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Decommissioning of deep and ultra-deep water oil and gas pipelines: issues and challenges

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Abstract: In the offshore oil and gas industry, when production facilities reach the end of their economic life, field owners need to decide whether to replace, extend the life of, or decommission assets. Although life extension is a popular choice among end-of-life (EOL) management strategies, decommissioning of assets is inevitable. The decommissioning of deep and ultra-deep water pipelines used for the transport of oil and gas products has become a serious issue in recent years because it is a complex process and presents challenges to stakeholders. The current paper presents the experiences of pipeline decommissioning in different regions of the world, and then highlights issues and challenges related to decommission of pipelines in deep and ultra-deep waters. These issues and challenges can be broadly categorised into technical, financial or economic, health and safety legislation, environmental, and human or organizational aspects. Technical challenges are associated with the selection of appropriate decommissioning procedures for handling hazardous pipelines. Asset managers are also under pressure to reduce the costs associated with pipeline decommissioning operation as it involves huge financial commitments to companies. The decommissioning of deep and ultra-deep water pipelines may involve dangerous activities, which could adversely affect the immediate environment; therefore, asset managers must ensure that the impact of decommissioning processes on the environment is minimized. Human resource issues, such as lack of requisite skills, knowledge and experience about deep and ultra-deep water pipelines decommissioning, as well as their safety, are another challenge. In order to address the challenges identified in the study, some directions for future research are suggested.

Keywords: End-of-life (EOL); Decommissioning; Subsea pipeline; Life extension, Oil and gas, Deep-water installation.

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1. Introduction

Offshore petroleum reserves, which are located subsea, have led to the deployment of heavy-duty infrastructure as well as large-diameter pipelines to transport large quantities of oil over long distances from offshore platforms to refineries. When these assets (topside or subsea) reach the end of their service life with no future use, they must be decommissioned to ensure easy navigation of ships and safety for other users of sea (Tularak and Khan, 2007).

Decommissioning of offshore oil and gas assets has attracted the attention of practitioners, academics and the general public in recent years. According to Prasthofer (1998), there are over 7000 platforms distributed worldwide that may require decommissioning over the next 25 years. Ruivo and Morooka (2001) defined decommissioning as an end-of-life (EOL) management strategy that involves "*dismantling, decontamination and removal of process equipment and facility structures"* whilst Wiseman (2001) described decommissioning as "*the total demolition, decontamination, disassembling and removal of production facilities, when a field's life comes to an end"*. Generally, decommissioning in the offshore oil and gas industry can be described as the process of safeguarding oil and gas wells, processes and pipelines when reaching the end of their economic lives by taking into account health and safety and environmental protection issues.

Experiences of decommissioning in the offshore oil and gas industry has been growing in recent years. For example, about 7% of the infrastructure in the United Kingdom Continental Shelf (UKCS) has been decommissioned by 2011 (Bureau Veritas, 2011). About 88 oil and gas facilities have also been decommissioned in the North Sea by 2014 (Decom North Sea and Scottish Enterprise, 2014), among which there were 55 fixed platforms, 22 floating steel structures, three concrete gravity base platforms and eight other facilities. Aguilar *et al.* (2016) suggested that over 800 wells could be abandoned in the next few decades in the North Sea.

In the Gulf of Mexico (GoM), about 100 decommissioning operations take place every year (Islam and Khan, 2007). In a study, Boschee (2012) indicated that almost 1948 installations were removed from the GoM between 2000 and 2011, with the years 2009 and 2011 recording 11.65% and 11.85% of the removals respectively. Also, since 2003, the trend of installation removals has been on rise in the GoM as compared to new installations which are on the decline. In the Norwegian Continental Shelf (NCS), decommission is considered to be a relatively new activity and only a few platforms have been decommissioned to date (Jørgensen, 2002). Decommissioned offshore oil and gas facilities include pipeline bundles, Floating Production Storage and Offloading (FPSO) vessels, steel platforms, concrete platforms, topside process facilities and subsea installations such as manifolds and wellheads.

Pipelines are one of the key modes of transporting oil and gas products from the point of production to the point of use. The pipeline assets include flowlines (with the diameter up to 14"), umbilicals and power cables (with the diameter up to 8") and trunklines (with the diameter ranging from 16" to 32"). Data from Oil and Gas UK (2013) reveals that approximately 692km of flowlines (both rigid and flexible), 79km of umbilicals and power cables, and 62km of trunklines in the North Sea have been decommissioned by the end of 2013. The bar chart in Figure 1 illustrates the number of flowlines, umbilicals and power cables and trunklines decommissioned in the North Sea by 2013.

