Sustainability in the Decommissioning Process of UK Offshore Installations and the Management of Hazardous Waste

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ABSTRACT

The decommissioning of offshore oil and gas installations is a complex process that poses significant environmental, regulatory and operational challenges. The handling of hazardous waste materials adds further difficulty, affecting compliance, cost efficiency and the overall sustainability of the process. The aim of this study is to develop a framework to improve the sustainable management of hazardous waste generated during the decommissioning of offshore oil and gas installations in the UK sector.

The study combines several methods. A review of existing literature was used to identify the main factors that influence hazardous waste handling. Expert discussions were held to collect industrial experience and professional judgement. The Analytic Hierarchy Process was then used to rank the importance of these factors, with "regulatory compliance" and "knowledge sharing" identified as the most influential. Bayesian Network modelling was used to examine how these factors interact and how uncertainty moves through the system. The results from these stages were brought together to form the integrated framework. These methods were integrated to develop a decision-support framework that combines qualitative expert knowledge with quantitative modelling to enhance the understanding and management of hazardous-waste processes during decommissioning.

The framework consists of six main elements: liability identification, regulatory compliance, knowledge sharing, hazardous waste monitoring, cost reduction and waste-stream optimisation. It was applied to two completed offshore decommissioning projects to assess its suitability and effectiveness: the Goldeneye gas platform, a fixed installation in the UK Central North Sea, and the Brent Delta topside, part of the Shell Brent field decommissioning programme. Data were taken from public reports and expert interviews. Applying the framework showed that early material identification and clearer knowledge sharing helped to reduce uncertainty in waste outcomes, while better coordination and record keeping improved waste-routing decisions and reduced reliance on landfill. The analysis also highlighted continuing problems with waste-inventory control and differences in how regulations are interpreted.

The study demonstrates that improved communication, data management and regulatory alignment are as important as technical solutions. The framework links these elements in one clear structure that can be applied to other decommissioning projects. Its main value is that it combines expert opinion and objective data in a transparent model that can be updated as new information becomes available. This study provides a practical approach for industry and regulators to improve the sustainability of offshore decommissioning. Future work could incorporate live data from monitoring systems and include broader social and economic impacts to make the framework more complete and predictive.

ACKNOWLEDGMENTS

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I would also like to thank Dr Eduardo Blanco Davies, Dr Ava Shahrokhi and Professor Ana Armada Bras for their invaluable guidance. Their individual expertise, experience and feedback were instrumental in shaping my research.

I would also like to extend my heartfelt thanks to my family, whose support and understanding have made this journey possible. The past few years have been particularly challenging and filled with periods of uncertainty and personal turmoil, and their strength, reassurance, and belief in me have been a constant source of motivation. Without them, this achievement would not have been possible.

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
ALARP	As Low as Reasonably Possible
ASCOPE	ASEAN Council on Petroleum
ASEAN	Association of Southeast Asian Nations
BEIS	Department for Business, Energy and Industrial Strategy
BN	Bayesian Network
BOE/day	Barrels of Energy Per Day
BOEM	Bureau of Ocean Energy Management
BP	British Petroleum
CDM	Construction (Design and Management) Regulations
COBSEA	Coordinating Body on the Seas of East Asia
CoP	Cessation of Production
D&R	Decommissioning and Restoration
EA	Environmental Assessment
EEZ	Exclusive Economic Zones
EU	European Union
GACERE	Global Alliance on Circular Economy and Resource Efficiency
GDPR	General Data Protection Regulation
GoM	Gulf of Mexico
HSE	Health & Safety Executive
IMO	International Maritime Organisation
MARPOL	The International Convention for the Prevention of Pollution from Ships
MCDM	Multicriteria Decision Making
MER	Maximising Economic Recovery
MMO	Marine Management Organisation
NORM	Naturally Occurring Radioactive Material
NSTA	North Sea Transition Authority
OGA	Oil & Gas Authority
OGUK	Oil and Gas UK
OPRED	Offshore Petroleum Regulator for Environment and Decommissioning

OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
P&A	Well Plugging & Abandonment
PETRONAS	Petroliam Nasional Berhad
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SEPA	Scottish Environment Protection Agency
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
USA	United States of America
WFD	Waste Framework Directive

CHAPTER 1: INTRODUCTION

1.1 Introduction

The decommissioning of offshore oil and gas installations is a complex and costly process that brings together technical, environmental and regulatory challenges. Over the next two decades, a large number of ageing structures in the UK Continental Shelf will require full or partial removal. This scale of activity raises concerns about safety, cost, and long-term environmental impact.

