x | x |
| A Multi-Attribute Knowledge Criticality Framework for Ranking Major Maintenance Activities: Case Study of Cement Raw Mill Plant | | 6 | x | x | X | X | x | x | | | | X | x | | x | | x | x |
| Knowledge Management and Experience Transfer in Major Maintenance Activities: A Practitioner’s Perspective | Journal article | 4 | x | x | X | X | x | | | | X | X | x | | | | x | x |
| Assessment of Barriers to Knowledge and Experience Transfer in Major Maintenance Activities | | 5 | x | x | X | X | x | x | | | X | X | x | | | | x | x |
| Knowledge Criticality Assessment and Codification Framework For Major Maintenance Activities | | 6 | x | x | X | X | x | x | | | | X | x | | x | | x | x |
| Development of an Interactive Web-Based Knowledge Management Platform for Major Maintenance Activities: Case Study of Cement Manufacturing Systems | | 7 | x | x | X | X | x | x | | | | X | x | | x | | x | x |

Note: C1-Conceptualization; C2-Methodology; C3-Validation; C4-Formal data analysis; C5-Investiagtion; C6-Writing-Original draft preparation; C7-Writing review and editing; C8-Supervision

*Chapter 2 was split into two parts. General Literature Review (Part 1) and Systematic Literature Review (Part 2)

# Ethics Approval to Conduct Research

MANCHESTER 1824

The University of Manchester

Mechanical, Aerospace and Civil Engineering Department Panel

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Ref: 2020-8009-13470

09/03/2020

Dear Ms Lilian Iheukwumere esotu, , Dr Akilu Yunusa-Kaltungo

**Study Title**: Development of a knowledge based framework for the management of Major overhauls, Outages, shutdowns and Turnarounds (MoOSTs)

Mechanical, Aerospace and Civil Engineering Department Panel

I write to thank you for submitting the final version of your documents for your project to the Committee on 28/02/2020 14:36 . I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation as submitted and approved by the Committee.

Please see below for a table of the titles, version numbers and dates of all the final approved documents for your project:

| Document Type | File Name | Date | Version |
|---|---|---|---|
| Additional docs | Interview questions | 03/10/2019 | 1 |
| Consent Form | Sample Consent form_GDPR Non Medical v1.7 FINAL | 03/10/2019 | 1 |
| Participant Information Sheet | Information sheet for conducting the research | 03/10/2019 | 1 |
| Letters of Permission | Introductory letter | 03/10/2019 | 1 |
| Data Management Plan | Development_of_a_Knowledge_Based_Framework_for_the_Management_of_Major_Overhauls,_Outages,_Shutdowns | 27/02/2020 | 1 |
| Additional docs | Sample Consent form_GDPR Non Medical v1.7 FINAL (1) | 27/02/2020 | 1 |
| Additional docs | Development_of_a_Knowledge_Based_Framework_for_the_Management_of_Major_Overhauls,_Outages,_Shutdowns (1) | 27/02/2020 | 1 |
| Additional docs | Information sheet for conducting the research | 27/02/2020 | 1 |
| Additional docs | Introductory letter | 27/02/2020 | 1 |
| Additional docs | Interview questions | 27/02/2020 | 1 |

This approval is effective for a period of five years and is on delegated authority of the University Research Ethics Committee (UREC) however please note that it is only valid for the specifications of the research project as outlined in the approved documentation set. If the project continues beyond the 5 year period or if you wish to propose any changes to the methodology or any other specifics within the project an application to seek an amendment must be submitted for review. Failure to do so could invalidate the insurance and constitute research misconduct.

## Sample of Participant Consent Form

MANCHESTER 1824
The University of Manchester

# Participant Consent Forms

(**Version 1, Date 08/05/2019**)

**Development of a Knowledge Based Framework for the Management of Major Overhauls, Outages, Shutdowns, and Turnarounds (MoOSTs)**

1. The data from this interview is completely annoymous and can not be traced back to participants.
2. The issues being researched are not likely to upset or disturb participants.
3. Any sensitive or confidential data collected and/or observed will be presented annonymously.
4. The data will be used for the purpose within the remit of the original consent provided by the data particpants.
5. The researcher is willing to clarify any activities as might be required by the participants.