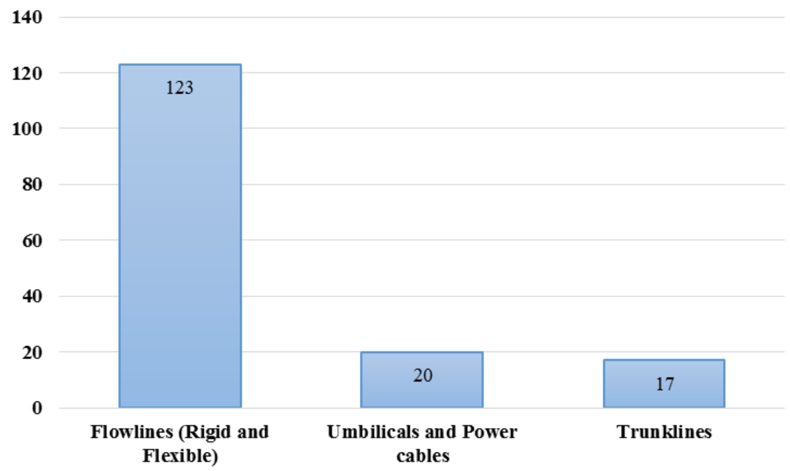

Figure 1. Number of flowlines, umbilicals and power cables, and trunclines decommissioned in the North Sea by 2013.

All the above-mentioned decommissioning projects were carried out in shallow waters with water depths of up to 140m. However, there are pipelines that have been installed in deep and ultra-deep waters with a depth of more than 1000m. Decommissioning of transportation pipelines in water depths exceeding 1000m is very complex and presents new challenges to current decommission strategies used in the offshore oil and gas industry.

This paper presents the experiences as well as best practices gathered from oil and gas decommissioning projects in different regions of the world while also highlighting the current and future challenges that may confront deep and ultra-deep water pipelines decommissioning. In order to identify and discuss the challenges associated with deep and ultra-deep water pipelines decommissioning, a thorough content analysis of industrial reports, journal articles and conference publications was undertaken. Also, interaction among industrial experts with several years of experience in decommissioning was an essential component in identifying the challenges.

The rest of the paper is organized as follows. In Section 2, the commonly used end-of-life management strategies for subsea assets are introduced. Section 3 provides an overview of subsea pipeline decommissioning experiences and best practices. Section 4 outlines the issues and challenges likely to confront the offshore oil and gas industry in relation to deep and ultra-deep water pipelines decommission and then suggests some directions for future research. Finally concluding remarks are given in Section 5.

2. Subsea asset end-of-life strategies

This section of the paper reviews the available end-of-life (EOL) management strategies for subsea assets. These include: (i) replacement of old facilities with entirely new ones either due to safety or regulatory requirements, (ii) life extension which involves the decision to extend the service life of existing facilities and (iii) decommissioning which involves dismantling and removal of the whole facility or some parts of the facility. In what follows, a brief overview of these EOL strategies will be presented.

2.1. Replacement

Replacement actions in most cases return a system or component to *"as good as new (AGAN)*" condition. However, its implementation is expensive and may cause long downtimes, therefore a decision to select replacement as the most suitable EOL must consider factors such as consequences of equipment unavailability, economic implications of replacement alternative and implications of lack of good quality data. Due to variable factors, the decision to replace a facility becomes critical only when there exists some difficulty in acquiring obsolete parts, overly increasing maintenance cost, changes in regulations, insurance consideration, warranty consideration, the high attrition rate of staff and aging workforce. Some replacement work conducted in the offshore oil and gas industry, as opposed to life extension or decommissioning. Chu *et al.* (2010) explained the pipeline replacement process for Matterhorn field which is located at the water depth of 800ft to 1200ft in the GoM. Wright (2013) discussed the replacement of an obsolete crane with a new one on a Bridge Linked Platform (BLP), and changing the old accommodation module with an updated module on an existing FPSO. Zuffetti *et al.* (2013) discussed the replacement of a single hull Floating Storage and Offloading (FSO) in the ROSPO field (which is an offshore oil field located off the coast of Pescara, Italy) with a new double hall and double bottom as the single hull did not comply with the European environmental and marine regulations.

2.2. Life extension

Life extension, as an EOL strategy, has been a topical issue in the offshore oil and gas industry (Shafiee and Animah, 2017). This strategy is employed when an asset reaches the end of its original design life but provided that the asset is economically and technically viable, its life is further extended. Life extension decision-making process comprises of economic, technical and organizational aspects. This process includes a detailed condition assessment of the critical subsystems and components in order to determine their level of sustainability during the extended period of operation while taking into account the requisite safety concerns. Studies conducted by various authors in the offshore oil and gas industry show that extending the service life of the offshore oil and gas facilities beyond their original design life is highly beneficial.