A major difficulty within decommissioning is the management of hazardous waste. Materials such as naturally occurring radioactive material (NORM), asbestos, heavy metals, and chemical residues must be identified, treated, and disposed of in line with strict regulations. Poor management of these wastes can increase project cost, cause delays, and create serious environmental risk. At the same time, growing pressure to meet national sustainability goals has placed more attention on how these materials are handled, reused, or recycled.

Existing guidance and legislation give a foundation for safe removal and disposal, but they do not always address the uncertainty and variation seen in real projects. Decision-making often depends on incomplete information and inconsistent interpretation of regulations. This can result in inefficiencies and reliance on landfill, reducing the overall sustainability of the process. A more structured and evidence-based approach is needed to understand how the different technical, economic, and regulatory factors interact and how they influence waste outcomes.

This study responds to that need. It develops an integrated Bayesian-based framework designed to improve the sustainable management of hazardous waste during offshore oil and gas decommissioning. The framework brings together expert judgement, analytical hierarchy ranking, and probabilistic modelling to show how uncertainty affects decisions and outcomes. By applying the framework to real decommissioning case studies within the UK sector, this study provides new insight into how hazardous-waste management can be made more consistent, transparent, and sustainable.

1.2 Background

There are over 290 offshore installations within the United Kingdom Continental Shelf (UKCS), with 24 new licenses awarded in 2024 alone (NSTA, 2024). When an offshore installation reaches the end of its life, it will be required to be decommissioned in line with current regulations. Decommissioning these installations is challenging due to the different nature of each one. The installation may have changed the owner, mode of operation, and workforce over its lifetime. With these changes, information concerning the materials may have been lost or failed to have been passed on. This results in incomplete material and equipment inventories. Prior to the commencement of decommissioning, surveys and materials testing must take place, but often, these are inadequate and fail to identify the types and quantities of hazardous materials present. Failure to identify and qualify these materials can result in improper handling of materials, increased risk of loss of containment, and reduced recycled materials. This research project builds on the work completed previously by the author (Ford et al., 2021). The previous project highlighted the issues concerning the identification of hazardous waste during the offshore decommissioning process and the understanding of the current legislation.

1.3 Project Aims & Objectives

The aim of this study is to develop a framework to improve the sustainable management of hazardous waste generated during the decommissioning of offshore oil and gas installations in the UK sector.

To achieve this aim, the study has the following objectives:

i. To identify the key factors that influence hazardous-waste management across the decommissioning process.
ii. To determine the relative importance of these factors through expert judgement using the Analytic Hierarchy Process (AHP).
iii. To determine the most influential factors across the waste stream by conducting a multi-attribute decision analysis that combines AHP rankings with Bayesian Network (BN) results.
iv. To integrate the outcomes of the AHP and BN analyses to enhance understanding and support the development of a structured framework for sustainable hazardous-waste management.

v. To evaluate the effectiveness of the proposed framework using two completed offshore decommissioning case studies within the UK sector.

This study adopted a mixed-method approach that combined a critical literature review, expert elicitation, AHP analysis and BN modelling. The findings from each stage were integrated to create a practical framework that was validated through two real offshore decommissioning case studies.

1.4 Scope and Limitations of Research

It is important to highlight the assumptions and limitations that define the scope of this research and clarify its applicability. While the developed models and framework provide valuable insights into offshore decommissioning within the UKCS, they do not encompass all potential scenarios, regions, or waste types associated with decommissioning activities. The specific limitations and assumptions underpinning the research are outlined as follows:

Geographical and Structural Focus: The research is specifically designed for offshore oil and gas installations undergoing decommissioning within the UKCS. The installation is considered to be of a fixed steel jacket type, which represents the majority of ageing structures in the waters of the United Kingdom (UK). While the general framework may have broader applicability, variations in international regulations, environmental conditions, and decommissioning practices outside the UKCS are not accounted for.

Key Factors and Process Assumptions: The models have been developed based on the key factors identified in previous chapters. These factors focus on the sustainability of the decommissioning process and the handling of generic hazardous waste materials. The models assume that the decommissioning process follows a standard sequence of events as outlined in regulatory guidelines, although project-specific variations may occur in practice.

