A technical evaluation to analyse of potential repurposing of submarine pipelines for hydrogen and CCS using survival analysis

Ramy Magdy A. Mahmoud[1,*], Paul E. Dodds[2]

[1] UCL Energy Institute, University College London
[2] UCL Institute for Sustainable Resources, University College London
* Corresponding author: 14 Upper Woburn Place, London WC1H 0NN, UK.
E-mail address: ramy.mahmoud.18@ucl.ac.uk

ABSTRACT

The UK oil and gas sector is mature and a combination of a dwindling resource base and a move towards decarbonisation has led to lower investments and an increasing decommissioning bill. Many existing offshore assets are in the vicinity of potential renewable energy developments or low-carbon facilities. We propose a technical evaluation process to understand whether pipelines might be repurposed to reduce the costs of low-carbon energy investment and oil decommissioning.

We identify survival analysis as an effective method to investigate the potential of pipelines repurposing based on historical failure records, as it deals with acceptable levels of data gaps and does not require associated field costs for detailed inspection. It provides a close estimate of the anticipated remaining life when compared to feasibility studies. We use survival analysis to examine several repurposing case studies for low-carbon investments. It also demonstrates that several pipeline systems have the potential to operate safely beyond their design life. Detailed records of failure will allow for further development of this methodology in the future.

KEYWORDS

Energy Transition; Repurposing; Submarine Pipeline; CCS; Hydrogen

1 INTRODUCTION

Decades of offshore oil and gas development have left behind a substantial number of offshore assets that require decommissioning. The UKCS (United Kingdom Continental Shelf) volume of decommissioning between 2020 and 2029 will include 7,790 km of subsea assets (i.e. pipelines and cables) which comes at a bill of £1.7 billion (OGUK, 2020). The need for CO_2 reduction and lower prices of oil and gas would reduce exploration and production of fossil fuels and could lead to the early retirement of assets (Oudman, 2017). In parallel, The Crown Estate (2019) launched the UK's first leasing round of offshore wind in a decade (i.e. Round 4), which offers the opportunity of 7 to 8.5 GW by 2030. Parallel decommissioning and low-carbon developments in the North Sea could offer opportunities for energy transition and integration, which could repurpose existing assets as a part of several types of investment (OGUK, 2019):

- Offshore energy hubs: convert natural gas to hydrogen.
- Power to gas: hydrogen generation using offshore wind power.
- CCS: use of assets to collect, transport and store CO_2.

Therefore, the number of hydrogen and CO_2 pipelines is likely to grow in the upcoming years. Offshore transportation of oil and gas has been practiced and executed for decades, and there is heritage of lessons learnt to deal with the challenges that confronted the sector such as corrosion control, deep water installation, in addition to geological, environmental and geotechnical obstacles. Transportation of hydrogen and CO_2 remain a niche sector with growing potentials and the risks are much similar. However, there would be further issues in material performance such as embrittlement, and unlike hydrocarbons assets designed to an average of 25 year design life, hydrogen and CO_2 facilities are probably required to operate for a various duration depending on the project nature.

1.1 Hydrogen production

Hydrogen is expected to have a substantial role in the lowest-cost route for the UK to meet emission targets (Mackinnon and Gomersall, 2019; Peters et al., 2020). Peters et al. (2020) emphasise that repurposing existing platforms to deploy power-to-gas (i.e. hydrogen) technology would enable far offshore wind farms to transport energy at a lower LCOE (Levelised Cost of Energy), which will avoid excessive power loss via long-distance submarine cables.

Transportation costs of hydrogen are significant, between 23% to 58% of project CAPEX (Babarit et al., 2018), so repurposing pipelines could have a positive effect on future developments and LCOE accordingly. Cerniauskas et al. (2020) estimated that 80% of German natural gas onshore pipelines could be repurposed for hydrogen transport, which would reduce transmission costs by 60%.

1.2 CCS

Repurposing of pipelines for CCS was early investigated by Rabindran et al. (2011). Brownsort et al. (2016) demonstrate that existing pipelines suitable for CO_2 transportation could offer savings to CCS projects. Onyebuchi *et al.* (2018) estimate CO_2 transportation as 21% of the total cost of a CCS project.

The rapid growth of CCS would require a parallel CO_2 transportation network. Spinelli et al. (2014) expect that a huge number of pipelines would be required to accommodate CCS needs, and Kjärstad et al. (2013) provided a projection of 6,200 km subsea pipelines, mostly in the North Sea, would be required in Europe by 2050. Repurposing could be one of the solutions to meet the massive demand for CO_2 transportation.

1.3 Historical repurposing of offshore facilities

Oil falling prices between 2014 to 2016 have accelerated the efforts in life extension and repurposing in the oil and gas sector such as:

- Subsea wells can be used for geothermal production applications such as enhanced geothermal systems and borehole heat exchangers (Caulk and Tomac, 2017; Weijermars et al., 2018),
- Upgrade or conversion of floating units (Martijn Van Wijngaarden and Daniels, 2019),
- Converting structures directly for renewable energy generation, CCS, and hydrogen production (Jepma and Van Schot, 2017; Leporini et al.,2019; Sedlar et al. 2019; Kolian et al., 2019).

Upgrade, modification, employment in a new function, and even relocation of existing fixed and floating structures have been historically proven. In contrast, the potential for repurposing subsea pipelines has not been applied on a wide scale to date, owing to historical market needs (i.e. type of commodities), and geographical aspects. Pipelines are unique forms of structures, and their operating experience is a function of length and years of service.

Life extension of transmission pipelines is a continuous request by operators, but repurposing was not a repetitive process in the past. Conventional methods of pipeline life extension have been early discussed by Jansen and Van Der Schot (2005) and Rincón et al. (2007). Recent fluctuation in the energy market motivated further development of conventional methods to increase the duration of operation, so Selman and Hubbard (2016) developed the engineering process for life extension, while Nezamian et al. (2016) carried out a similar programme for a gas distribution network. A breakthrough in pipeline repurposing occurred in the Lucius project, by reusing of Phoenix gas pipeline, 47 miles long, for oil service (Schronk et al., 2015).

1.4 Current proposals for pipelines repurposing

Transportation of hydrogen and CO_2 is anticipated in large quantities in the North Sea within two decades, as discussed in sections 1.1 and 1.2. The Oil and Gas Technology Centre (2020) suggests that approximately 30% of existing pipelines could be repurposed for the transportation of hydrogen, and a smaller subset could be used for CO_2, but these findings require further investigation and revisiting the methods for qualification. Recent studies and proposals for UK low carbon hydrogen programmes emphasised previous opportunities, examples include:

- Acorn hydrogen feasibility study supported the reuse of existing pipelines for CCS and described that as a low-cost and high-capacity solution (Pale Blue Dot Energy, 2019).
- Reuse of ethylene - out of service - pipeline to transport hydrogen is the lowest cost option for project Hysecure (Inovyn Enterprises Limited, 2019).
- Gigastack feasibility study relied on generating hydrogen from wind power offshore which could be transported via an existing system (Element Energy, 2020).

These proposals demonstrate the benefits of repurposing, there are challenges though, discussed hereafter.

1.5 Benefits and challenges of repurposing

Repurposing existing assets would reduce transportation costs of hydrogen and CO_2, as discussed in sections 1.1 and 1.2. There are further potential benefits. First, the reduction of the assets' footprint would reduce the environmental impacts of low-carbon energy (Oudman, 2017; Schronk et al., 2015). Second, delaying decommissioning would have a positive economic benefit as these costs would be discounted in the future. Energy companies are already prolonging asset lifetimes to delay decommissioning (Shah et al., 2018; IEA, 2020; Levar et al., 2016).

There are five key challenges to repurposing:

1. Legal: as repurposing does not eliminate decommissioning costs entirely, there is a need to decide if there is a change in ownership and a transfer in liabilities of decommissioning commitments and costs. Many fields have shared ownerships and equity interests which makes it even more complicated (Kolian et al., 2019).

2. Environmental: when existing assets are to be reused, residual content should not be discharged into the environment (Herdeiro et al., 2005). Brandt and Mohd Sarif (2013)

highlighted challenges for process safety (i.e. continuous safe operation) with higher risks of failure of older assets.

3. Engineering, safety, and reliability: studies of time-based degradation have issues such as un-inspectable and non-inspectable components, cumulative effects of damage, insufficient records, and possibly high cost of repair or mitigation (Igbadumhe et al., 2017). Therefore, a detailed investigation is needed to understand and deal with underlying causes of defects or failure (Rincón et al., 2007). Dodds and Demoullin (2013) investigated the conversion of the UK gas distribution networks to transport hydrogen and highlighted several issues such as high leakage, loose joints, and poor-quality material. UK offshore pipelines are more reliable than the onshore gas distribution network, as they are designed, constructed, welded, and maintained to higher standards. Offshore pipelines are not installed with joints to avoid the release of containments or ingress of seawater.

4. Geographical: the location of existing assets might not necessarily be identical if compared with the new development, so it is important to evaluate any necessary field modifications, assets extension or increase in capacity.

5. Economic: Brandt and Mohd Sarif (2013) compare the economic benefits with associated risks and a higher probability of failure. Although repurposing reduces or delays investments in new assets, the older assets were designed for a different purpose and are likely to perform more poorly than a new asset that has been specifically designed for low-carbon investment. Operators would expect tangible economic benefits if they were to accept higher probabilities of failure, shorter life expectancy, and possibly less capacity, so need to account for possible failures that could lead to shutdown and ceased production.

1.6 Scope and structure of this paper

Offshore assets are likely to operate beyond the date of decommissioning owing to underestimated design life that relies on these parameters:

- Margins in engineering design such as safety factors or conservative estimation of data gaps.
- Systems are designed against higher loads (e.g. environmental) or for a broad range of operational cycles.
- Systems' operational life is related to hydrocarbon reservoir averaged as 25 years rather than to system capacity.
- Lower degradation rates than anticipated.
- Early retirement.

An accurate estimation of previous parameters would support evidence to extend the life of offshore assets to the utmost duration. Life extension assessment was commonly practised near the end of design life, but a broader assessment is needed if the asset is redeployed for a new function. In this paper, we propose a technical evaluation process to understand whether pipelines might be repurposed. The evaluation should not require upfront field costs, and be able to assess numerous assets with old records and incomplete data in a time/cost-efficient manner to keep pace with energy transition demands.

The paper investigates the reliability and failure rates of existing pipeline systems and discusses the strengths and weaknesses of various methods of life extension. A life extension method is selected and developed, as required, to technically evaluate the potential of repurposing pipelines, then applied to three case studies. Results are discussed and the framework appraised in this article is offered to support decisions during field transformation studies.