Because of the increasing interest in life extension across the offshore oil and gas industries, some researches have focused on developing a framework to support life extension decision-making process. Galbraith *et al.* (2005) in collaboration with Cranfield University and the UK health and safety executive (HSE) developed a capability maturing model (CMM) for assessing the technical status of offshore installations to support life extension decision making process. Rincón *et al.* (2007) presented successful case studies of pipelines life extension using integrity management practices. Hudson (2008) and Hudson (2009) provided a practical approach to ensure optimal use of assets, time and resources during life extension period of operation. Saunders and Sullivan (2010) discussed various requirements, methods and technologies developed for life extension of flexible pipes. The study also demonstrated through a case study that with proper integrity management systems the life of flexibles pipes can be extended beyond their original design lives. Hokstad *et al.* (2010) proposed a framework for life extension decision-making process integrating material degradation, obsolescence and organisational issues to ensure acceptable technical integrity of offshore assets throughout life extension period. Vaidya and Rausand (2011) proposed a framework for technical health assessment of critical assets for life extension and applied it to a subsea raw seawater injection system. Liu *et al.* (2014) proposed a framework for managing life extension in Chinese offshore Bohai bay. Brandt and Mohd Sarif (2013) in a study proposed equipment health assessment technique for life extension decision-making and applied it to topside systems.

Ramírez and Utne (2013, 2015) developed a virtual age model for assessing the technical capabilities of repairable safety critical components for life extension. A case study involving fire water pump life extension was used to validate the model. Leira *et al.* (2015) outlined the processes involved in qualifying flexible risers for extended operation. A case study involving specific riser configuration was used for purpose of illustration. Shafiee *et al.* (2016) developed a techno-economic feasibility analysis framework to support life extension decision making of safety critical installations. The framework was subsequently applied to support life extension decision making process for water deluge system in the offshore oil and gas industry. Animah and Shafiee (2018) proposed a systematic framework which establishes an integration between three individual life assessment modules, namely: condition assessment, remaining useful life (RUL) prediction and life-extension decision-making. In order to achieve a successful life extension project, a suitable strategy must be selected. Examples of such strategies include repair, remanufacturing, reconditioning, retrofitting and refurbishment. Animah *et al.* (2017) proposed a multi-stage approach to analyze the impact of life-extension on the performance of industrial equipment in terms of total operating cost and carbon footprint. For the purpose of clarity, the proposed model was applied to an air compressor system and the results were discussed in details.

2.3. Decommission

Decommission characterizes the final stage of asset life cycle, when life extension and replacement strategies are no longer technically or economically viable. This is considered as the least preferred EOL strategy by asset managers in the majority of the industries. In the offshore oil and gas sector, the decision to decommission the assets that are underwater is considered to be complex and critical (Kaiser and Pulsipher, 2004), as it must take into account several factors such as cost, health and safety, and environmental impacts. Currently, there is a very limited research on the decommissioning operations of subsea assets, as this strategy is relatively new in the offshore oil and gas industry. Prasthofer (1998) in a study presented some solutions to the technical and operational challenges associated with decommissioning, removal and disposal of large steel and concrete platforms. Decommissioning strategies for processing facilities and deck and jacket structures include relocating the asset for re-use, removal and scrapping, possible conversion to artificial reef sites and disposing-off in deep water if the asset does not pose any hazard. Ruivo and Morooka (2001) proposed full removal, partial removal and trenching and burial as suitable decommission strategies for pipelines. Kaiser and Pulsipher (2004) discussed the decision-making factors required for explosive or non-explosive decommissioning methods. The study further proposed a predictive model to quantify the decision to use explosive method. Ekins *et al.* (2006) performed a comparative study involving material and energy flow analysis with associated financial inflows of different decommission strategies for different components of offshore oil and gas structure. Philip *et al.* (2014) presented the overview of decommissioning process for subsea pipelines. Kaiser (2015) developed a decommission risk metric which was defined as the ratio of the expected value of field's reserves to its expected cost of decommissioning. The metric helped in providing details of future decommissioning activities. Jais *et al.* (2016) in a study described how operators in South East Asia developed the decommission capabilities of in-house staff in collaboration with other international experts.

3. Decommissioning of subsea pipelines: best practices

Various types of offshore oil and gas infrastructures have been decommissioned over the past decades. In what follows, we briefly discuss the decommissioning experiences and best practices in the United Kingdom Continental Shelf (UKCS), the Norwegian Continental Shelf (NCS), Gulf of Mexico (GoM), Australia, South East Asia, Brazil and Sub-Saharan Africa.