Simplification of Waste Classification: Offshore installations contain diverse equipment and materials, with waste characteristics varying based on age, location, and operational history. To maintain feasibility, the models adopt a generalised waste classification system rather than analysing individual material types, such as naturally occurring radioactive material or low specific activity scale. This approach prevents excessive network complexity and the need for extensive data beyond the scope of this research.

Data Sources and Uncertainty: The models rely on expert opinions, subjective data, and publicly available reports from the Health and Safety Executive (HSE), Offshore Petroleum Regulator for Environment and Decommissioning (OPRED), and decommissioning close-out documentation. While these sources provide valuable insights, they introduce a degree of uncertainty and potential bias. Missing conditional probability data was completed using established probabilistic methods, such as the weighted sum algorithm, though this compromises precision in the absence of comprehensive real-world datasets.

Environmental and Operational Risks: The models simplify failure scenarios, such as tote tank failures and containment breaches, using probabilistic estimates derived from historical incidents. However, real-world conditions may introduce unforeseen environmental, operational, and mechanical risks that are not explicitly modelled. Additionally, transport-related failures are considered, but factors such as human error, adverse weather, and complex mechanical malfunctions fall outside the model's scope.

Regulatory and Stakeholder Assumptions: The research assumes that all stakeholders involved in the decommissioning process have access to and correctly interpret legislative requirements. In practice, regulatory complexities often lead to varying levels of understanding. Similarly, the proposed framework emphasises stakeholder collaboration and knowledge sharing, but industry practices, confidentiality agreements, and competitive interests may limit the extent of information exchange.

Framework and Comparative Limitations: The developed framework is designed to enhance hazardous waste handling and sustainability outcomes within UKCS decommissioning projects. While some principles may be applicable to other regions, differences in regulatory frameworks, environmental policies, and industry standards could influence their effectiveness outside the UK. The comparison with nuclear decommissioning offers valuable insights but is inherently limited by fundamental differences in waste classification, radiological hazards, and risk management practices.

Despite these limitations, the research presents a robust foundation for understanding key interactions within offshore decommissioning. The models and framework can be refined with additional data, real-time case studies, and adaptive regulatory updates to further enhance their applicability across diverse decommissioning projects and international contexts.

1.5 Thesis Structure

The thesis is divided into ten chapters, as shown in Figure 1-1, each building on the findings of the previous chapter to form a cohesive body of research and meeting the objectives. Following the introductory chapter, the research methodology is outlined, followed by the development and refinement of Bayesian networks using both subjective and objective data. The study culminates in the development of a decommissioning framework, which is validated through case studies. Finally, the thesis concludes with a discussion of findings, limitations, and opportunities for future research. The following provides a summary of each chapter.