2 RELIABILITY AND FAILURE RATES OF NORTH SEA PIPELINES

The North Sea is a location for hundreds of submarine pipelines that have been developed for over five decades. Modern developments in UKCS are carried out under stringent safety regulations and monitoring of failure incidents. Energy institute (2015) publishes a summary for pipeline and riser loss of containment (i.e. PARLOC) in UKCS, discussed in this section.

2.1 Population

PARLOC data are rich in the population (1372 pipelines). Pipelines were classified according to ranges of length, size, and fluid type but not in accordance with material type. Material is critical for repurposing and degradation studies; it might be difficult to capture pipeline material for old systems though. Treemaps in Figure 1 present the PARLOC pipelines population by operating experience (length x age).

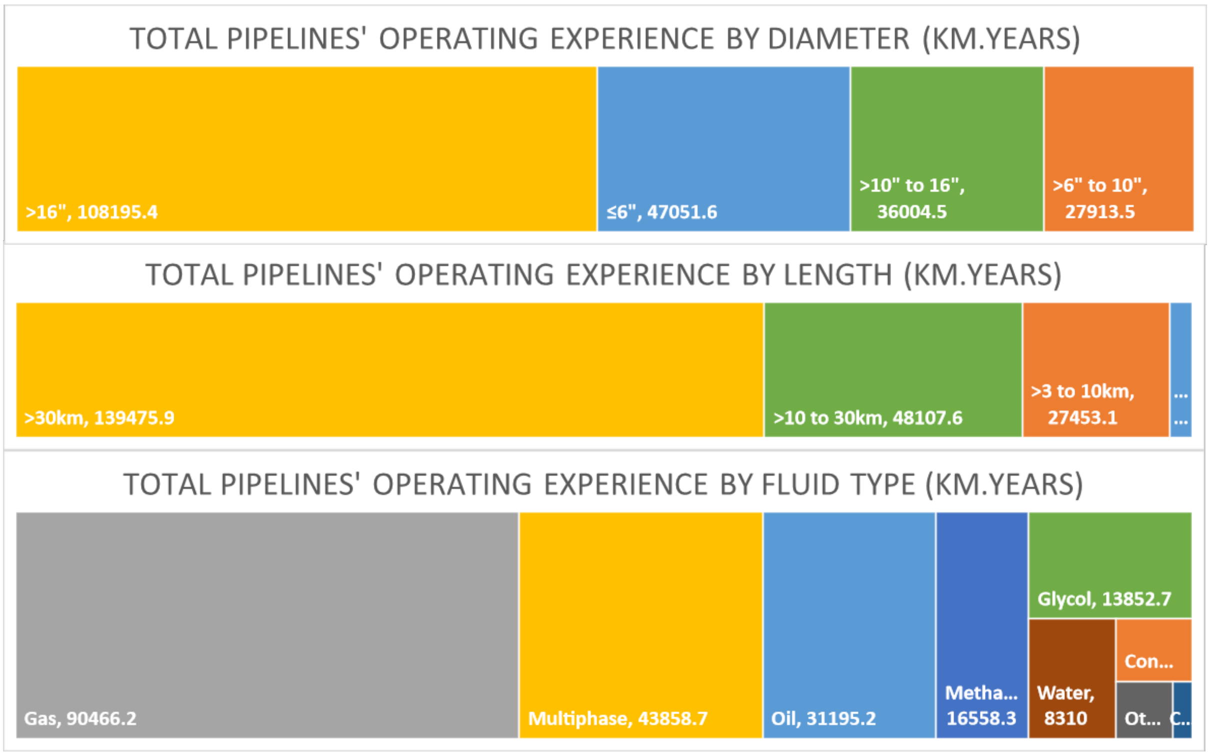


Figure 1. Total pipelines’ operating experience by diameter, length, and fluid type (Energy Institute, 2015)

2.2 Limitation

There is a clear recommendation for cautious use of these data for regions outside UKCS. PARLOC also does not list the specifics about each pipeline and failure incident separately, instead, it provides aggregated data, and is useful to use, but for early decision-making. Detailed assessments would require further details such as near-miss incidents, most of which were omitted from the report.

2.3 Duration

The latest PARLOC revision covers consecutive 12 years (from 2001 to 2012), so it is not biased by outdated practices of design, installation, or operation. Yet, 12 years is considered approximately 50% of the pipeline typical design life. If a pipeline operates for more than 12 years, PARLOC considers its age as 12 years. A longer study period could be established with earlier revisions of PARLOC, which provide the preceding failure rates, but there are some levels of censoring due to lost records owing to the change of the originator and the poorness of old records in general.

Earlier revisions of PARLOC have been updated and refined between 1990 and 2001. PARLOC 2001 collated all incidents in the North Sea but highlighted that the changes in safety regulations in 1989 were followed by an increased number of reported incidents. Hence, older data in the North Sea do not reflect a precise failure rate.

2.4 Incidents and failure rates

PARLOC average failure frequency for pipelines is given as 4.23×10^{-4} between 2001 and 2012. This is improved than in the older revision, 4.88×10^{-4}. Yet, some systems are more reliable than others such as gas pipelines and large diameter pipes. Estimated incidents for different locations and systems are distributed in Figure 2 and Figure 3.

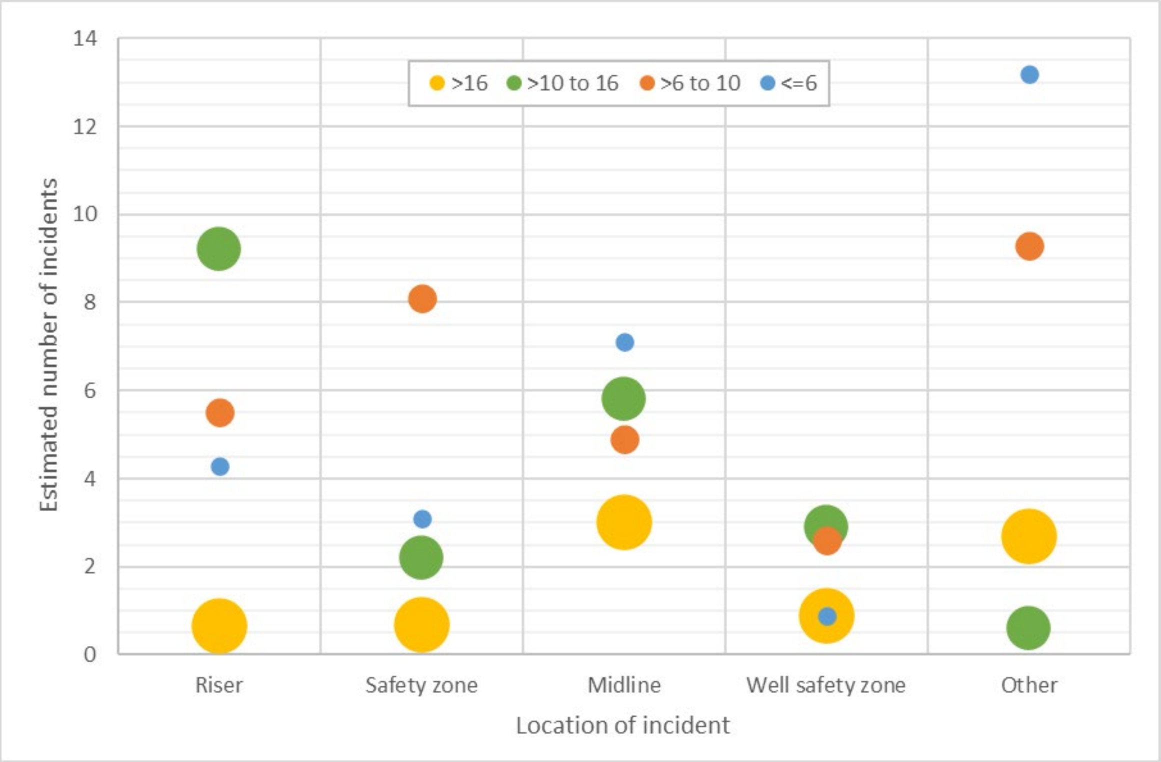


Figure 2. Number of incidents by location and pipeline diameter (Energy Institute, 2015)

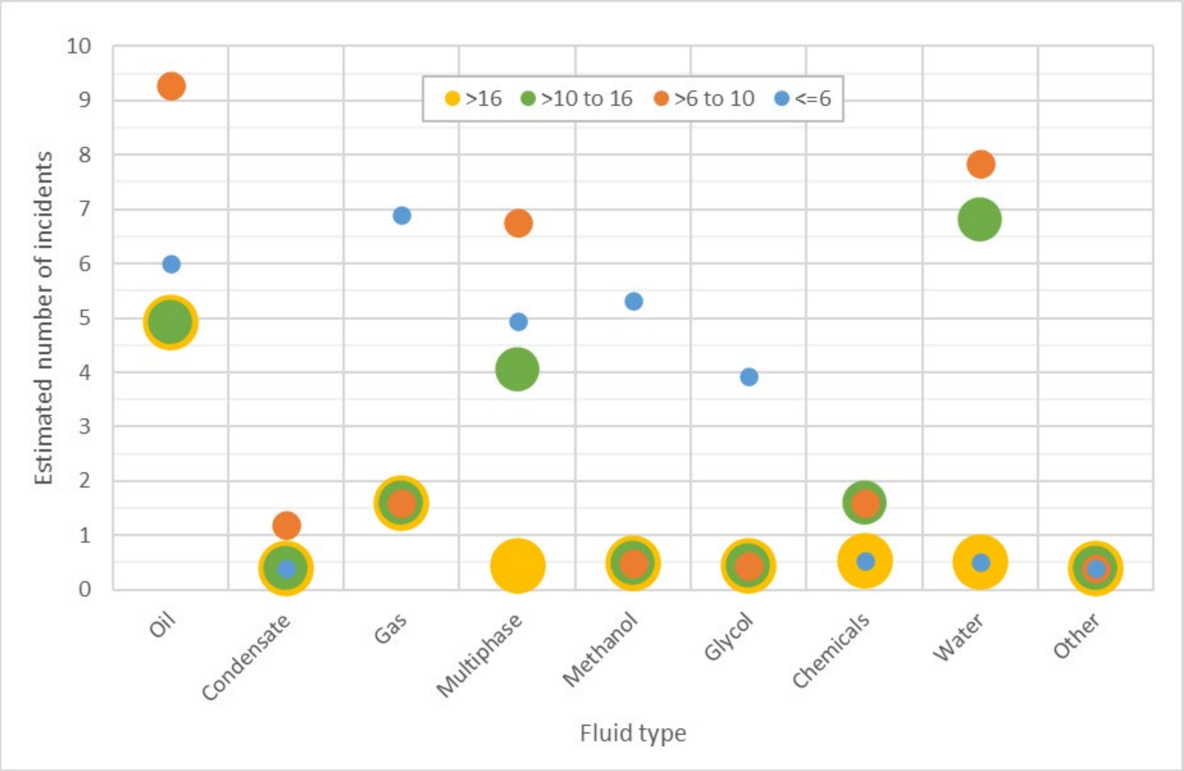


Figure 3. Number of incidents by pipeline fluid and diameter (Energy Institute, 2015)

2.5 Modes of failure

DNV GL (2017) categorises all threats that could lead to the failure of offshore pipeline systems. PARLOC's definition of the cause of failure is aligned with DNV threats as shown in Table 1. DNV however expands the definition under each threat into several sub-categories, while PARLOC lists the cause of failure as one of five general categories. Expanding this definition will be beneficial for repurposing, however, this level of detail is difficult to be captured in the field.