3.1 The United Kingdom Continental Shelf (UKCS)

The past decade has witnessed considerable growth in the UKCS decommissioning industry. According to Ekins *et al.* (2006), the decommissioned structures in the UKCS include Brent Spur, Maureen and the Ekofisk platforms. Though, decommissioning is still a relatively immature activity in the UKCS and a lot can be learned from the best practices implemented in other areas. Table 1 summarizes the details of the approved decommissioning activities in the UKCS.

Table 1. Approved decommissioning projects in the UKCS between 1998–2016

Asset	**Quantity**
Pipeline Bundles	50
FPSO's	14
Subsea Installations	19
Topsides	1
Platforms	37
Manifold, Compressions & Wellheads	3
Mooring Buoy	4
Mobile Jack-up	1
Total	**129**

Since the 1990s, the oil and gas pipelines decommissioning in the UKCS has continued to grow at a steady rate. However, by 2013, less than 2% of the UKCS's pipelines have been decommissioned. Among these, almost 80% of the pipelines had a diameter of fewer than 16 inches and the longest pipeline decommissioned was 35 km long (Borwell, 2014). The Oil and Gas UK's report (2013) forecasted that from the year 2013 to 2022, more than 2,300 km of pipelines are planned to be decommissioned in the UKCS. According to West (2015), there should have been more decommissioning activities in the UKCS than the current numbers. Therefore, as the bulk of the UK oil and gas reserves are in the North Sea, decommissioning activities are projected to significantly increase in the next 20 years.

3.2 The Norwegian Continental Shelf (NCS)

In the NCS, 23 decommission projects are planned to take place from the year 2015 to 2024 (Oil and Gas UK (2016). The facilities to be decommissioned include subsea tie-backs to full platform removal. These projects consist of 14 total or partial platform removals, 26 pipelines with a total length of 360 km and 284 wells to be plugged. One of the biggest decommission projects in the NCS to date involves the Frigg platform, and by 2010, other platforms earmarked for decommissioning in the NCS including AF Miljøbase Vats, Aker Stord, Scanmet AS and Lyngdal Recycling. The Climate and Pollution Agency (2010) estimated that decommissioning of an entire platform in the NCS costs £16 billion. However, following evidence in past literature, there are less decommissioning activities in the NCS as compared to the UKCS. Hence, considering the huge number of platforms and subsea systems operating in this area, the NCS still presents an opportunity to the decommissioning market in the North Sea.

3.3 Gulf of Mexico (GoM)

The GoM represents the biggest decommissioning offshore oil and gas market in the world. It has experienced increased decommissioning activities, due to the rising number of aging installations coupled with low oil prices, making life extension unattractive. For instance, Figure 2 shows the trend of newly installed and decommissioned platforms in the GoM during 1990–2011.

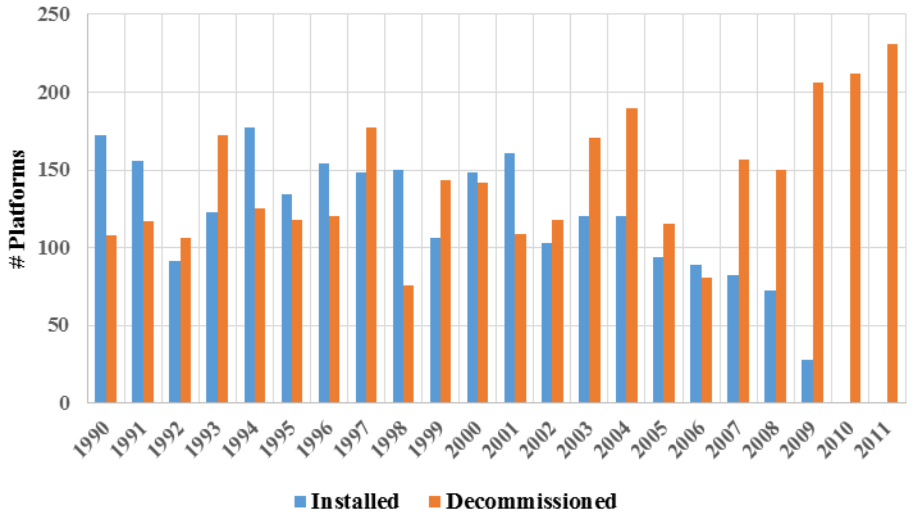

Figure 2. Number of newly installed and decommissioned platforms in the Golf of Mexico between 1990 and 2011.