If you are happy to participate please complete and sign the consent form below

| | **Activities** | Initials |
|---|---|---|
| 1 | I confirm that I have read the information above contained in (**Version 1, Date 08/05/2019**) for the above study and have had the opportunity to consider the information and ask questions and had these answered satisfactorily. | |
| 2 | I understand that my participation in the study is voluntary and that I am free to withdraw at any time without giving a reason and without detriment to myself. I understand that it will not be possible to remove my data from the project once it has been anonymised and forms part of the data set.<br><br>I agree to take part on this basis | |
| 3 | I agree to the **interviews** being **audio / video recorded**. | |
| 5 | I agree that any data collected may be published in anonymous form in **academic books, reports, conference proceedings or journals** | |

| | | |
|---|---|---|
| 7 | I agree that the researchers may retain my contact details in order to provide me with a summary of the findings for this study. | |
| 8 | I agree that I have no medical conditions or discomfort that might be aggravated by my participation in this research | |
| 8 | I understand that there may be instances where there might be need to break off into focus groups during the course of the research and information is revealed among participants which might break confidentiality, but notwithstanding, anonymity of all data sources would be guaranteed in the summary of findings. | |
| 9 | I agree to take part in this study | |

**Data Protection**

**The personal information we collect and use to conduct this research will be processed in accordance with data protection law as explained in the Participant Information Sheet and the Privacy Notice for Research Participants.**

________________________ ________________________ ______________

Name of Participant Signature Date

Lilian Iheukwumere-Esotu ________________________

Name of the person taking consent Signature Date

[One copy of the signed consent form will be for the participant.]
[The other signed consent forms, interview data, visual data and questionnaires in the possession of the researcher, will be locked in a cabinet in a secure location and digitised as soon as possible. The digital format will be in the University of Manchester's research data storage (RDS) for security]

## Introductory Letter

Dear (name of Particpant)

I am a Ph.D. student in the school of Mechanical, Aerospace and Civil Engineering (MACE) at the University of Manchester. I would like to invite you and your team to participate in a research I am undertaking as part of my studies. The research has been approved by the University's Departmental Ethics Panel. My research explores the experiences of people who have been involved in major overhauls, outages, shutdowns and turnarounds.

If you agree for you and your team to participate this will involve been interviewed once and it is expected that the interviews will last no longer than one hour for each participant. Also, follow up questionnaires will be sent to all participants in an encrypted email of word and pdf document subsequently. The proposed site for the interview would be at your place of work at a time that is convenient to get everyone on board. I would want to record and transcribe the interview using an audio recorder. All the interview data will be treated with confidentiality and locked up in a secured storage facility. However information about the research including interview data, and survey responses will be shared with my supervisors and other appropriate staff at the university. This should not cause any sense of panic as all the required information from the interview and survey are not intended to negatively impact on you or your team. Furthermore, responses are totally anonymous and can never be matched to any one individual.

Consent forms, with additional information sheet with the details below will be provided to each participant:

1. Who is conducting the research?
2. Why it is being conducted (including the true purpose of the research)?
3. Why they have been asked to take part?
4. What it requires of them (including the amount of time they will be required to commit and what they will have to do)?
5. What will happen to the data they provide
6. Whether and how their anonymity and confidentiality will be maintained
7. That their participation is voluntary and they are free to withdraw at any time without detriment (where possible)

I appreciate you giving time to this research and if you have any questions please do contact me via my email ………………………………………………. My supervisor Dr…………… is also copied in this email and you can contact him at…………………………………

Thank You

(Name of researcher)

If you are willing to participate in the research project outlined above please sign below.

Signature……………………………………………………..

Print name…………………………………………………..

Date…………………………………………………………….

# Sample Questionnaire

**Title of Research Study: Development of a Knowledge Based Framework for Managing Major Overhauls, Outages, Shutdowns, and Turnarounds (MoOSTs)**

Lilian Iheukwumere (PhD Candidate) and Dr. Akilu Yunusa-Kaltungo (Academic Supervisor)
The University of Manchester, United Kingdom
Department of Mechanical, Aerospace and Civil Engineering
Email: lilian.iheukwumereesotu@manchester.ac.uk; akilu.kaltungo@manchester.ac.uk

**Research study summary**

You are being invited to participate in a research project being conducted by a PhD candidate as a requirement for completion of her PhD thesis.