Table 1. Threats by DNV and causes of failure by PARLOC

PARLOC causes of failure	DNV threats
Impact	Third-party
Material	Corrosion / erosion
Operations and maintenance	Incorrect operation
Construction	DFI (design, fabrication, and installation)
Other	Structural/natural hazard

Repurposing a pipeline to a different service will be accompanied by a change in operational parameters (e.g. pressure, temperature, corrosion rates, pipeline weight), so loads, resistance and even cathodic protection system efficiency would be different. Hence, understanding the detailed cause of failure will help to decide if it remains valid, improves or becomes obsolete.

2.6 Database

PARLOC relies on databases for reported failures by operators, and there is a possibility that some failures were not captured. There is also some estimation in the assets database and the originators assumed that there are no missing assets except interconnectors, which have been omitted. The full content of the data is confidential, unfortunately, and only aggregated results are published.

One of the major strengths of PARLOC is the treatment of gaps and duplications by submitting questionnaires to operators and considering incomplete descriptions as missing data, so they would not be ignored. Yet, no response was received from non-OGUK operators, and identification of the relevant operator was not a straightforward process in the first place. Originators have used smoothing and redistribution techniques to ensure that rare incidents are estimated.

2.7 Failure rates for hydrogen and CO_2 pipelines

Existing failure rates discussed in section 2.4 do not include failure rates for hydrogen. The field and experimental data that address this issue are quite limited, but some sources discussed it. Introducing hydrogen to gas distribution pipelines will accelerate the degradation of the system and would trigger additional modes of failure (e.g. material embrittlement). This was predicted using Monte Carlo simulations by Zhang and Adey (2007). Results determined that hydrogen would increase the probability of failure from 3.0×10^{-4} to 6.411×10^{-3}. However, this work is sceptical about the estimation of cracks in a weld in general.

Duncan and Wang (2014) estimated the likelihood of pipeline failure in CO_2 and highlighted that natural gas pipelines statistics were used in the absence of carbon dioxide records. They also argue that natural gas failure records are not appropriate as analogues for CO_2 transport. Similar to hydrogen, there are additional risks for CO_2 pipelines such as ductile fracture. The risks of CO_2 pipeline failure based on several databases are in the range of 1.2×10^{-4} to 6.1×10^{-4} per km.year but a lower failure rate is possible.

Hence, there is an acceptable level of studies that discuss failure rates of pipelines as well as an understanding of modes of failure. The future developments of hydrogen and CO_2 pipelines will improve field and experimental data, and accordingly the failure rates. The next section illustrates the different methods used to analyse the technical potential for life extension of pipelines and could be developed for repurposing assessments.

3 OVERVIEW OF METHODS TO ASSESS PIPELINE INTEGRITY

Franklin et al. (2008), in a study requested by ISO (International Organization for Standardization), highlighted that the approaches to pipeline life extension differ and recommended a standardised approach to enable regulators to approve life extension requests. To date, methods still vary across the industry, explained hereafter.

3.1 Integrity evaluation

Integrity evaluation is to assess or redesign the pipeline considering current conditions and introduced loads. This method relies mostly on industrial standards, summarised by H. Oliveira and V. Oliveira (2019). Schronk et al. (2015) used this method to redesign the Phoenix pipeline for new service, but required excessive field operations (i.e. cleaning, measurements, inspection, and hydrotest). This method is difficult to apply on a wide scale, owing to the associated costs. Igbadumhe et al. (2017) relied on historical inspection data and focused on time-based degradation mechanisms using FMEA (i.e. failure mode effects and analysis) and risk assessments. This was a good approach to avoid field inspection costs but utilised a qualitative risk assessment which could be tolerated and consequently affect the results.

In integrity evaluation, detected defects and remnant structural capacity are benchmarked against operational loads and introduced parameters. Detailed inspection to reflect the current state of the facilities is ideal prior to these assessments, but they come at a considerable amount of offshore work and costs. Industry recommended practices used in this method have some conservatism in their methodologies, which could underestimate actual system capacities (refer to section 1.6). There are also questions concerning how data gaps are dealt with using this method.

3.2 Integrity management practices

Integrity management (i.e. IM) strategies have become an element of project development that should be in place prior to commissioning. Having a strategy does not qualify assets for extended life but rather ensures that a subsea asset reaches the end of design life in a robust state. A typical integrity management process (i.e. cycle) is described by DNV GL (2017) encompasses:

- Risk assessment and IM planning,
- inspection, monitoring and testing,
- integrity assessment, and
- mitigation, intervention and repair.

Early work by Jansen and Van Der Schot (2005) developed a robust RBA (i.e. risk-based assessment) methodology that extended two pipelines by at least 10 years. They aimed to avoid conservatism in the integrity evaluation method (refer to section 3.1). RBA became a proven method to define safeguarding pressure (i.e. operating envelopes). This method required an ILI (i.e. in-line inspection) every three years, and it only focused on corrosion, so there are uncertainties with different modes of failure. Similar work by Rincón et al. (2007) demanded additional fieldwork besides inspection (i.e. repair and hydrotest).

Gabetta et al. (2015) relied on qualitative risk assessments associated with the IM process which are based on round table judgemental opinions. Risk assessments also utilise the operator’s bespoke risk matrix, accordingly the definition of acceptable risk in a specific case could differ from one operator to another. Additionally, IM practices struggle sometimes with a lack of data. Solving out data gap problems is left to the user and misestimation of these gaps could lead to inaccurate assessments or undervalued capacities.

Adding financial evaluation to this method forms an effective assessment. Nezamian et al. (2016) described this as cost-risk-benefit-analysis (i.e. CBRA) and used it to evaluate various assets, while Rabindran et al. (2011) used a similar approach for repurposing pipelines for CO_2 transportation. Dealing with data gaps in both studies was unsatisfactory as no well-defined approach was in place.

3.3 Monte Carlo simulations

Life extension problems would be solved by generating probabilities of failure based on inspection data, operational simulations and degradation models (Dellarole et al., 2017). A sample of how Monte Carlo is used for engineering is explained by the following function and Figure 4.

$$g(x) = R - S$$

Where g(x) is the failure function, R is Resistance, and S is the load.

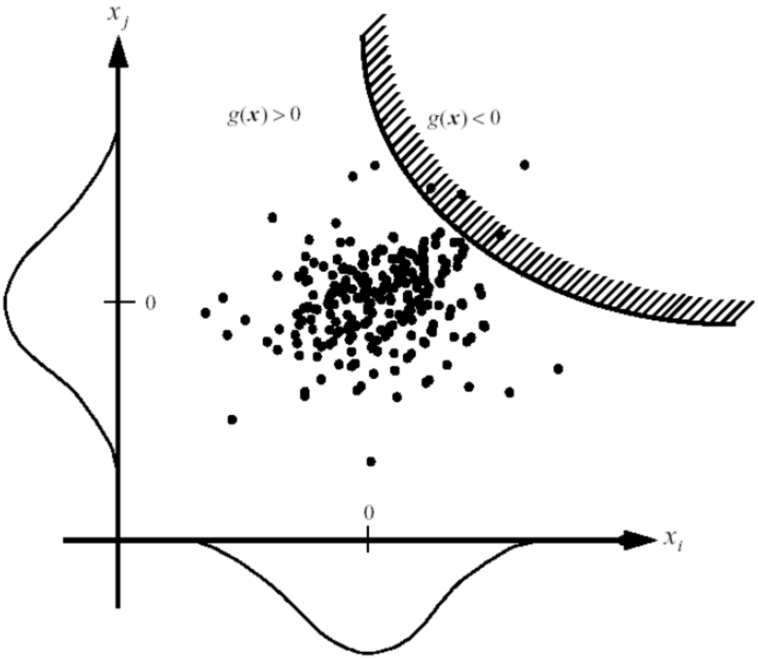


Figure 4. Monte Carlo method solutions for engineering

Historical use of this method focused on degradation due to corrosion and did not offer a holistic assessment for different modes of failure. As such, Selman and Hubbard (2016) followed ISO 12747 and Norsok Y-002 and conducted data gap analysis through flow assurance modelling based on historic and future data. Dellarole et al. (2017) used this method and utilised a quantitative risk-based assessment to avoid weaknesses of qualitative risk assessment. This method requires expansion to provide complete solutions for repurposing and account for all possible modes of failure.

3.4 Life cycle assessments/costs

Life cycle assessment (LCA) requires to be combined with an economic evaluation for efficient solutions. Although combined assessments could be extensive and grow in complexity, they are useful in some cases, for example, recent environmental and economic challenges on biochemical projects dictated a life cycle assessment and techno-economic assessment, (Ögmundarson et al., 2020). There should be a way to indicate a technical assessment for repurposing and the LCA method does not provide it by default.

Leporini et al. (2019) utilised LCA with discount cash flow analysis to assess the reuse of platforms for renewable energy generation, against decommissioning, which did not provide a technical assessment as part of the solution. Animah et al. (2018) utilised LCCB (i.e. life-cycle-cost-benefit) analysis to identify the optimum strategy for life extension. In this method, only costs (e.g. capital, installation, operation, and maintenance) were analysed without any technical aspects. This study also struggled with some data limitations which constrained the analysis.

3.5 Survival analysis

This method has been used for both technical and economic evaluations. It provides an estimation of when a specific event of interest would occur in the future. It has been widely applied to biomedical science but was also utilised in several fields such as economics, finance, and healthcare. In engineering, some successful applications for repair against replacement of equipment relied on survival analysis. The method could be developed for machine learning purposes which would be suitable for future means of data acquisitions (Wang et al., 2019). The survival function is principally expressed as follows:

$$P(T \leq t) = F(t) = \int_0^t f(t)dt$$

The probability of failure (P) of a subject at a time less than or equal to (t) is described as the cumulative distribution function, F(t), which equals the probability density function, f(t). The probability of a subject surviving beyond time t is defined as:

$$S(t) = P(T > t) = 1 - F(t)$$

The hazard function is used to estimate the risk for an event to occur during a time interval (δt), it is expressed as follows, where H(t) is the cumulative hazard function.:

$$h(t) = \lim_{\delta t \to 0} \frac{P(t \leq T \leq t + \delta t | T > t)}{\delta t} = \frac{-d}{dt} \log S(t) = \frac{-d}{dt} H(t)$$

Kaplan-Meier estimate is perhaps one of the best options in survival analysis (Kishore et al., 2010). It does not have many assumptions and is described as a purely descriptive method. The survival probability (S_t) at any time (t_i) is estimated by the following equation.

$$S_i = \prod_{t_i < t} \frac{n_i - d_i}{n_i}$$

Where n_i is the number of subjects living at t_i and d_i is the number of subjects who have died. If all subjects are observed, then all subjects are dead by the time (t). The death of a subject could be translated into a loss of sufficient capacity to operate or loss of value in the case of pipelines. The use of survival analysis for repurposing has not been applied, and it would require using actual historical data of failure, data must be of good quality, contain a good population and cover an acceptable duration.