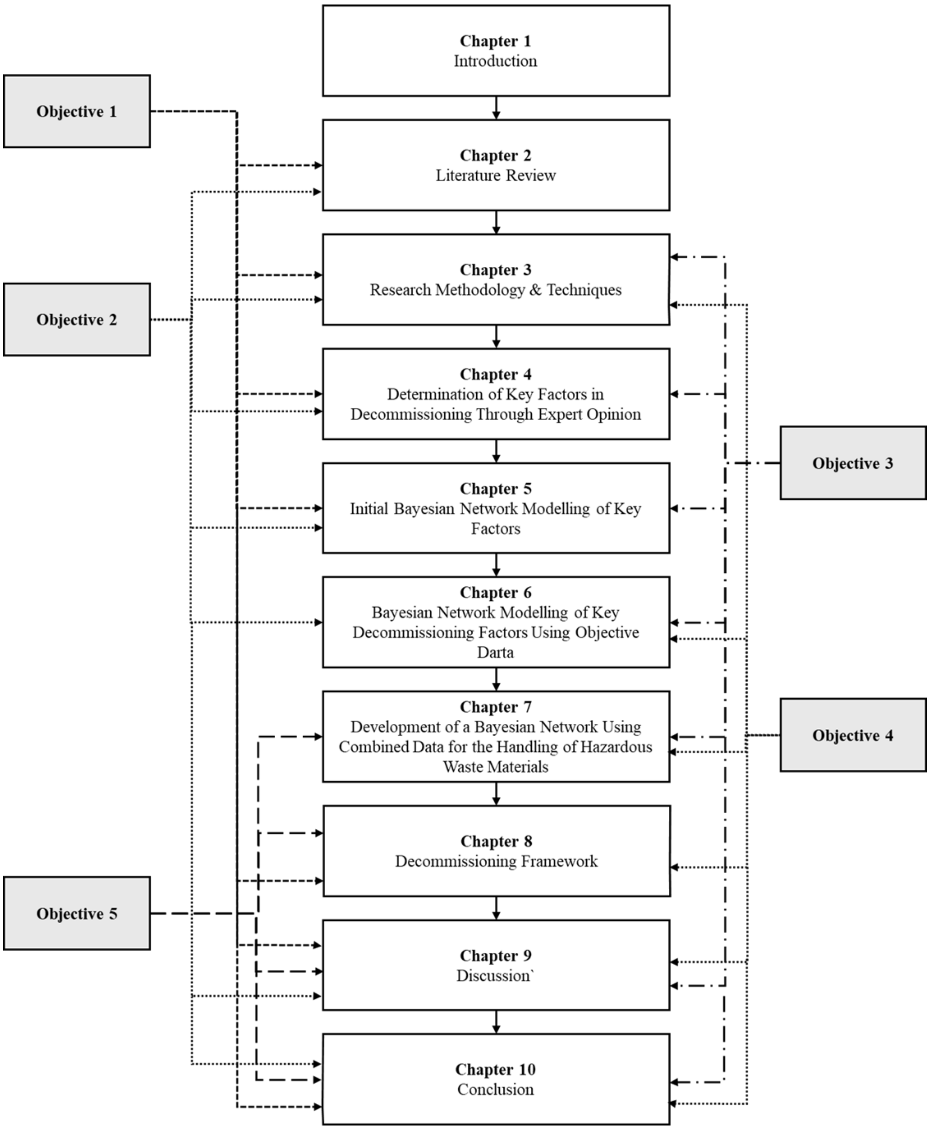


Figure 1-1: Overview of thesis chapter structure.

Chapter 1: Introduction

This chapter defines the research aims and objectives, providing the background and rationale for the study. It includes an outline of the thesis structure and a review of the current decommissioning landscape within the UKCS. The chapter also explores the offshore decommissioning process, with particular emphasis on the management and processing of hazardous waste materials.

Chapter 2: Literature Review

This chapter reviews the relevant academic, industry and regulatory literature. It outlines current knowledge surrounding offshore decommissioning practices and waste stream governance. Gaps in the existing literature are identified, supporting the need for the research. This chapter also provides the context for the selection of methods used in the later stages of the project.

Chapter 3: Research Methodology and Techniques

This chapter presents the research methodology, detailing the approach adopted for the study. It outlines the application of the analytical hierarchy process (AHP) used to assess expert responses and prioritise key decommissioning factors. The methodologies applied throughout the study are explained, ensuring transparency in the research process.

Chapter 4: Determination of Key Factors in Decommissioning through Expert Opinion

This chapter describes how expert advocacy discussions informed the AHP. The application of Pearson's correlation coefficient supported the identification of key factors influencing the decommissioning process. The findings from this stage formed the foundation for the development of subsequent Bayesian network (BN) models.

Chapter 5: Initial Bayesian Network Modelling of Key Factors in Decommissioning

This chapter focuses on the development of an initial Bayesian network model using subjective data obtained from expert discussions, the literature review, and the AHP. The model was verified through sensitivity analysis and a series of test cases, ensuring the robustness of the network structure.

Chapter 6: Bayesian Network Modelling of Key Decommissioning Factors Using Objective Data

This chapter expands upon the initial model by developing a Bayesian network based on objective data sourced from publicly available decommissioning reports and datasets. The model was further validated through sensitivity analysis and scenario-based testing, ensuring its applicability to real-world decommissioning scenarios.

Chapter 7: Development of a Bayesian Network Using Combined Data for the Handling of Hazardous Waste Materials

This chapter outlines the development of an integrated Bayesian network, combining the subjective and objective models established in the previous chapters. The combined network provided a comprehensive risk assessment tool for hazardous waste management during decommissioning. Sensitivity analysis and test cases were again employed to verify the model's validity.

Chapter 8: Decommissioning Framework

This chapter presents a proposed decommissioning framework informed by the findings from previous chapters. A comparative analysis is conducted between current oil and gas decommissioning practices and the established nuclear decommissioning framework. The application of the proposed framework is demonstrated through case studies of decommissioning projects within the UKCS, highlighting key issues and showcasing how the framework can be practically implemented.