**Please note, for the purpose of this research, MoOSTs activities refers to planned maintenance that requires partial or total shutdown of all production activities. Practitioners involved in MoOSTs within their organisations are encouraged to fill out this survey to the best of their knowledge.**

**PARTICIPANT CONSENT**

- o Yes, I agree to participate
- o No, I decline to participate

PART 1

Demography information and Background Questions for all Participants

Q1. What is the highest level of school you have completed or the highest degree you have received?

- o Doctorate degree
- o Graduate degree (e.gMsc, MBA, PGDdip, PGDcert)
- o Bachelor degree
- o Associate degree
- o Some college but no degree
- o High school degree or Equivalent (e., A levels, GSCE)
- o Others (Please specify)……………………………………

Q2. Describe your job class (e.g., Supervisory, planning, scheduling, Engineering, Inspection, and Technician)

Kindly specify……………………………………………………

Q3. What industry are you practising in?

Kindly specify……………………………………………………

Q4. Where is your primary job location (Name of country)?

Kindly specify…………………………………………………………

Q5. What is the number of years you have spent in this organisation?

Kindly specify…………………………………………………………

Q6. How many years of experience do you have working on MoOSTS?

Kindly specify…………………………………………………………

Q7. When are you likely to retire (Years)?

Kindly specify…………………………………………………………

Q8. What is the number of people involved in maintenance in your organisation?

Kindly specify…………………………………………………………

Q9. What is the number of people involved in MoOSTs in your organisation?

Kindly specify…………………………………………………………

Q10. How many MoOSTs projects have you been involved in?

Kindly specify…………………………………………………………

Q11. Approximately what percentage of staff have left your organisation in the last 5 years (i.e less than 5%, 5-10% etc)?

Kindly specify…………………………………………………………

Q12. What were the possible drivers that necessitates MoOSTs in your organisation?

Please circle the reason(s) you agree with.

- Statutory requirements
- Preventive/scheduled maintenance
- To increase production
- Predictive maintenance
- Breakdown maintenance
- Others (kindly specify)……………………………………………………….

Q13. What is the frequency for performing MoOSTs within your organisation?

- Every 0-6 months
- Twice a year
- Once a year
- Once every 2-5 years
- 0nce every 5 years and above

Q14. What determines the MoOSTs budget and scope of activities?

- The scope of work determine MoOSTs budget
- The amount set aside for MoOSTs from the maintenance budget is used to determine the tasks to be performed

Q15. Approximately what percentage of your MoOSTs budget is estimated from the maintenance budget?

- Less than 5%
- 5%-10%
- 11% -25%
- 26%-50%
- 76%-100%

Q16. What percentage of MoOSTs that you have been involved in exceeded estimated costs?

- Less than 5%
- 5%-10%
- 11% -25%
- 26%-50%
- 76%-100%

Q17. What percentage of MoOSTs that you have been involved in were completed below the estimated costs?

- Less than 5%
- 5%-10%
- 11% -25%
- 26%-50%
- 76%-100%

Q18. What percentage of MoOSTs that you have been involved in were completed before the estimated timelines?

- Less than 5%
- 5%-10%
- 11% -25%
- 26%-50%
- 76%-100%

Q19. What percentage of MoOSTs that you have been involved in were completed after the estimated timelines?

- Less than 5%
- 5%-10%
- 11% -25%
- 26%-50%

- 76%-100%

Q20. What percentage of MoOSTs activities, if any, was contracted out?

- Less than 5%
- 5%-10%
- 11% -25%
- 26%-50%
- 76%-100%

Q21. What were the main reason(s) for delays during MoOSTs, please specify if more than one reason.

- Unplanned work
- Discovery work
- Change orders
- Weather
- Inaccurate schedule
- Labour and materials delay
- Other (Please specify)
- Labour and materials delay
- Other (Please specify)

Q22. What common approach(es) and documentation templates i.e meetings and/or reporting systems are utilised for knowledge management during MoOSTs in your organisation? Please select more than one if applicable.