4 TECHNICAL EVALUATION PROCESS FOR PIPELINE REPURPOSING

4.1 Comparison and selection

A comparison between life extension methods explained in section 3, is given in Table 2. The aim is to select the optimum method for early decision-making and wide-scale repurposing.

Table 2. Comparison between methods for repurposing

Method	Integrity evaluation	Integrity management practices	Monte Carlo simulations	Life cycle assessment	Survival analysis
Type of assessment	Engineering	Engineering	Mathematical	Environmental and economic	Statistical

Method	Integrity evaluation	Integrity management practices	Monte Carlo simulations	Life cycle assessment	Survival analysis
Analyses applications	Integrity evaluation, fit for purpose analysis, study of time-based degradation	Risk-based assessment, adjusting operating envelopes, CBRA	Corrosion models, degradation mechanisms	LCA, LCCB	Variable applications
Strengths	Verified method to calculate current system capacity	Effective way of maintaining the system for prolonged life	Deterministic way of estimation by randomising parameters	Useful to address current environmental and economic challenges	Aggregating implicit and unforeseen parameters of survival
Weaknesses	Requires physical confirmation of defects, conservatism in standards	Risk assessments could be influenced by several factors	Focuses on corrosion and does not address several modes of failure	Lacks technical assessments, could grow in complexity	Requires historical and acceptable quality of data
Field operations	Essential	Regular	Highly recommended	Unlikely	Not required
Data gaps	Lead to conservative assessments	Lead to higher risk (e.g. higher probabilities of failure)	The method solves acceptable limits of data uncertainty	Contingencies account for missing data	The method accepts some levels of data censoring

Each method has different strengths and weaknesses, and in general, they have been tailored per each project individually, and for these reasons, all have been applied simultaneously and it was difficult for standardizing (Franklin et al., 2008). Some methods were found to be conservative in underestimation of the system's remaining capacity (Jansen and Van Der Schot, 2005). If several parameters are to be considered in life extension, then the process could be extensive and complicated (Nashikkar et al., 2015). There is also a need for methods that minimise associated field costs to practically assess many assets (Bhowmik, 2020). Data gaps have a direct impact on remnant design life. They lead to conservatism in design or higher probabilities of failure. They are proven to be a major impediment to life extension in previous methods (Igbadumhe et al., 2017).

This study will apply the survival analysis described in section 3.5 as it accounts for implicit parameters of survival (highlighted in section 1.6). The method was selected based on the comparison in Table 2, which demonstrates that survival analysis can be used for wider applications unlike LCA, it does not require pre-assessment costs like integrity evaluation, and it deals with data gaps without risk assessments, unlike integrity management cycles. It also addresses several modes of failure without being complicated in the case of Monte Carlo simulations.

4.2 Evaluation process based on survival analysis

A schematic of a survival model for subsea assets is shown in Figure 5.

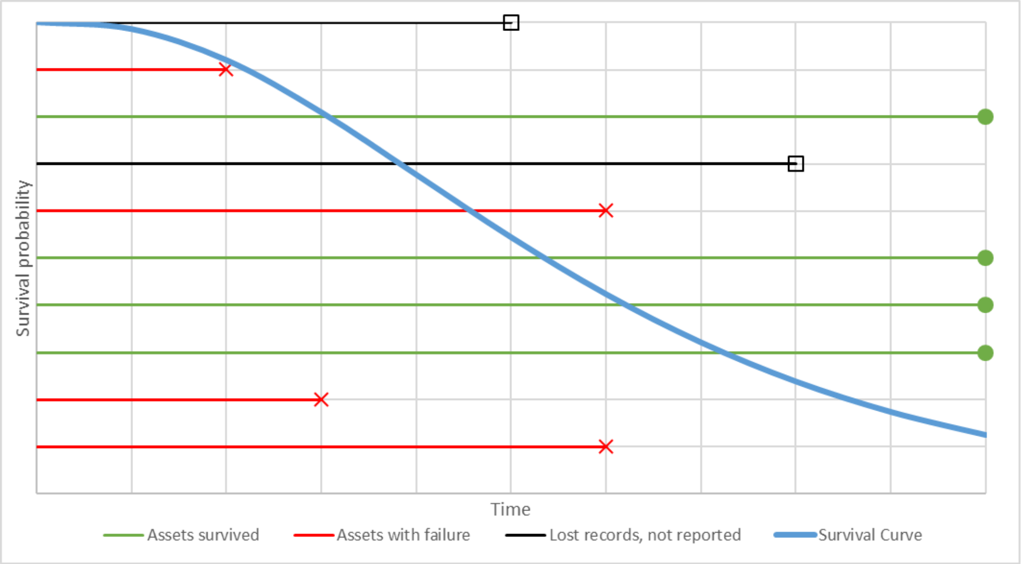


Figure 5. A schematic of subsea assets survival model

In the case of subsea assets, subjects living are pipelines in operation, while dead subjects are assets with incidents of failure. The death of a subject is a loss of sufficient capacity to operate or loss of value. The analysis will use PARLOC data in section 2 to build survival curves for pipeline systems based on the Kaplan-Meier estimate described in section 3.5 and applies it to case studies to assess the survival probability when repurposed, and accordingly remaining life. The weakness of the survival analysis method is the quality of the data set, therefore the study will verify PARLOC data discussed in section 2 against another data set to examine the quality and establish a confidence level in the failure rates.

4.3 Examination of survival rates

The credibility of PARLOC records was verified via comparison with another set of data. DNV GL (2015) publishes offshore and onshore reliability data handbook, which collects and exchanges reliability data between worldwide oil and gas operators. The handbook classifies failure modes and estimates failure rates from a wide variety of geographic areas. The estimated failure rates of this second population are constantly independent in time, given that the pipeline is in the useful phase (i.e. not in the wear-out phase). Pipeline population and monitoring duration in are much less than for PARLOC but the data was collected specifically for the determination of the reliability of subsea systems. This study also examined the earlier revisions: PARLOC 2001 (Mott MacDonald Ltd., 2003), PARLOC 96 (AME Ltd, 1998), and PARLOC 94 (AME Ltd, 1996). Extended survival curves between 1991 to 2013 with a comparison to the second population are in Figure 6.

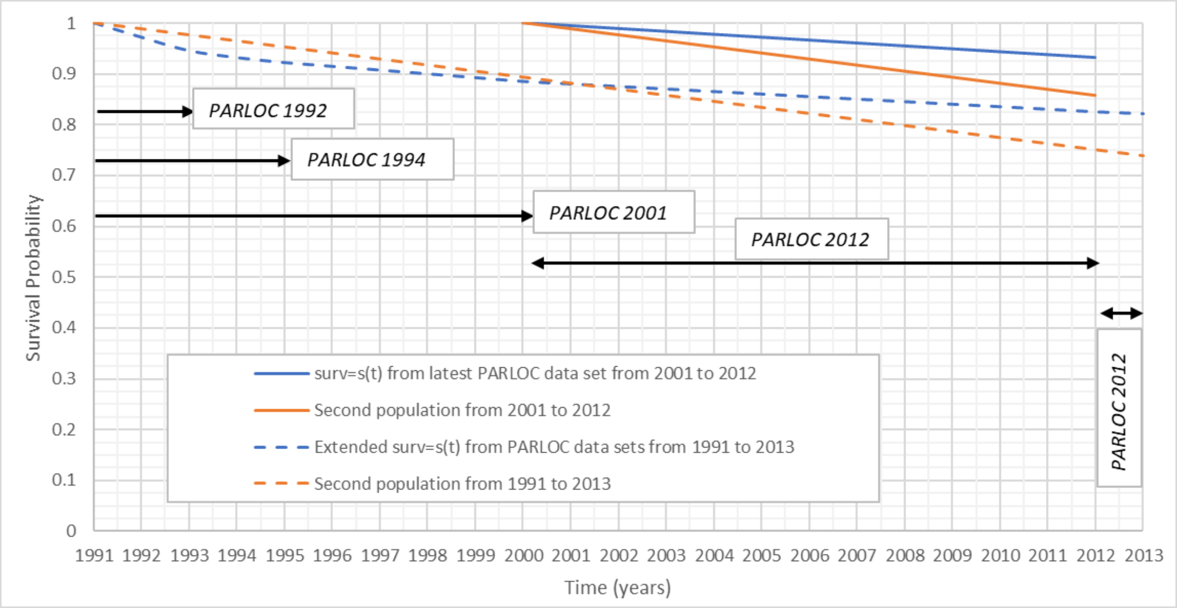
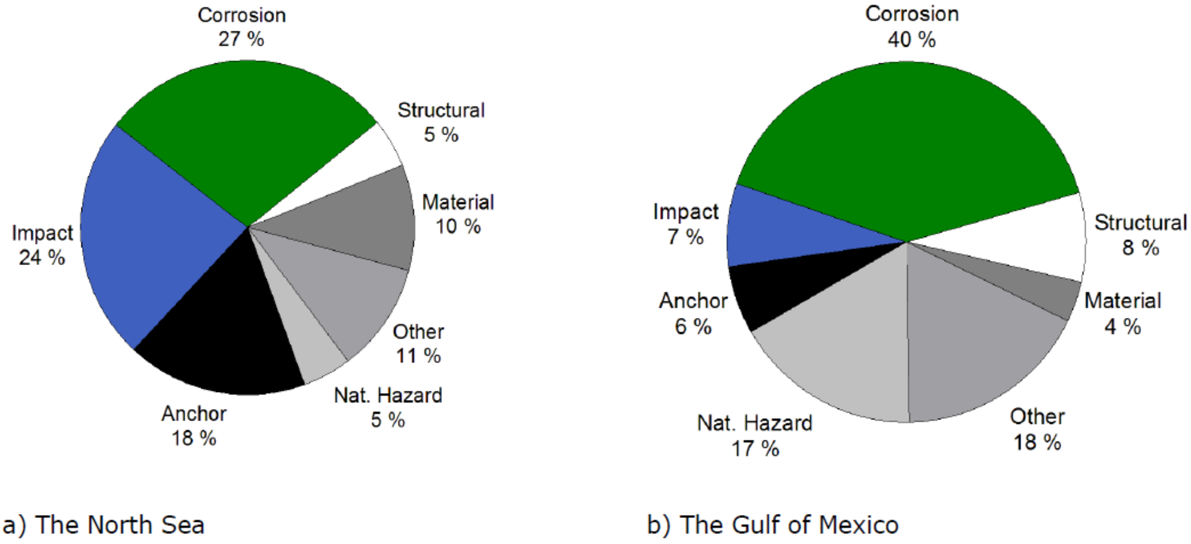


Figure 6. Survival probability of different populations

All incipient and degradation incidents have been omitted in this verification, and only critical failures were considered as they are relevant to incidents reported by PARLOC. Survival probability was found as 0.932 and 0.858 for PARLOC and the second sample respectively over 12 years of operational life as shown in Figure 6. The difference in these probabilities is expected as safety regulations and design practices are slightly less in other regions than in the North Sea. This is indicated by Figure 7 as 70% of incidents in the Gulf of Mexico are due to mechanical issues, unlike in the North Sea where they are 53% (DNVGL, 2017).



a) The North Sea

b) The Gulf of Mexico

Figure 7. A comparison between pipeline incidents in the North Sea and Gulf of Mexico (DNVGL, 2017)

As highlighted by PARLOC, change in safety regulations in 1989 and amended by 1996 resulted in an increased number of reported incidents during that period but records seem at an average level beyond 1996, which explains the higher failure rates during that period. The upcoming revision of PARLOC is expected to offer a similar level of detail and accuracy given in 2015, and this will provide an opportunity to have a precise survival curve of around 25 years of operational life, equivalent to the average design age.