In surveying literature on decommissioning in the GoM, Hakam and Thornton (2000) discussed the possibility of reefing and reuse of GoM platform complex. Thornton and Wiseman (2000) provided an overview of the decommissioning operations, outlined challenges facing regulators, and then identified the resources required for decommissioning in the GoM. Kaiser and Pulsipher (2005) described the Louisiana and Texas artificial reef programme and further discussed regulatory requirements and decommissioning strategies available to operators. Kaiser (2006) described the decommissioning regulatory requirements in the GoM and subsequently developed cost functions for shallow-water decommission application in the GoM. Kaiser and Dodson (2008) assessed the trend of plugging and abandonment cost in the GoM using data from 1156 wells obtained during 2002 and 2007.

Kaiser *et al.* (2009) examined the cost of platform removal operations in shallow waters in the GoM. The study determined the cost of preparation, pipeline abandonment and removal cost using first-order regression models. Kaiser *et al.* (2003) discussed the cost components of various decommissioning strategies and also developed decommissioning cost functions for the GoM region based on actual field data. Kaiser and Liu (2014a) applied work decomposition algorithms developed by ProServ to determine the cost of decommission strategies such as well plugging and abandonment. The paper considered different assets including pipelines, umbilicals, flowlines and deck and hull removal of 42 floating structures in the GoM. Price *et al.* (2016) developed an efficient and effective decommission approach which incorporates multiple services and manages them as a single point project, with the aim of executing decommissioning project safely and at a fixed cost to operators. The approach was subsequently validated in the GoM on an eight-pile platform in 2015. Siems (2016) employed a new technology and methodology to optimize decommissioning process in the GoM. According to Dempsey *et al.* (2000), the majority of the pipelines decommissioned in the GoM were not removed after receiving waiver on complete removal from regulatory authorities. However, considering the water depths these abandoned pipelines could pose risk to ship navigation and obstruct other user of the sea in the future.

3.4 South-East Asia region

Although about %36 of installations in the South-East Asian oil fields are between ages of 20 and 30 years and %12 are over 30 years very few decommissioning projects have been carried out in this region (Lyons, 2012). Therefore, the region has experienced limited decommissioning experiences and thus, there will be an opportunity to learn lessons from best practices in the North Sea and GoM. At the time when it is uneconomical and challenging for the operators to extend the service life of installations, decommissioning will be the only option. These installations are aging rapidly and therefore, there is a need for operators in this region to develop the capacity of staff members. This can be accomplished through collaboration with international companies having the required experience, in order to handle the challenges ahead. According to Jais *et al.* (2016) decommissioning staff capacity should be enhanced in the areas of technical know-how, cost estimation, in-house organizational culture, standard management systems and other aspects involving senior management of the companies. Moreover, regulatory bodies, as a matter of urgency should develop decommission regulatory approval process for operators. This is because operators in countries like Thailand, Indonesia and Malaysia are required to decommission part of their assets in next few years due to the low oil prices. For instance, there are about 50 wells earmarked for decommissioning in Malaysia in 2016. However, currently, there is no legislation governing decommissioning of the offshore oil and gas assets in Malaysia (http://analysis.decomworld.com/).

3.5 Australia

Decommissioning experiences in Australia are limited as compared to the UK and the USA. Dempsey *et al.* (2000) indicated that by the year 2000, only two FPSO installations were fully decommissioned in Australia, making it a relatively new area of operation. These FPSOs are the Marathon’s Talisman off Western Australia and the BHP Petroleum Skua Venture in the Timor waters. Most of the FPSO facilities were re-used, while it was not clear what happened to the pipelines. However, it is estimated that about 60 structures are planned to be decommissioned in Australia (http://www.decomworld.com) and this number is expected to increase to 100 in the next 25 years, with an estimated cost of AUD$1.2 billion (http://www.ampla.org). For instance, a group led by Cheveron Corp has presented decommission plan for the Thevernard Island oil and gas facilities in the water depth between 12 and 18m in Western Australia. However, these subsea pipelines will be disconnected and left in place (http://www.ogj.com/articles).

3.6 Brazil

Brazil with 156 oil platforms holds the second largest oil reserves in South America after Venezuela (Brazilian Navy, 2015). Out of these platforms, 18 fixed platforms are between the ages of 25-30 years, while 47 fixed platforms are over 30 years. However, six fixed platforms in the Mero field including PGA-6, PAP-1, PRB-2, PCAR-1, PCM-11, and BAS-37 have been decommissioned in Brazil till date (Mimmi *et al.*, 2015). The PAP-1 jacket structure and topside facilities were reused, PRB-2 jacket structure was used as an artificial reef, while the topside processing facilities were removed and subsequently scrapped. PCM-11 topside facilities were re-used by another platform, while the jacket structure was left in place. However, it was not reported how the subsea pipelines were decommissioned.