- Post-project evaluations/Post-mortem reviews
- Project status review; daily/weekly/monthly site meetings
- After action reviews
- Before action reviews
- Emergency reviews due to unforeseen circumstances
- Other reasons, please specify

Kindly specify……………….

Q23. When do you capture knowledge obtained from MoOSTs. You can select more than one option.

- After execution and closure of MoOSTs
- Live capture during MoOSTs
- No we don't capture

Q24. Do you have a web based information and communications technology application for capturing/representing knowledge during and/or after MoOSTs.

- Yes
- No

- Maybe

Q25 what is the name of the web based IT tool used for capturing and representing knowledge in your organisation e.g. group wave, expert directories, intranet/extranet knowledge bases?

- Please specify the name……………………
- No, we don't have

## Question Guide for Semi Structured Participants Interview are Available.

1. What are the major maintenance activities performed during MoOSTs?
2. How is the team formed, is it always the same core team or is it formed for every new MoOSTs project?
3. What are the main reasons for delays during MoOSTs?
4. What is the normal duration for MoOSTs Planning?
5. How long does the MoOSTs execution normally last?
6. What is the impact of delays on production costs? (Please asides from a summary, provide monetary figures).
7. What is the ICT utilized for planning, capturing knowledge during MoOSTs?
8. Is the communication process during MoOSTs paper based, electronic or a mix of both?
9. Do you organize meetings during MoOSTs to discuss ongoing projects? If yes, who participates at these meetings, how long do they last, where are they organized?
10. Do you review MoOSTs project? If yes before or after?
11. Do you write reports? If yes, who writes the report, and how is it stored?
12. Could you give me any example of the issues that are treated in the reports or reviews?
13. What happens to the information that are generated from review meetings during MoOSTs?
14. Do you reference these reports in subsequent MoOSTs projects?
15. How are contractors briefed during MoOSTs, is there a representative?
16. How do you prioritize the knowledge you capture?
17. What happens to the information that are generated, are they saved? If yes, how are they saved and shared (paper based, online repository or real time, intranet, web based that is continually updated and made available immediately)?
18. What is the process for debriefing contractors?
19. Do you have any formalized approaches of learning from experience? I.e., is there a way experts are able to transfer their expertise across projects?
20. Can you give examples from your personal experience on how you learned new lessons?
21. In your opinion, what are the major barriers to knowledge management and learning from experience?
22. How do you think the barriers you have identified can be overcome, what measures do you envisage?

## Synthesized Pairwise Comparison Results using AHP Software ‘Transparent Choice.’

Table A1. Criteria weights by aggregate of all evaluators for main classes of probable causes.

| S/No. | Criterion | Weight | |
|---|---|---|---|
| | | Local | Global |
| 1 | Individual barriers | 0.28 | 0.28 |
| 2 | Organization barriers | 0.65 | 0.65 |
| 3 | Technology barriers | 0.07 | 0.07 |

Table A2. Criteria weights by aggregate of all evaluators for individual barriers.

| S/No. | Criterion | Weight | |
|---|---|---|---|
| | | Local | Global |
| 1 | b1 | 0.03 | 0.03 |
| 2 | b2 | 0.03 | 0.03 |
| 3 | b3 | 0.03 | 0.03 |
| 4 | b4 | 0.26 | 0.26 |
| 5 | b5 | 0.26 | 0.26 |
| 6 | b6 | 0.06 | 0.06 |
| 7 | b7 | 0.06 | 0.06 |
| 8 | b8 | 0.16 | 0.16 |
| 9 | b9 | 0.11 | 0.11 |

Table A3. Criteria weights by aggregate of all evaluators for organization barriers.

| S/No. | Criterion | Weight | |
|---|---|---|---|
| | | Local | Global |
| 1 | c1 | 0.03 | 0.03 |
| 2 | c2 | 0.03 | 0.03 |
| 3 | c3 | 0.02 | 0.02 |
| 4 | c4 | 0.32 | 0.32 |
| 5 | c5 | 0.08 | 0.08 |
| 6 | c6 | 0.13 | 0.13 |
| 7 | c7 | 0.13 | 0.13 |
| 8 | c8 | 0.26 | 0.26 |