4.4 Effect of pipeline characteristics and fluid type

The overall survival curve exhibited in Figure 6 can be used to estimate the survival probability of pipelines in the North Sea, however, this curve reflects an average of all modes of failure for all products and pipe characteristics, which might be conservative or underestimating. Therefore, it might be prudent to develop a specific survival curve for each system that resembles similar characteristics and applicable modes of failure. Figure 8 compares the overall survival probability in accordance with pipeline diameter and length. Pipeline total length is a function of operating experience (i.e. exposure), as a result, a shorter pipeline length (i.e. ≤3 km) is supposed to be less vulnerable (e.g. less exposed to dropped objects), and by examining survival curves in Figure 8, they tend to perform better and have higher survival probability than for all systems.

Different pipeline diameters have also different survival probabilities, it is obvious that larger diameters (i.e. >16”) are the best-performing systems and the smallest diameters (i.e. ≤6”) perform also better. One explanation for this is that above and below-average pipeline diameters have higher capacities (i.e. wall thickness) than required, to account for loads during handling (i.e. lifting) and installation by maintaining an acceptable D/t ratio (i.e. diameter to thickness).

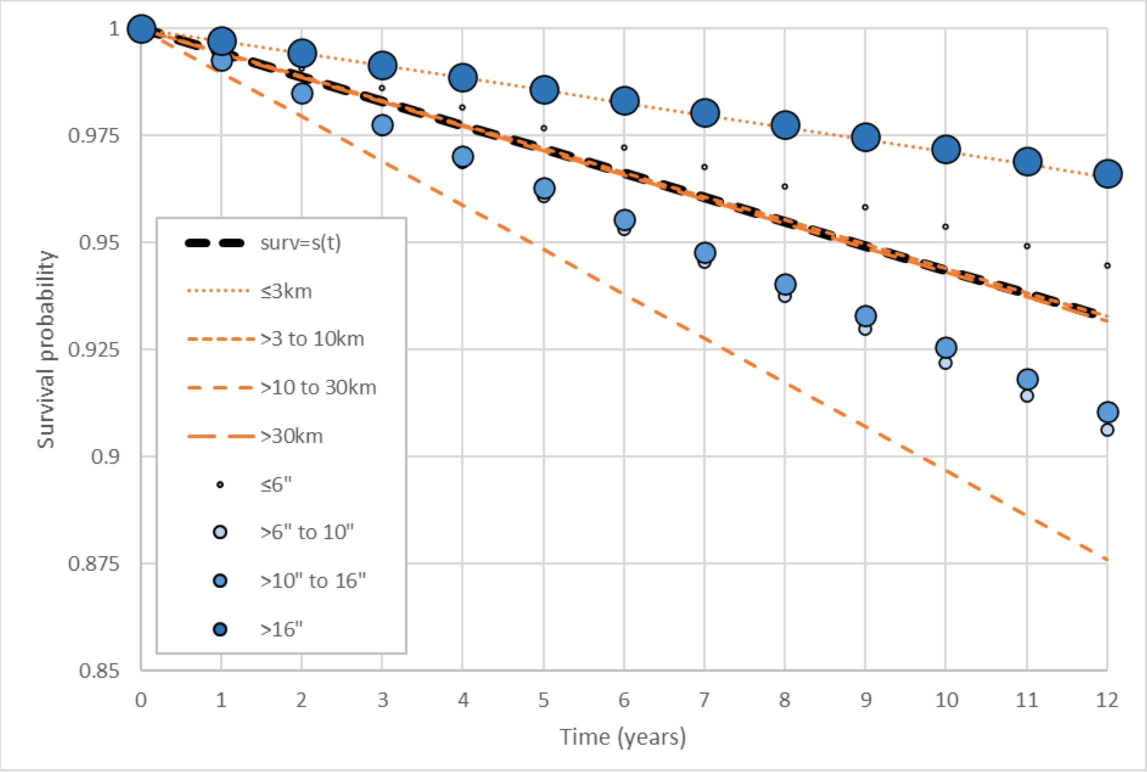


Figure 8. Survival probability of different pipeline diameters and lengths based on PARLOC data

Survival curves for fluid transported by pipelines are shown in Figure 9 with a comparison to the overall survival probability.

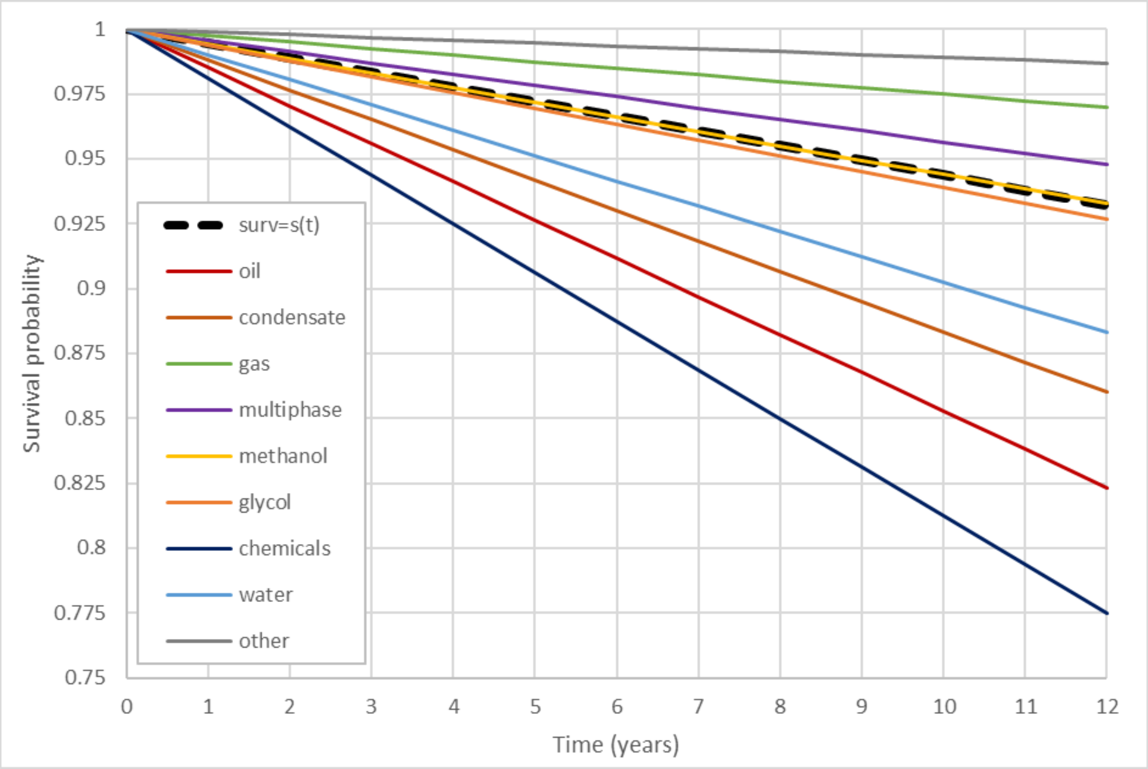


Figure 9. Survival probability of different pipeline content based on PARLOC data

As per Figure 9, pipelines designed for other (i.e. uncommon) fluids are the most survived systems, this is probably due to specific considerations during design (e.g. high corrosion allowance). Gas pipelines have a good survival probability which is very promising since there is a considerable number of gas transportation systems in the North Sea (refer to Figure 1). Pipelines designed to carry oil and chemicals seem to go through more rapid degradation than other systems.

5 CASE STUDIES OF NORTH SEA PIPELINE REPURPOSING

In this section, we examine three case studies. The selection criteria ensured that all of them are proposed for repurposing and located in the North Sea for the validity of PARLOC data.

5.1 Overview of the case studies

ERM (2019) found that it is worth exploring the potential of repurposing existing assets in the North Sea such as the Miller pipeline to St Fergus for Dolphyn hydrogen project. The project integrates a wind turbine, desalination unit, and electrolyser onto a single substructure to produce hydrogen. It also studied the option of a centralised electrolyser for the entire wind farm (400 wind turbines), which would produce 4 GW converted to 360,000 tonnes of H_2 per year by 2037. The Miller pipeline length is approximately 240 km. It is planned for decommissioning with other facilities in the Brae field, as shown in Figure 10 (Marathon Oil, 2017).