3.7 Sub-Saharan African region

Similar to many other regions, decommission activities in Sub-Saharan African (SSA) region is relatively new. Currently, an estimated 867 offshore platforms, 877 subsea wells and over 15,000km of offshore pipelines have been installed in the SSA region. Although the majority of the offshore oil and gas installations operating in SSA are in their early life stages, some are aging and will need to be decommissioned in the near future. Though no large structure decommissioning operations have occurred in Sub-Saharan Africa, about 50 small scale decommissioning projects have taken place in Nigeria and Angola. The SSA region presents a real opportunity for the decommissioning market and the regulators in this region must put in place a right legal framework in order to support the decommissioning projects in the future.

4. Pipeline decommissioning challenges in deep and ultra-deep waters

Despite some experiences with pipelines decommissioning in shallow-waters, decommission of pipelines in deep and ultra-deep-water still present its own distinct challenges since this is an unexplored area in the industry. This section of the paper presents the challenges associated with decommission of deep and ultra-deep water pipelines in the offshore oil and gas industry.

4.1 Whole life cost prediction for decommission of deep and ultra-deep water pipelines

The present state of the oil and gas market has placed many companies in a challenging economic situation. Currently, decommissioning cost estimates are based on the expected values, which are often calculated according to various assumptions depending on the operator. According to Decom North Sea and Scottish Enterprise (2014), a number of institutions have projected the decommissioning cost in the North Sea for the next decade. However, there are considerable differences in these estimates. The uncertainty of decommission expenditure predictions have the tendency to unduly delay deep and ultra-deep water pipelines decommission activities. Therefore, accurate prediction of these expenditures is an essential component of the decommissioning decision-making process. However, this is a serious challenge for the offshore oil and gas industry, as it is tough to identify an appropriate decommissioning cost estimation model. Whole life cost (WLC) analysis methodology has been developed over the years to support the decision-making process during design, installation, operations and maintenance of industrial assets. However, this tool has rarely been applied to the pipeline decommissioning project in the offshore oil and gas industry. One of the primary challenges that must be addressed in this regard is applying the current cost into future. Thus, decommissioning cost estimation models for deep and ultra-deep water application must incorporate diverse decommission strategies in order to facilitate sensitivity analysis of these strategies on the basis of cost and to reduce the level of uncertainty. Finally, the decommissioning cost estimation models should be developed on the case-to-case basis, as each project is accompanied by its own unique and peculiar factors. However, the underlying principles can remain applicable to all the projects.

4.2 Scheduling deep and ultra-deep water pipeline decommissioning task

Kaiser and Liu (2014b) indicate that the estimates for the timing of deep and ultra-deep water decommissioning operations have not been reported. The main aim of scheduling the pipeline decommissioning task is to help optimize the decommissioning operations. Deep and ultra-deep water pipeline decommissioning scheduling is very complex and challenging for many offshore oil and gas companies. This is because some factors like weather favorability, regulatory permit acquisition and the current stance of the oil market must be considered. These factors have the capacity to cause serious disruptions in decommissioning activities by extending or shortening the lead times for decommissioning of pipelines. This is because decommissioning schedules can be altered at short notices which present significant challenges for the companies. According to Oil and Gas UK's report (2015), shifting of decommissioning projects' schedules has shortened the peak period for decommissioning activities in the central and northern regions of the North Sea by three years. This is now a challenge for companies to handle. The decommissioning schedules include a date for signing contracts, due dates for actual decommission operations, dates of applying for regulatory approval, dates for vessel release, as well as a detailed list of both technical and human resources required. In certain countries, the application process for regulatory approval is slow, manual and prescriptive, thereby causing delays in scheduling time.

In many jurisdictions, the start time as well as the duration for deep and ultra-deep water pipelines decommission are left at the discretion of the operating companies. This presents a challenge when unproductive pipelines are left in-place, without beginning the pipeline preparation till the end of the field's life. Operating companies should be encouraged to report idle deep and ultra-deep water pipelines to the regulators so that the pipeline preparations can commence prior to actual decommission operation and save time and cost during decommission.

4.3 Standardization of deep and ultra-deep water decommissioning procedure

Currently, a major challenge in deep and ultra-deep water pipelines decommissioning is that these procedures are fragmented and not standardized in many countries (Brown, 1997). This means that there are no guidelines to support the deep and ultra-deep water pipeline decommissioning operations, which are considered extremely complex. Therefore, efforts must be made to bring together companies, regulators and sub-contractors and amalgamate the best practices from other industries in order to develop appropriate guidelines for deep and ultra-deep water decommissioning analysis. These guidelines must involve a sequence of operations for effective decommissioning, as well as sections for certification of qualified personnel by reputable institutions, such as DNVGL.