Table A4. Criteria weights by aggregate of all evaluators for technological barriers.

| S/No. | Criterion | Weight | |
|---|---|---|---|
| | | Local | Global |
| 1 | d1 | 0.15 | 0.15 |
| 2 | d2 | 0.17 | 0.17 |
| 3 | d3 | 0.11 | 0.11 |
| 4 | d4 | 0.07 | 0.07 |
| 5 | d5 | 0.46 | 0.46 |
| 6 | d6 | 0.04 | 0.04 |

## Outcomes of Pairwise Comparison and Syntheses of the Three Main Classes of Probable Causes

Table A5. Synthesised matrix of the three main classes of probable causes.

| | I | O | T | Priority Vector | Transparent Choice |
|---|---|---|---|---|---|
| I | 0.24 | 0.23 | 0.38 | 0.28 | 0.28 |
| O | 0.71 | 0.68 | 0.54 | 0.64 | 0.65 |
| T | 0.048 | 0.10 | 0.08 | 0.08 | 0.07 |
| - | - | - | - | $\sum = 1$ | - |

Note: $\lambda_{max}$ = 3.065, CI = 0.0325, RI = 0.58, CR = 0.06 < 0.1 OK.

Table A6. Synthesised matrix for sub-criteria associated with individual barriers.

| I | b1 | b2 | b3 | b4 | b5 | b6 | b7 | b8 | b9 | Priority Vector | Transparent Choice |
|---|---|---|---|---|---|---|---|---|---|---|---|
| b1 | 0.030 | 0.030 | 0.030 | 0.041 | 0.041 | 0.018 | 0.018 | 0.023 | 0.016 | 0.028 | 0.03 |
| b2 | 0.030 | 0.030 | 0.030 | 0.041 | 0.041 | 0.018 | 0.018 | 0.023 | 0.016 | 0.028 | 0.03 |
| b3 | 0.030 | 0.030 | 0.030 | 0.041 | 0.041 | 0.018 | 0.018 | 0.023 | 0.016 | 0.028 | 0.03 |
| b4 | 0.212 | 0.212 | 0.212 | 0.286 | 0.286 | 0.263 | 0.263 | 0.352 | 0.245 | 0.259 | 0.26 |
| b5 | 0.212 | 0.212 | 0.212 | 0.286 | 0.286 | 0.263 | 0.263 | 0.352 | 0.245 | 0.259 | 0.26 |
| b6 | 0.091 | 0.091 | 0.091 | 0.057 | 0.057 | 0.053 | 0.053 | 0.039 | 0.027 | 0.062 | 0.06 |
| b7 | 0.091 | 0.091 | 0.091 | 0.057 | 0.057 | 0.053 | 0.053 | 0.039 | 0.027 | 0.062 | 0.06 |
| b8 | 0.152 | 0.152 | 0.152 | 0.095 | 0.095 | 0.158 | 0.158 | 0.117 | 0.326 | 0.156 | 0.16 |
| b9 | 0.152 | 0.152 | 0.152 | 0.095 | 0.095 | 0.158 | 0.158 | 0.029 | 0.082 | 0.119 | 0.11 |
| - | - | - | - | - | - | - | - | - | - | $\sum = 1$ | - |

Note: $\lambda_{max}$ = 9.447, CI = 0.0559, RI = 1.45, CR = 0.039 < 0.1 OK.

Table A7. Synthesised matrix for sub-criteria associated with organizational barriers.