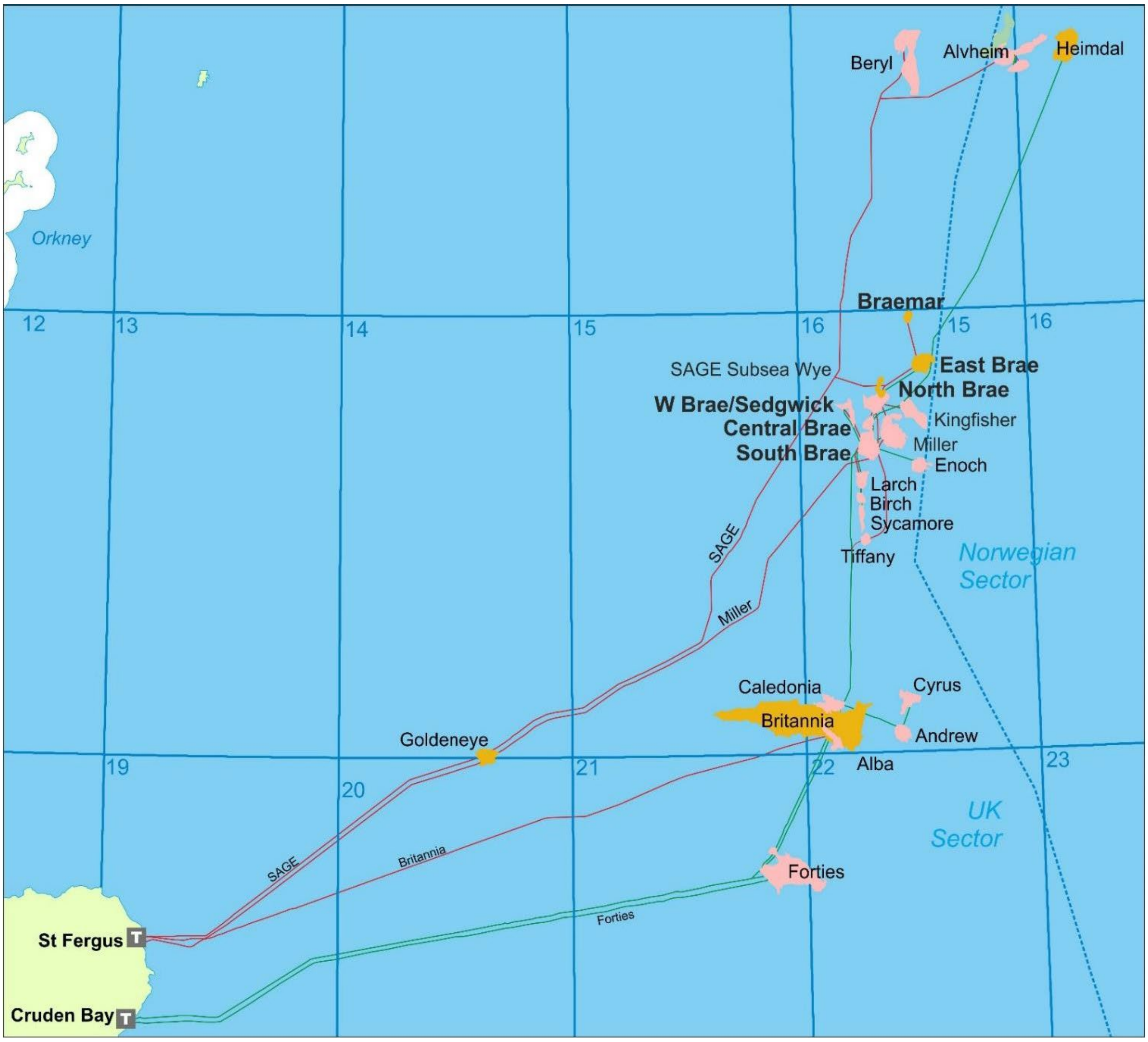


Figure 10. Brae field (Marathon Oil, 2017)

Several facilities in the Atlantic and Cromarty fields are planned to be decommissioned, which include pipeline systems. Mackinnon and Gomersall (2019) assumed that existing Atlantic and/or Goldeneye pipelines could be repurposed for CO_2 in the ACORN project, a massive project that produces 6 tonnes/h of H_2 and receives 51 tonnes/h of CO_2 from multiple sources. A field schematic is presented in Figure 11 (BG Group, 2016).

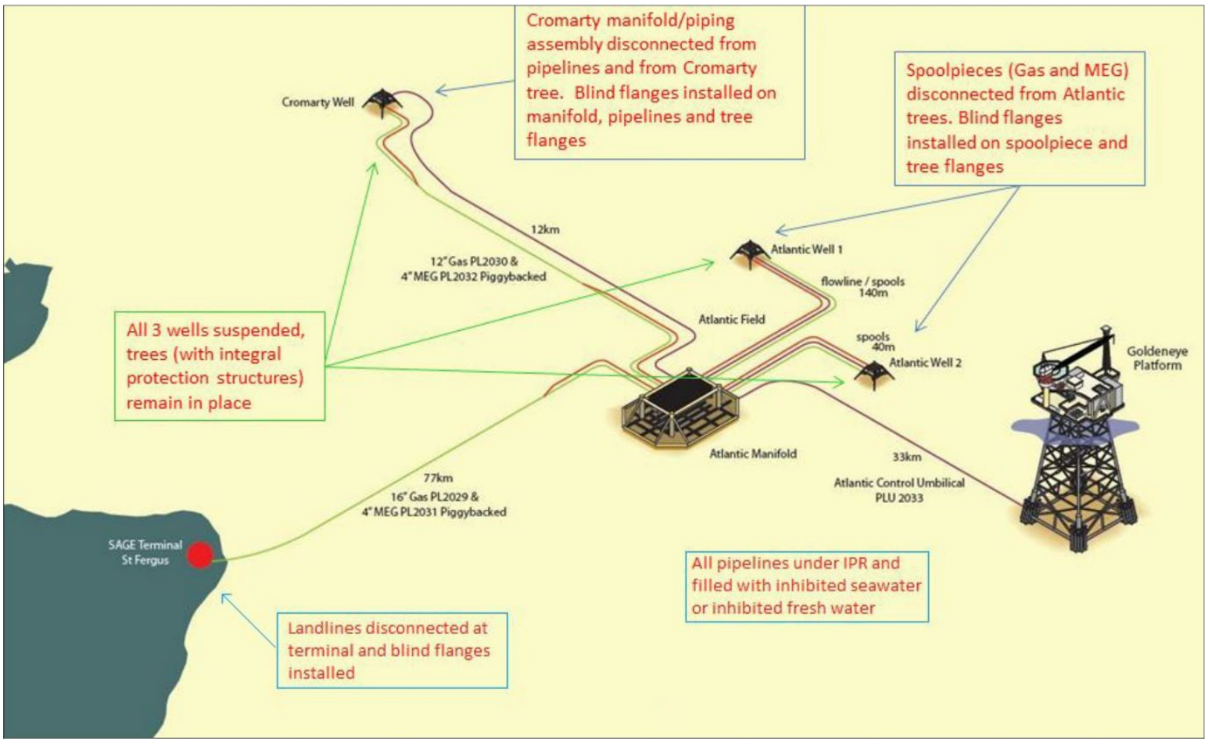


Figure 11. Atlantic and Cromarty fields (BG Group, 2016)

5.2 Pipelines’ survival probabilities

In order to build the correct survival curves for the pipelines proposed for repurposing, pipelines’ main characteristics are required, as summarised in Table 3.

Table 3. Case studies’ data (Pale Blue Dot Energy, 2018)

Parameter	**Pipeline**		
	Miller	**Atlantic**	**Goldeneye**
Length (km)	240	79.2	101
Diameter (inch)	30	16	20
Service (content)	Gas	Gas	Gas
Proposed service	Hydrogen	CO_2	CO_2
Estimated remaining life at 2018 (years)	10	6-10	8-10
Original design life (years)	20	20	20
Commissioning	1992	2006	2004
Cease of production	2007	2011	2011
The proposed date for the new service	2023	2023	2023

All the selected pipelines were for gas service, did not go through a full operational life, and were found suitable for repurposing. It is not clear how the estimated remaining life was determined during the feasibility study by Pale Dot Blue Energy (2018), but this will be re-evaluated using the survival analysis.

Survival curves were tailored for each pipeline considering that it will go through three phases: normal operation with gas content, a shutdown period with a lower failure rate (i.e. from environmental and third party only), and the last phase when the pipeline is carrying a new product (i.e. hydrogen or CO_2). Survival curves were established for similar characteristics (i.e. diameter, length, service, applicable modes of failure) and presented in the following Figure 12. The figure splits the three phases for each pipeline (i.e. production, shutdown and repurposing).

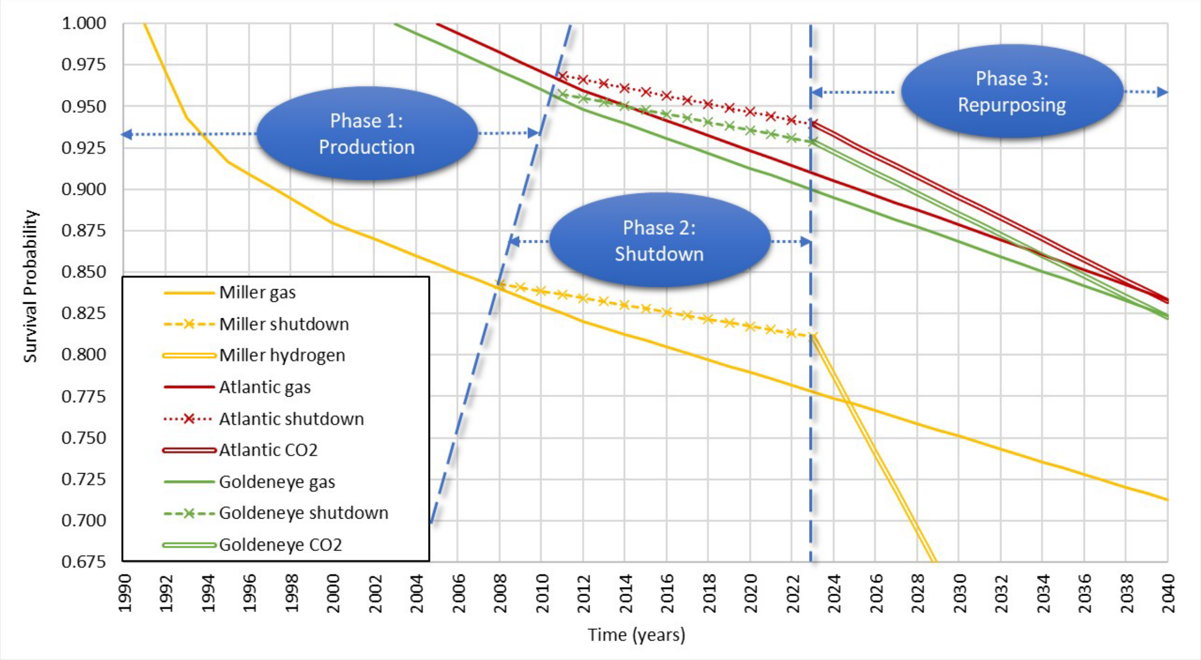


Figure 12. Survival curves during the entire operational life

The Miller pipeline is the oldest as it started operation in 1992 and was designed to operate until 2012 when its survival rate would have become 0.82 if it continued producing gas. Operations ceased in 2007 eliminating some risks (e.g. internal corrosion) and therefore the survival curve is enhanced. Introducing of hydrogen in 2023 initiated rapid degradation due to a higher probability of cracks development. The Miller pipeline will achieve the same survival probability of 0.82 by 2018 (i.e. 6 years after shutdown), which is before hydrogen production. The initial accelerated descending survival probability of the Miller pipeline is because of old records between 1992 and 1996 (refer to the discussion in section 4.3).