Chapter 9: Discussion

This chapter critically discusses the findings of the research, comparing them with existing literature and industry practices. It reflects on the strengths and limitations of the models developed and highlights unexpected outcomes. The discussion also considers the broader implications of the research for policy, regulatory compliance, and future applications.

Chapter 10: Conclusion

The final chapter provides a reflective conclusion to the research. It summarises how each objective has been achieved, outlines the key contributions to knowledge, and presents recommendations for future research. The chapter concludes by reinforcing the value of a Bayesian Network-based framework to improve hazardous waste management during offshore decommissioning.

1.6 Novelty of the Research

Offshore decommissioning has been widely studied in terms of cost management (Abdo et al., 2018; Tan et al., 2021; Li & Hu, 2025) and operational efficiency, but limited research has focused on how key regulatory and sustainability factors interact to influence decision-making.

The novelty of this research lies in the following areas:

Application of Bayesian Networks: This research applies Bayesian network modelling, focusing specifically on the key factors affecting the handling of hazardous waste materials during offshore decommissioning, allowing for a probabilistic assessment of key factors and their interactions.

Integration of Expert Knowledge: The research incorporates insights from industry experts through advocacy discussions and the Analytical Hierarchy Process to ensure that the model reflects real-world decommissioning challenges.

Assessment of Knowledge Sharing and Regulatory Compliance: Unlike traditional decommissioning models, which focus on cost and logistics, this research highlights the role of knowledge sharing, liability management, and legislative understanding in ensuring safe and sustainable decommissioning.

Comparative Analysis of Decommissioning Practices: The study provides a comparative evaluation of decommissioning regulations and practices in the UK, Gulf of Mexico, and Association of Southeast Asian Nations (ASEAN), identifying gaps and best practices that can inform future decommissioning strategies.

By addressing the identified gaps in current research, this research project aims to provide a novel, holistic framework for use in the decommissioning of offshore oil and gas installations, offering practical insights for both industry and regulatory bodies.

1.7 Publications Generated from the Research

During the course of the research, the following publications were produced:

- Ford, J., Loughney, S., Blanco-Davis, E., Shahrokhi, A., Calder, J., Ogilvie, D. and MacEachern, E., 2021, September. Benchmarking and compliance in the UK Offshore Decommissioning hazardous waste stream. In *Proceedings of the 31st European Safety and Reliability Conference (ESREL 2021)* (pp. 2555-2561). Research Publishing Services.
- Ford, J., Loughney, S., Blanco-Davis, E., Shahrokhi, A., Bras, A.A. and Wang, J., 2023. Identification of Key Factors in the Decommissioning of Offshore Oil and Gas Installations. In *Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)* (pp. 1608-1615), Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio. Research Publishing, Singapore. doi: 10.3850/978-981-18-8071-1_P015-cd
- Ford, J., Loughney, S., Wang, J., Zawawi, N., and Yaakob, O., 2024. WP1C Report - Development of Guidelines and Code of Practices for Safe & Sustainable Decommissioning or Repurposing of Structures in The Region. In *Engineering X*

Safer End of Engineered Life - Offshore & Ships Safe and Sustainable Decommissioning of Offshore Structures Taking into Consideration the Peculiarities of the ASEAN & South Asia Regions.

- Ford, J., Loughney, S., Blanco-Davis, E., Shahrokhi, A., Armada Bras, A., & Wang, J. (2024). Bayesian Network Analysis of Offshore Decommissioning Waste Management. In: Kolowrocki, K. & Kosmowski, K. (eds.) *Advances in Reliability, Safety and Security.* ESREL 2024 Monograph Book Series, Part 10. Polish Safety and Reliability Association, Gdynia, pp. 49–58.

1.8 Concluding Remarks

The key points from this chapter are outlined below to reinforce the purpose and scope of the research:

- Offshore oil and gas decommissioning presents complex challenges due to the involvement of multiple stakeholders, varying asset conditions, and differing regulatory requirements.
- Hazardous waste materials represent a particular concern due to their potential environmental impact and the legal duties associated with their handling.
- The aims and objectives were defined to address these gaps by exploring the legal, operational, and decision-making processes through a structured methodological approach.
- A research framework is proposed that combines expert judgement with probabilistic modelling to understand and evaluate the factors influencing hazardous waste outcomes during decommissioning.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the existing literature on the regulatory frameworks, waste stream management, and decommissioning practices within the UK and other jurisdictions. It identifies current research gaps, highlights the complexity of offshore decommissioning, and provides the background context for the development of the analytical framework used in this study.