4.4 Selection of suitable pipeline decommissioning strategy

Shallow water pipelines decommissioning strategies involve partial removal, full removal, abandonment or re-use of the pipelines for other purposes (Bijker and Chen, 2001). Each of these strategies is sensitive and complex. Selecting the most appropriate strategy among the above-mentioned alternatives for deep and ultra-deep water application is challenging when complying with regulatory standards as well as reducing the overall decommissioning cost. This is because the selection criteria (such as safety, cost, and added value) for decommissioning of deep and ultra-deep water pipelines are often conflicting and cannot be easily converted into quantitative values. Currently, the use of accumulated experience of experts is primarily employed for determining the most suitable decommissioning strategy for deep and ultra-deep water pipelines, which does not necessarily lead to an optimal solution. Therefore, appropriate alternative selection tools, such as Multi-Criteria Decision Making (MCDM) Approach and Cost Benefit Analysis (CBA) are recommended to decision makers in order to rank and choose the most appropriate deep and ultra-deep water pipeline decommissioning strategy. Applying these tools to the problem offers the advantage of making complex decommission decision-making process relatively simpler.

4.5 Workforce-related challenges

The offshore oil and gas industry has been experiencing personnel shortfalls, in terms of numbers, skills, and experience. This is partially due to the plummeting oil and gas prices, as well as the phenomenon of a great crew change. For instance, electric line operations on the rigless plugging and abandonment (P&A) are one of the sectors experiencing manpower shortages, which directly affects the decommissioning of subsea pipelines. The P&A workers are involved in the jet-cutting of tubing and casing, the setting of bridge plugs, and downhole delivery of cement (dump-bailing), among other tasks. The shortfall in personnel may also be because of the aging workforce, early retirement of essential workers and inability on the part of companies to attract young people into the offshore oil and gas industry. It is predicted that oil and gas companies will face shortages of nearly 15,000 engineers, including those with decommissioning experience (http://accelrys.com). In addition, the shift from shallow water decommissioning to deep and ultra-deep water decommission will require a different set of the workforce with superior experience in order to successfully remove pipelines in water depths greater than 100m.

4.6 Technological challenges

Limited decommissioning experiences in the offshore oil and gas industry has attracted the need for more advanced technologies. However, decommissioning of pipelines in deep and ultra-deep waters still involves some level of technical challenge. The technologies executing these operations are currently lagging behind, in terms of development and also face the dearth in the capacity to undertake deep and ultra-deep water operations effectively. Unlike shallow water decommissioning where divers are used to support pipeline decommission operations (Byrd *et al.*, 2014), deep and ultra-deep-water pipelines decommissioning operation requires highly skilled remote operating vehicles (ROV). Some other technical issues are yet to be resolved during the decommissioning of deep water pipelines to make it a reliable cost-effective cutting method and large-capacity crane barges due to the weight of some of the pipelines.

4.7 Regulatory, health and safety, and environmental issues

A statistical probability of serious and fatal accidents occurring during the decommissioning process of the "Ekofisk" oil field was estimated in Ekins *et al.* (2006). Health and safety issues during the decommissioning activities may be because of the exposure to hazardous materials, diver exposure, use of explosives, and multiple heavy lifts (Prasthofer, 1998). However, factors like water depth, remote operations and unacceptability of the incidents from regulators' perspective lead to significant risk levels that have not been handled by some companies in the offshore oil and gas industry before. This indicates that deep and ultra-deep water decommissioning operations pose a significant risk to the health and safety of the personnel because of their complex nature. On the other hand, decommissioning activities also result in potential environmental dangers for the sea environment. Therefore, subsea pipelines decommissioning project must be supported by a thorough assessment of environmental impact.

Decommissioning projects in many jurisdictions are regulated either by national or international laws. For instance, in the UKCS, decommissioning of platforms is executed according to the Petroleum Act (1998) and OSPAR convention (2007). Similarly, some other international regulations that may support deep and ultra-deep water pipelines decommissioning are the Geneva Convention (1958), United Nations Convention on the Law of the Sea (1982) and International Maritime Organization Guidelines and Standards (1988). However, the problem is that currently, in many countries like the UK, pipeline decommissioning is not governed by any specific regulations. In absence of proper legal framework for deep and ultra-deep water pipelines decommissioning, operators are confronted with the task of not being able to determine the scope of their operations.