Atlantic and Goldeneye were installed while records of failure in the North Sea are more consistent, hence survival curves are more uniform than for the Miller Pipeline. The survival probability for 20 years of design life is 0.895 approximately for both pipelines. Under new operational conditions which include shutdown and repurposing for CO_2, the Atlantic and Goldeneye pipelines reach this survival probability in 2030 and 2029, respectively. This means that Atlantic and Goldeneye pipelines can be repurposed for CO_2 for 7 years and 6 years respectively before reaching the original design life probability, which is aligned with the feasibility study results by Pale Blue Dot Energy in Table 3. Therefore, survival analysis provides a close estimate of the anticipated remaining life if it relies on a reliable database.

The pipeline system could operate for a longer period after repurposing but with a higher probability of failure, which can only be determined by the operator's acceptable risk. The operator will have a choice between inspection and assessment for life extension, repair or replace the system. This would rely on many parameters at that stage such as reservoir remaining capacity and costs of repair with the availability of spares and intervention vessels. In this study, it is difficult to determine the maximum acceptable risk level, so the anticipated probability of failure at the end of the original design life was selected.

6 DISCUSSION

6.1 Advantages of survival analysis

Survival analysis provides a close estimate of the anticipated remaining life without field operations as demonstrated in the assessment of Atlantic and Goldeneye pipelines in section 5.2, and the comparison to the feasibility study by Pale Blue Dot Energy (2018). Older pipelines installed before 1996 such as Miller will have a conservative estimation of survival probability due to the inconsistency of old records. This study relied on historical failure rates recorded until 2012-2013 (Energy Institute, 2015; Mott MacDonald Ltd., 2003; AME Ltd., 1998; AME Ltd., 1996). Great efforts were spent by Energy Institute (2015) to refine and treat the data in PARLOC 2012 compared to older revisions, and the same level of treatment is anticipated in the newer revisions, which will accordingly enhance survival analysis results.

6.2 Understanding survival probabilities

It is important to emphasise that recorded incidents for a pipeline system carrying specific fluid (e.g. oil) do not reflect the survival probability of oil content, but rather the survival probability for pipelines designed for oil service. In other words, if the same pipeline was designed for gas instead of oil, pipeline characteristics, risks and capacity would be different. Hence, survival probabilities reflect system capacity, margins in design and vulnerability (refer to section 1.6). Pipelines designed for gas service have a higher survival probability as explained in Figure 9, and medium-size pipes (i.e. >6" to 16") have higher failure rates than sizes outside of this range (refer to Figure 8). So, survival analysis is a method that could estimate the pipeline system capacity based on its characteristics whether structural, operational or even geographical.

6.3 Quality of failure data

Recorded failure rates in the North Sea are aligned with the anticipated general behaviour for pipeline systems as discussed in section 4.4, for instance, large-diameter pipelines are expected to have lower failure rates and multiphase systems confront higher corrosion rates. Evaluation of the survival of a system relies on these real-life records. The comparison between PARLOC and another data set in Figure 6 proved that survival probabilities in PARLOC are higher which would reflect a better performance by pipelines in the North Sea.

Survival curves established in this study (Figure 8 and Figure 9) were limited to the parameters available in the PARLOC data set. The current classification of data will not allow for investigating specific modes of failure such as ductile fracture, which can be addressed through knowledge of line-pipe material. Detailed parameters of pipelines and failure records such as material types, corrosion rates, near-miss incidents and chemical treatment would assist in tailoring a specific survival curve for each system and adjust it whenever a given parameter changes. The aim is to resemble any pipeline system using historic data to estimate its remaining capacity.

6.4 Expansion of survival analysis method

The method presented in this article could be developed into a machine learning tool (e.g. survival trees), and the analysis could replicate characteristics, service, and age, thus providing a real-life estimation. Studying the reliability of pipelines using machine learning techniques has recently received more attention, as shown in the work by Pourahmadi and Saybani (2022), and by Abyani et al. (2022), both studies have only focused on corrosion though. Some experiments used sensors to collect real-time data for offshore structures and processed these data using machine learning methods to avoid frequent inspection (Basso and Copello, 2019; Bhowmik, 2020), yet there are questions if this concept could be applied at present time to a wider scale. Survival analysis employs a prepared set of data and could offer a broad approach for repurposing in the future as it could also accommodate an assessment of potential economic benefits.

6.5 Risks of repurposing

The risks of failure for any pipeline system are unavoidable during operation and for repurposed pipelines, risks grow. Operators must have emergency procedures and quick responses for repair and intervention. Also, operating procedures must consider the reduced capacity and well define the allowable operating envelope, incidental pressures and line packing conditions. Pipelines with higher probabilities of failure could offer a short-term solution that discounts the investments in a new pipeline system. Otherwise, they could be a storage facility to balance the shipping of hydrogen or CO_2.

Upstream facilities must be prepared for shutdown in case of failure to avoid the injection of large quantities of fluid into seawater. Carbon dioxide or hydrogen release offshore is less risky than the release of oil or chemicals, yet dissolved carbon dioxide would be harmful to flora and fauna. Regular inspection during operation and assessments of the system would provide leading indicators of a future failure.

6.6 Economical evaluation

A shutdown is accompanied by an economic loss in addition to costs of repair. The economic evaluation of the existing system against the new facility is vital for the operator’s decision to adopt repurposing in new field development. This has not been discussed in this article and should be considered in further research. The economic investigation could consider the loss of production, costs of repair and rehabilitation, and costs of enhancing inspection and assessment programmes, against the discounting of investment in a new pipeline system.

7 CONCLUSIONS

Survival analysis has a lot of potential for early decision-making and wide-scale assessments of repurposing of submarine pipelines, as demonstrated by the Atlantic and Goldeneye case studies in section 5.2. This method provides an estimation of the remaining life and replicates the feasibility studies' probability of failure based on real-life data.

PARLOC data are considered a reliable source for survival analysis as discussed in section 2. The data were verified through a comparison with a separate population in Figure 6. Pipelines in the North Sea seem to perform better than in other regions due to UKCS safety regulations (refer to Figure 6 and Figure 7). It was noticed that gas transmission pipelines and specific pipe diameters are among the most reliable systems that could have a prolonged life (refer to Figure 2 and Figure 3). Further assessments could even classify pipelines' reliability per location, operators, frequencies of integrity management cycles or any other criteria if the data is deemed available.

It is difficult to build reliable survival curves for North Sea assets that go back before 1996 as there is an increased number of reported incidents, owing to the introduction of safety regulations in 1989, as found in the Miller case study (refer to section 5.2). There is a uniform reporting level of accidents from 1996, and the next revision of PARLOC is expected to cover another 10 years with reliable and detailed records. Such data would help to tailor the survival curve over a longer period that exceeds the standard design life of the system (i.e. 25 years). The expansion in hydrogen and CO_2 assets over the upcoming years, would also improve the failure rates of these systems, as it will rely on field and experimental data rather than engineering assessments.

Failure rates of submarine pipelines are lower in recent years, a reflection of the increased reliability of the systems due to capacities in design, successful integrity management processes and safety regulations. Hence, repurposing pipelines is an increased opportunity as newly installed pipelines perform better and are well maintained compared to old systems. But estimated remaining design life should not be rejected if less than the investment cycle in the hydrogen or CCS project, instead it should be evaluated against economic benefits such as discounting, otherwise used as a storage facility to balance with shipping.

It is recommended that future records of failure to include near-miss and degradation events, and pipeline material, in addition to costs and duration of repair and shutdown. This would increase the accuracy of survival analysis and provide bases for economic evaluation. It would also allow for the assessment of different modes of failure such as ductile fracture and material embrittlement, issues that increase with transportation of hydrogen and CO_2. A detailed study of economic implications due to system failure in CCS and hydrogen projects is considered continuity of this study. Survival analysis could be extended to study loss in capacity or value, therefore it could become an advanced tool that assesses both technical and economic aspects.

8 AKNOWLEDGEMENT

The authors express their gratitude to the Energy Institute, originators of PARLOC data, which were used in this research. We also thank the reviewers of this paper for their valuable comments that contributed to our work.

9 BIBLIOGRAPHY

[1] Abyani, M., Bahaari, M.R., Zarrin, M., Nasseri, M., 2022. Predicting failure pressure of the corroded offshore pipelines using an efficient finite element based algorithm and machine learning techniques. Ocean Eng. 254, 111382. https://doi.org/10.1016/j.oceaneng.2022.111382

[2] AME Ltd, 1998. PARLOC 96: The update of loss of containment data for offshore pipelines, the Health and Safety Executive.

[3] AME Ltd, 1996. PARLOC 94: The update of loss of containment data for offshore pipelines. Heal. Saf. Exec.

[4] Animah, I., Shafiee, M., Simms, N., Erkoyuncu, J.A., Maiti, J., 2018. Selection of the most suitable life extension strategy for ageing offshore assets using a life-cycle cost-benefit analysis approach, Journal of Quality in Maintenance Engineering. https://doi.org/10.1108/JQME-09-2016-0041

[5] Babarit, A., Gilloteaux, J.C., Clodic, G., Duchet, M., Simoneau, A., Platzer, M.F., 2018. Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters. Int. J. Hydrogen Energy 43, 7266–7289. https://doi.org/10.1016/j.ijhydene.2018.02.144

[6] Basso, A., Copello, S., 2019. Machine learning application in jacket life extension. Offshore Mediterr. Conf. Exhib. 2019, OMC 2019 1–11.

[7] BG Group, 2016. Atlantic & Cromarty Fields - Draft Decommissioning Programmes, UK Government Website.

[8] Bhowmik, S., 2020. Life extension of offshore structure using machine learning. Offshore Technol. Conf. Brazil 2019, OTCB 2019 29–31.

[9] Brandt, H., Mohd Sarif, S., 2013. Life extension of offshore assets - Balancing safety & project economics. Soc. Pet. Eng. - SPE Asia Pacific Oil Gas Conf. Exhib. APOGCE 2013 Maximising Matur. Elev. Young 2, 983–991. https://doi.org/10.2118/165882-ms

[10] Brownsort, P.A., Scott, V., Haszeldine, R.S., 2016. Reducing costs of carbon capture and storage by shared reuse of existing pipeline—Case study of a CO2 capture cluster for industry and power in Scotland. Int. J. Greenh. Gas Control 52, 130–138. https://doi.org/10.1016/j.ijggc.2016.06.004

[11] Caulk, R.A., Tomac, I., 2017. Reuse of abandoned oil and gas wells for geothermal energy production. Renew. Energy 112, 388–397. https://doi.org/10.1016/j.renene.2017.05.042

[12] Cerniauskas, S., Jose Chavez Junco, A., Grube, T., Robinius, M., Stolten, D., 2020. Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a Germany case study. Int. J. Hydrogen Energy 45, 12095–12107. https://doi.org/10.1016/j.ijhydene.2020.02.121

[13] Dellarole, E., Sotgiu, M.G., Sodini, S., Frassi, A., Varano, F., Bonuccelli, M., 2017. Quantitative risk-based methodology for pipeline integrity management. Offshore Mediterr. Conf. Exhib. 2017, OMC 2017 12747, 1–13.