| **O** | **c1** | **c2** | **c3** | **c4** | **c5** | **c6** | **C7** | **C8** | **Priority Vector** | **Transparent Choice** |
|---|---|---|---|---|---|---|---|---|---|---|
| c1 | 0.030 | 0.037 | 0.024 | 0.059 | 0.014 | 0.019 | 0.020 | 0.021 | 0.028 | 0.03 |
| c2 | 0.030 | 0.037 | 0.024 | 0.074 | 0.023 | 0.019 | 0.015 | 0.021 | 0.030 | 0.03 |
| c3 | 0.030 | 0.037 | 0.024 | 0.053 | 0.010 | 0.014 | 0.011 | 0.021 | 0.025 | 0.02 |
| c4 | 0.182 | 0.007 | 0.167 | 0.370 | 0.204 | 0.474 | 0.307 | 0.577 | 0.286 | 0.32 |
| c5 | 0.152 | 0.110 | 0.167 | 0.123 | 0.068 | 0.047 | 0.034 | 0.038 | 0.092 | 0.08 |
| c6 | 0.152 | 0.184 | 0.167 | 0.074 | 0.136 | 0.095 | 0.204 | 0.064 | 0.134 | 0.13 |
| c7 | 0.152 | 0.257 | 0.214 | 0.123 | 0.204 | 0.047 | 0.102 | 0.064 | 0.146 | 0.13 |
| c8 | 0.273 | 0.331 | 0.214 | 0.123 | 0.341 | 0.285 | 0.307 | 0.192 | 0.258 | 0.26 |
| - | - | - | - | - | - | - | - | - | ∑ = 1 | - |

Note: $\lambda_{max}$ = 8.688, CI = 0.09828, RI = 1.41, CR = 0.07 < 0.1 OK.

Table A8. Synthesised matrix for sub-criteria associated with technological barriers.

| T | d1 | d2 | d3 | d4 | d5 | d6 | Priority Vector | Transparent Choice |
|---|---|---|---|---|---|---|---|---|
| d1 | 0.153 | 0.124 | 0.094 | 0.184 | 0.161 | 0.227 | 0.157 | 0.15 |
| d2 | 0.153 | 0.124 | 0.281 | 0.122 | 0.096 | 0.227 | 0.167 | 0.17 |
| d3 | 0.153 | 0.041 | 0.094 | 0.184 | 0.096 | 0.136 | 0.117 | 0.11 |
| d4 | 0.051 | 0.062 | 0.031 | 0.061 | 0.069 | 0.136 | 0.068 | 0.07 |
| d5 | 0.459 | 0.622 | 0.469 | 0.429 | 0.482 | 0.227 | 0.448 | 0.46 |
| d6 | 0.031 | 0.025 | 0.031 | 0.020 | 0.096 | 0.045 | 0.041 | 0.04 |
| - | - | - | - | - | - | - | ∑ = 1 | - |

Note: $\lambda_{max}$ = 6.451, CI = 0.09015, RI = 1.24, CR = 0.073 < 0.1 OK.

# Description of Hierarchy Elements

Table A9. Hierarchy elements and their brief descriptions.

| Assigned Code | Hierarchy Elements | Brief Description of Hierarchy Elements |
|---|---|---|
| b1 | Low conscientiousness | Employees who score low on the ability to systematically codify experiences (i.e., tacit knowledge) gained from each MoOSTs cycle into written documents/procedures (explicit knowledge) that can benefit others in the future. |
| b2 | Low agreeableness | Employees who score low on cooperative interactions and willingness to work with others in order to learn and share knowledge for mutual benefits of the team. |
| b3 | Low openness | Employees who score low in the ability to actively seek and imbibe new learning experiences from social workplace teams or individuals. |
| b4 | Lack of practical/technical skills | Employees with little or no training, practical involvement for performing MoOSTs, and technical skills for accomplishing maintenance tasks will be unable to transfer same skills to others. |
| b5 | No awareness of strategic business orientation | Employees who are unaware of links between their immediate responsibilities to the entire business goals. |
| b6 | Lack of communication skills | Employees who lack requisite oral, written, and behavioural skills necessary to encourage human interactions within their workplace can limit the extent of sharing. |
| b7 | Lack of psychometric skills | Employees who lack aptitude (competencies, absorptive, and retentive capacity) can hamper learning and sharing. |
| b8 | Nonconformance to practical standards | Employees who are not trained on performance orientations based on adherence to practical standards for performing MoOSTs activities can limit the ability to transfer lessons learned. |
| b9 | Nonconformance to legal requirements | Employees who are not trained on performance orientations based on adherence to legal standards for performing MoOSTs activities can limit the ability to transfer lessons learned. |
| c1 | Limited participation in decision-making | Organizations where decisions are taken unilaterally in isolation, without seeking inputs from people involved in different facets of MoOSTs limit the extent of learning and sharing. |
| c2 | Chaotic environment during MoOSTs restricts sharing | Training and sharing experiences through contact time and interactions are restricted in MoOSTs environment because they are usually temporary and require large numbers of outsourced staff at different locations in the plant. |
| c3 | Limited job autonomy | Organizations that limit capabilities of employees to actively seek for problems and improvement areas within systems can limit individual learning experiences. |
| c4 | Restricted information flow | Bureaucratic and multilayered reporting organizations’ structure restricts information flow and limits sharing. |