4.8 Logistics-related issues

Logistics mobilization for offshore oil and gas decommissioning operations is a very crucial task and even more critical in deep and ultra-deep water pipelines decommissioning operations. Logistics support for decommissioning operations includes hiring of the helicopter, renting service vessel for crew transportation, preparation of vessel, hiring of extra accommodation, platform services, power generation and waste management (Oil and Gas UK, 2015). The cost associated with logistics support constitutes a significant portion of the decommissioning cost and therefore asset managers are confronted with the challenge of minimizing this cost. It is very unlikely that a single company can execute an entire decommissioning project and some portions of the operations are often outsourced to specialized companies called subcontractors. Philip *et al*. (2014) suggests that based on the complexities involved in decommissioning operations, some aspects of these projects must be assigned to specialists in order to execute the projects in a timely manner. In deep and ultra-deep water pipelines decommissioning operations, it is expensive and complex to retain the decommissioning operations in-house as it requires significant investment to train personnel, equip specialized units and determine the scope of the work to facilitate the tendering process. Hence, outsourcing the decommissioning operations is probably an efficient strategy that enables the companies to reduce the cost of deep and ultra-deep water decommissioning. The decommissioning contracts are classified into operator-led-reimbursable with the lump-sum and the engineering, procurement, removal and disposal (EPRD) arrangements (for more see, Oil and Gas UK (2015)). It is suggested that a high-quality industry decommissioning contracting model is developed to support the operations, especially in deep and ultra-deep waters.

4.9 Knowledge management

Knowledge management involves the process of gathering, organizing and sharing the information to suitable personnel for appropriate action (Alavi and Leidner, 1999). At present, the offshore oil and gas industry faces “tremendous tasks and challenges” for implementing the knowledge management systems due to poor organizational culture (Saif, 2015).

The lifecycle of offshore oil and gas pipelines is comprised of design, installation, operation, and decommissioning. However, due to poor organizational culture, some companies are unable to consolidate the pools of data generated from various stages of the pipeline lifecycle in order to support the decommissioning operations. This has resulted in a lack of good quality data, which is essential for deep and ultra-deep water pipelines decommissioning operations. One of the reasons ascribed to lack of good quality data is that a significant number of fields have changed operatorship with time, thereby resulting in the loss of data during the process. For instance, in the GoM, numerous fields have been operating separately and over the time, some data has been missed during the transfer from one owner to another. Boschee (2012) suggested that due to the reduction of manpower for the offshore oil and gas industry in the mid-1980’s, there was a drop in the quality of records keeping. In fact, even usually, the culture of records keeping in the offshore oil and gas industry is relatively poor.

Furthermore, deep and ultra-deep water operations in offshore oil and gas sector represent a knowledge-intensive area that involves geologists, economists, petrochemists, corrosion engineers, subsea engineers, etc. However, knowledge and experience from various stages of asset life cycle are held by the people called experts (Edwards, 2008). But, it is challenging to bring these experts together for the pipeline decommissioning operations. Hence, one of the major trials facing the companies during these operations is the inability to pass the institutional memory. Shammas (2007) reported that by 2007 the average age of Statoil employees was 44 years and these employees served as a repository of very important information, knowledge, and experience that was essential for decommissioning operations. Moreover, the older workers did not have the sufficient analytical and computing skills that are in line with the fluctuating industry necessities.

5. Conclusions and future work

The trend of decommissioning activities is on the rise in the offshore oil and gas industry. However, there has been a growing concern to industry, government and environmental agencies over decommissioning of offshore pipeline assets especially in deep and ultra-deep waters. Activities such as installation, commissioning, fabrication, and maintenance come with possible health and safety hazards as well as environmental risks, but decommissioning presents potentially higher risks due to lack of data, knowledge and experience. Although the industry has gathered some experience and skills from shallow-water decommissioning, deep and ultra-deep water pipeline decommissioning present some unique challenges.

This paper outlined the issues and challenges involved in decommissioning of deep and ultra-deep water pipelines in the offshore oil and gas industry. Some of the key challenges identified in the study include: an inability to accurately predict pipelines decommission cost, knowledge management and workforce challenges. In addition, technological challenges, lack of analytical models for selection of the most suitable decommissioning strategy, lack of regulatory regimes for deep and ultra-deep water pipeline decommissioning as well as cost of procuring additional support vessels and accommodation for personnel have increased the complexities involved in deep and ultra-deep water pipeline decommissioning activities.

In order to achieve successful decommissioning of deep and ultra-deep water pipelines, the industry must develop improved, safe, environmentally friendly and cost-effective decommissioning strategy. Stricter and tighter regulations are required for deep and ultra-deep water pipelines decommissioning to prevent environmental impacts. Also, there is an opportunity for offshore oil and gas companies to reduce the risks and cost associated with decommissioning by considering other alternative end-of-life strategies such as life extension.

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