[14] DNVGL, 2015. Offshore and Onshore Reliability Data, Oreda.

[15] DNVGL, 2017. DNVGL-RP-F116 Integrity management of submarine pipeline systems 189.

[16] Dodds, P.E., Demoullin, S., 2013. Conversion of the UK gas system to transport hydrogen. Int. J. Hydrogen Energy 38, 7189–7200. https://doi.org/10.1016/j.ijhydene.2013.03.070

[17] Duncan, I.J., Wang, H., 2014. Estimating the likelihood of pipeline failure in CO2 transmission pipelines: New insights on risks of carbon capture and storage. Int. J. Greenh. Gas Control 21, 49–60. https://doi.org/10.1016/j.ijggc.2013.11.005

[18] Element Energy, 2020. Gigastack Bulk Supply of Renewable Hydrogen. Low Carbon Hydrog. Supply Program. 17.

[19] Energy Institute, 2015. Pipeline and riser loss of containment 2001 - 2012 (PARLOC 2012), Oil and Gas UK.

[20] ERM, 2019. Dolphyn Hydrogen Phase 1 - Final Report. Low Carbon Hydrog. Supply Program.

[21] Franklin, J.G., Stowell, B.E., Jee, T.P., Hawkins, M., 2008. Standardizing the approach for offshore pipeline lifetime extension. Soc. Pet. Eng. - 13th Abu Dhabi Int. Pet. Exhib. Conf. ADIPEC 2008 3, 1354–1360. https://doi.org/10.2118/118117-ms

[22] Gabetta, G., Morrea, S., Travaglia, F., Cioffi, P., Monaco, S., 2015. Integrity management of pipelines transporting hydrocarbons: An integrated approach. Soc. Pet. Eng. - Abu Dhabi Int. Pet. Exhib. Conf. ADIPEC 2015. https://doi.org/10.2118/177666-ms

[23] Herdeiro, M.A.N., Da Cunha, C.H.G., Motta, B.R.F., 2005. Development of the Barracuda and Caratinga subsea production system - An overview. Proc. Annu. Offshore Technol. Conf. 2005-May, 47–58. https://doi.org/10.4043/17054-ms

[24] IEA, 2020. World Energy Investment 2020, World Energy Investment Outlook: Special Report.

[25] Igbadumhe, J.F.E., Sharp, J. V., Furth, M., 2017. Management of integrity of ageing pipelines. SNAME Marit. Conv. SMC 2017 1, 1–9.

[26] Inovyn Enterprises Limited, 2019. PROJECT HYSECURE PHASE 1 SUMMARY, Low Carbon Hydrogen Supply Programme.

[27] Jansen, H.J.M., Van Der Schot, G.J.J., 2005. Life extension of degraded Main Oil Line pipeline sections through improved risk based integrity management, in: NACE - International Corrosion Conference Series. pp. 1–27.

[28] Jepma, C.J., Van Schot, M., 2017. On the economics of offshore energy conversion: smart combinations Converting offshore wind energy into green hydrogen on existing oil and gas platforms in the North Sea, Energy Delta Institute.

[29] Kishore, J., Goel, M.K., Khanna, P., 2010. Understanding survival analysis: Kaplan-Meier estimate. Int. J. Ayurveda Res. 1, 274. https://doi.org/10.4103/0974-7788.76794

[30] Kjärstad, J., Morbee, J., Odenberger, M., Johnsson, F., Tzimas, E., 2013. Modelling large-scale CCS development in Europe linking techno-economic modelling to transport infrastructure. Energy Procedia 37, 2941–2948. https://doi.org/10.1016/j.egypro.2013.06.180

[31] Kolian, S.R., Godec, M., Sammarco, P.W., 2019. Alternate uses of retired oil and gas platforms in the Gulf of Mexico. Ocean Coast. Manag. 167, 52–59. https://doi.org/10.1016/j.ocecoaman.2018.10.002

[32] Leporini, M., Marchetti, B., Corvaro, F., Polonara, F., 2019. Reconversion of offshore oil and gas platforms into renewable energy sites production: Assessment of different scenarios. Renew. Energy 135, 1121–1132. https://doi.org/10.1016/j.renene.2018.12.073

[33] Levar, J., Seah, H.H., 2016. Europa umbilical retermination. Proc. Annu. Offshore Technol. Conf. 3, 2807–2825. https://doi.org/10.4043/27134-ms

[34] Mackinnon, D., Gomersall, S., 2019. Acorn - A North East response to evolve and thrive through decarbonisation, in: Society of Petroleum Engineers - SPE Offshore Europe Conference and Exhibition 2019, OE 2019. https://doi.org/10.2118/195715-MS

[35] Marathon Oil, 2017. East Brae and Braemar Combined Decommissioning Programmes, UK Government Website.

[36] Martijn Van Wijngaarden, A., Daniels, N., 2019. Upgrading and conversion opportunities for floating offshore units. Proc. Annu. Offshore Technol. Conf. 6–9. https://doi.org/10.4043/29313-ms

[37] Mott MAcDonald Ltd., 2003. PARLOC 2001: The update of loss of containment data for offshore pipelines, Energy Institute.

[38] Nashikkar, D., Mo, W., Achanta, V., Lyon, S., 2015. Riser and subsea asset field life extension. 20th Offshore Symp. 2015 Futur. Offshore Technol. Sustain. Reliab. 504–514.

[39] Nezamian, A., Rodriques, C., Nezamian, M., 2016. Asset integrity management and life extension of gas distribution facilities and pipeline network. Soc. Pet. Eng. - SPE Trinidad Tobago Sect. Energy Resour. Conf. https://doi.org/10.2118/180889-MS

[40] Ögmundarson, Ó., Sukumara, S., Herrgård, M.J., Fantke, P., 2020. Combining Environmental and Economic Performance for Bioprocess Optimization. Trends Biotechnol. xx, 1–12. https://doi.org/10.1016/j.tibtech.2020.04.011

[41] OGUK, 2020. Decommissioning insight 2020. Int. Energy Agency 1–34.

[42] OGUK, 2019. UKCS Energy Integration Interim findings, Oil and Gas Authority UK.

[43] Onyebuchi, V.E., Kolios, A., Hanak, D.P., Biliyok, C., Manovic, V., 2018. A systematic review of key challenges of CO2 transport via pipelines. Renew. Sustain. Energy Rev. 81, 2563–2583. https://doi.org/10.1016/j.rser.2017.06.064

[44] Oudman, B.L., 2017. Green decommissioning: Re-use of North Sea offshore assets in a sustainable energy future. Offshore Mediterr. Conf. Exhib. 2017, OMC 2017 1–10.

[45] Pale Blue Dot Energy, 2019. Acorn Hydrogen Feasibility Study Pale - Pale Blue Dot Energy - Acorn Hydrogen: Project Summary, Low Carbon Hydrogen Supply Programme.

[46] Pale Blue Dot Energy, 2018. ACT Acorn Feasibility Study, Act Acorn.

[47] Peters, R., Vaessen, J., Meer, R. van der, 2020. Offshore Hydrogen Production in the North Sea Enables Far Offshore Wind Development 1–14. https://doi.org/10.4043/30698-ms

[48] Pourahmadi, M., Saybani, M., 2022. Reliability analysis with corrosion defects in submarine pipeline case study: Oil pipeline in Ab-khark island. Ocean Eng. 249, 110885. https://doi.org/10.1016/j.oceaneng.2022.110885

[49] Rabindran, P., Cote, H., Winning, I.G., 2011. Integrity Management Approach to Reuse of Oil and Gas Pipelines for CO 2 Transportation, in: 6th Pipeline Technology Conference 2011 Integrity.

[50] Rincón, P., González, F., Vinccler, H., 2007. Case studies of successful pipeline life extension using integrity management practices. NACE - Int. Corros. Conf. Ser. 071411–0714123.

[51] Schronk, L., Biggerstaff, G., Langmaid, P., Aalders, A., Stark, M., 2015. Lucius project: Export oil and gas pipeline development and execution. Proc. Annu. Offshore Technol. Conf. 5, 4002–4018. https://doi.org/10.4043/26006-ms

[52] Sedlar, D.K., Vulin, D., Krajačić, G., Jukić, L., 2019. Offshore gas production infrastructure reutilisation for blue energy production. Renew. Sustain. Energy Rev. 108, 159–174. https://doi.org/10.1016/j.rser.2019.03.052

[53] Selman, A., Hubbard, R., 2016. How to age gracefully - Pipeline life extension. Soc. Pet. Eng. - SPE Asia Pacific Oil Gas Conf. Exhib. 2016 25–27.

[54] Shah, I.H., Hiles, C., Morley, B., 2018. How do oil prices, macroeconomic factors and policies affect the market for renewable energy? Appl. Energy 215, 87–97. https://doi.org/10.1016/j.apenergy.2018.01.084

[55] Spinelli, C.M., Demofonti, G., Lucci, A., Di Biagio, M., Ahmad, M., 2014. CO2 pipeline transportation new needs. Proc. Int. Offshore Polar Eng. Conf. 3, 9–16.

[56] The Crown Estate, 2019. Information Memorandum: Introducing Offshore Wind Leasing Round 4, The Crown Estate.

[57] The Oil & Gas Technology Centre, 2020. Phase 1 Project Report Delivery of an offshore hydrogen supply programme via industrial trials at the Flotta Terminal HOP Project – HS413, Low Carbon Hydrogen Supply Programme.

[58] Victor H. G. Oliveira, E.V.A.O., 2019. Lifetime Extension: A Brazilian Subsea Systems Overview, in: Rio Oil & Gas Expo and Conference 2018 Proceedings.

[59] Wang, P., Li, Y., Reddy, C.K., 2019. Machine learning for survival analysis: A survey. ACM Comput. Surv. 51, 1–39. https://doi.org/10.1145/3214306

[60] Weijermars, R., Burnett, D., Claridge, D., Noynaert, S., Pate, M., Westphal, D., Yu, W., Zuo, L., 2018. Redeveloping depleted hydrocarbon wells in an enhanced geothermal system (EGS) for a university campus: Progress report of a real-asset-based feasibility study. Energy Strateg. Rev. 21, 191–203. https://doi.org/10.1016/j.esr.2018.05.005

[61] Zhang, L., Adey, R.A., 2007. Predicting the Probability of Failure of Gas Pipelines Including Inspection and Repair Procedures, in: International Conference on Hydrogen Safety. pp. 1–12.