| | | |
|---|---|---|
| c5 | Lack of leadership direction in championing values encouraging sharing | Absence of leadership strategies to implement and sustain sharing values can hamper employees' willingness to adapt. |
| c6 | Lack of a reward system | Organizations that do not offer incentives (which can be reflected in performance score cards, job security, etc.) to employees for sharing their experiences and or information. |
| c7 | Individualism is unduly encouraged | Organizations that encourage overtly competitive individuals rather than team building capacities when solving problems limit uptake of employees that are willing to share. |
| c8 | Knowledge retention of experienced staff is not prioritized | Organizations that do not recognise experienced employees as valuable assets in order to actively pursue efforts that promote acquisition, conversion, and diffusion of tacit to explicit knowledge during and after MoOSTs. |
| d1 | Inability to integrate with other processes | Installation of IT systems for MoOSTs activities have to be properly integrated into routine processes or it might limit employees' interactions such IT systems. |
| d2 | Lack of compatibility between diverse IT systems and processes | Organizations sometimes succumb to popular trends and acquire IT systems without thoroughly assessing the requirements and capabilities of their existing operational activities. |
| d3 | Lack of technical support | The inability of organizations to dedicate resources to respond to active queries within the IT system can limit the willingness of employees to interact with such systems. |
| d4 | Lack of employees' interest | Employees who are not interested or motivated to use available IT systems due to the inability of their Organizations to convince them on the intrinsic and extrinsic values such systems possess. |
| d5 | Lack of adequate training and development | Inability to allocate time and resources to train employees on different IT systems. |
| d6 | Unrealistic expectations of capabilities of IT systems by users | Limited information on the capabilities of existing IT systems can lead to employees having unrealistic expectations of what such systems can and cannot do, which can lead to disappointments and unwillingness to interact further with the system. |

## Further Details of the Sample Sizes within Each Participant Category

Table **A10. Group decision participants profiles and categories.**

| Participants Job Title | Sample Size | MoOSTs Responsibility | Category |
|---|---|---|---|
| Maintenance manager | 1 | Middle to senior management staff directly involved with MoOSTs, who makes/approves decisions on overall strategies. | A |
| Reliability manager | 1 | | |
| Health, safety, and environment manager | 1 | | |
| Contracts and purchasing manager | 1 | | |
| Maintenance planner | 1 | Supervisory staff involved with the implementation of engineering methods and/or techniques, who also has authority to make decisions during MoOSTs. | B |
| Shutdown executioner | 1 | | |
| Cost controller | 1 | | |
| Document controller | 1 | | |
| Maintenance technician | 2 | Shop floor staff experienced with handling plant assets and schematics showing working of the plant. | C |

## Comparison between Traditional Qualitative Method and Fuzzy Logic Method

| Traditional Qualitative Method | Fuzzy Logic Method |
|---|---|
| Degree of certainty given by statistical probability is meaningful only before the occurrence of the event. | Degree of membership with the fuzzy logic is relevant even after the event occurs. |
| An inextricable issue associated with the traditional method is uncertainty, due to inadequate data and imprecise information. The data obtained from an expert's judgement might lead to a subjective interpretation of available information, which cannot be treated solely by the traditional statistical method. | Fuzzy logic can overcome the imprecise nature of uncertainty based on the use of fuzzy membership function for dealing with uncertainty by providing a very precise approach. |
| The traditional method makes assumptions of the independence of events | Fuzzy logic does not make this assumption. |
| The traditional method assumes that all data are known. | Fuzzy logic never assumes that everything could be known. |

**Synthesized Matrix for Hierarchy of Labour and Source of Labour**

| Hierarchy of labour | | | | |
|---|---|---|---|---|
| | a1 | a2 | a3 | Criteria – normalized weight from AHP |
| a1 | 0.6536 | 0.6928 | 0.5556 | 0.634 |
| a2 | 0.2157 | 0.2309 | 0.3333 | 0.26 |
| a3 | 0.1307 | 0.2157 | 0.0037 | 0.11 |
| Source of labour | | | | |
| | b1 | b2 | b3 | Criteria – normalized weight from AHP |
| b1 | 0.7179 | 0.7500 | 0.6363 | 0.70 |
| b2 | 0.1795 | 0.1875 | 0.2727 | 0.21 |
| b3 | 0.1026 | 0.0625 | 0.090 | 0.09 |

**Nomenclature of Coding System used in Synthesized Matrix for Hierarchy of Labour and Source of Labour**

| Code | Nomenclature of codes used in Appendix C |
|---|---|
| a1 | Engineering/ shift manager |
| a2 | Supervisor |
| a3 | Technician |
| b1 | External |
| b2 | Combination (External and internal) |
| b3 | Internal |

## Score Details for Individual Assessment Criteria against Each participant for all the Rounds

| | Assessment Criteria | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Round 1 | | | | | | | | | | Round 2 | | | | | | | | | | Round 3 | | | | | | | | | |
| Participants | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 |
| 1 | 5 | 3 | 5 | 4 | 5 | 5 | 5 | 3 | 2 | 4 | 5 | 3 | 5 | 3 | 3 | 5 | 4 | 3 | 3 | 4 | 5 | 3 | 4 | 4 | 4 | 5 | 4 | 3 | 3 | 3 |
| 2 | 4 | 4 | 5 | 4 | 3 | 5 | 4 | 3 | 2 | 4 | 4 | 3 | 5 | 4 | 4 | 5 | 4 | 3 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 3 | 2 | 4 |
| 3 | 4 | 2 | 4 | 4 | 3 | 5 | 4 | 2 | 3 | 2 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 3 | 3 | 2 | 4 | 3 | 4 | 3 | 3 | 5 | 4 | 3 | 3 | 4 |
| 4 | 5 | 4 | 4 | 3 | 3 | 4 | 4 | 2 | 2 | 4 | 5 | 4 | 4 | 3 | 4 | 4 | 4 | 2 | 3 | 4 | 5 | 4 | 4 | 3 | 4 | 5 | 4 | 2 | 2 | 3 |
| 5 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 |
| 6 | 5 | 3 | 5 | 3 | 3 | 5 | 5 | 2 | 3 | 3 | 5 | 3 | 5 | 3 | 3 | 5 | 5 | 3 | 3 | 3 | 5 | 3 | 5 | 4 | 3 | 5 | 5 | 3 | 3 | 3 |
| 7 | 4 | 3 | 4 | 3 | 4 | 4 | 4 | 2 | 3 | 3 | 4 | 3 | 5 | 3 | 4 | 5 | 4 | 3 | 3 | 4 | 4 | 3 | 5 | 3 | 3 | 5 | 4 | 3 | 3 | 3 |
| 8 | 5 | 4 | 4 | 3 | 3 | 4 | 4 | 2 | 3 | 4 | 5 | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 3 | 4 | 5 | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 3 | 3 |
| 9 | 4 | 3 | 4 | 3 | 3 | 4 | 4 | 3 | 2 | 4 | 4 | 3 | 4 | 3 | 3 | 4 | 4 | 3 | 2 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 2 | 4 |
| Criteria Total | 40 | 30 | 39 | 31 | 31 | 40 | 38 | 25 | 23 | 31 | 40 | 31 | 40 | 30 | 31 | 40 | 37 | 27 | 25 | 28 | 40 | 27 | 38 | 31 | 31 | 42 | 37 | 26 | 24 | 31 |
| Criteria Average | 4.4 | 3.3 | 4.3 | 3.4 | 3.4 | 4.4 | 4.2 | 2.7 | 2.5 | 3.4 | 4.4 | 3.4 | 4.4 | 3.3 | 3.4 | 4.4 | 4.1 | 3 | 2.7 | 3.1 | 4.4 | 3 | 4.2 | 3.4 | 3.4 | 4.6 | 4.1 | 2.8 | 2.6 | 4.4 |

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