2.2 Background

The United Kingdom's (UK) oil and gas industry dates back to the 1850s (UKOOG, 2022). The first onshore oil was produced in 1851, and the first onshore gas was produced in 1896. Onshore oil and gas were harnessed using drilling and hydraulic fracturing techniques. With the arrival of both world wars, it was realised that the UK would have to focus on the production of oil and gas instead of its reliance on imports. Until then, the UK imported all its oil from the United States of America (USA) and Iran (Craig et al., 2018). This led to the introduction of government legislation to allow companies to explore for hydrocarbons more easily.

Following the Second World War, international oil production increased rapidly. Using technologies developed onshore during this boom, exploration moved offshore (Craig et al., 2018). The United Nations (UN) convention ratified the area over which a country held jurisdiction in 1964 as part of its territorial waters. The first discovery on the UKCS was that of natural gas made by British Petroleum (BP) in 1965 in block 48/6 (Kemp, 2011).

Investment in the UKCS increased, allowing the increase of oil and gas production from a relatively small amount in 1965 to 2.6 million barrels of energy per day (BOE/day) in 1985 and reaching its peak in 1999 of 4.5 million BOE/day (UKETI, 2024). The UK energy production is currently 1.23 million BOE/day and is expected to decrease to 0.83 million BOE/day by 2028 due to a shift towards more sustainable energy sources (NSTA, 2023).

In 2015, all United Nations (UN) Member States adopted the UN 2030 Agenda and its 17 sustainable goals (UN, 2015). Goal 12 addresses responsible consumption and production, particularly of raw materials, whilst Goal 13 highlights climate action and the move to reduce greenhouse gas emissions. Due to the current focus on sustainability and climate change, the environmental impact from the entire life cycle of an offshore installation must be minimised.

One of the most significant current discussions in the UK offshore oil and gas industry is that of decommissioning. Within the UKCS, 203 fields will undergo decommissioning activities during the 2018-2027 period, requiring the removal of 950,000 tonnes of topsides (SEPA, 2018). Decommissioning spending reached £ 1.6 billion in 2022 and is forecast to be at least £ 21 billion over the next decade (NSTA, 2023). Although decommissioning spending is set to decrease in line with targets set by the UK government, it is thought that decommissioning spending will peak in 2032 (NSTA, 2023) with the ever-increasing number of ageing installations.

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) requires the removal of all installations, including the wellheads and christmas trees (OSPAR, 2010). A decommissioning plan must be submitted to and approved by OPRED (OGUK, 2015). In 2018, 120,000 tonnes of waste was processed from decommissioned installations (OGUK, 2019), but this is estimated to increase each year. Hence, ensuring the waste is handled correctly, reused, or recycled where possible is essential. 20% of overall installations will be decommissioned over the next ten-year period (OGUK, 2019), along with 20% of wells and 25% of pipeline infrastructure.

2.3 Decommissioning Process

In line with current United Kingdom requirements, installations must be decontaminated from hazardous waste before any part can be reused or recycled. This hazardous waste must be handled, transported, and disposed of in a way that does not impact safety or the environment. The decommissioning process is subject to several regulations and guidance. Within the UKCS, decommissioning is governed by OPRED, which aims to reduce decommissioning costs by 35% by 2035 whilst still meeting all environmental goals (OGUK, 2019). UK regulations are driven by current international and European Union (EU) legislation, such as OSPAR and United Nations (UN) conventions. Operators are required to submit a decommissioning plan to OPRED for approval, highlighting how the following criteria will be met: safety, environmental impacts, technological feasibility, societal impacts and costs.

Planning the decommissioning for an installation begins at least three years before the Cessation of Production (CoP). This enables information about the installation's condition to be gathered and a decommissioning plan to be generated.

Prior to the removal of an installation, it must be prepared by decontaminating and removal of waste. OSPAR requires the removal of all installations, including wellhead and christmas trees (OSPAR, 2010). In 2018, 120,000 tonnes of waste were processed from decommissioned installations (OGUK, 2019), and this is estimated to increase by 39%. The decommissioning process has several phases, from the full production phase to the dismantling and disposal of the installation. A summary of the phases can be seen in Figure 2-1.

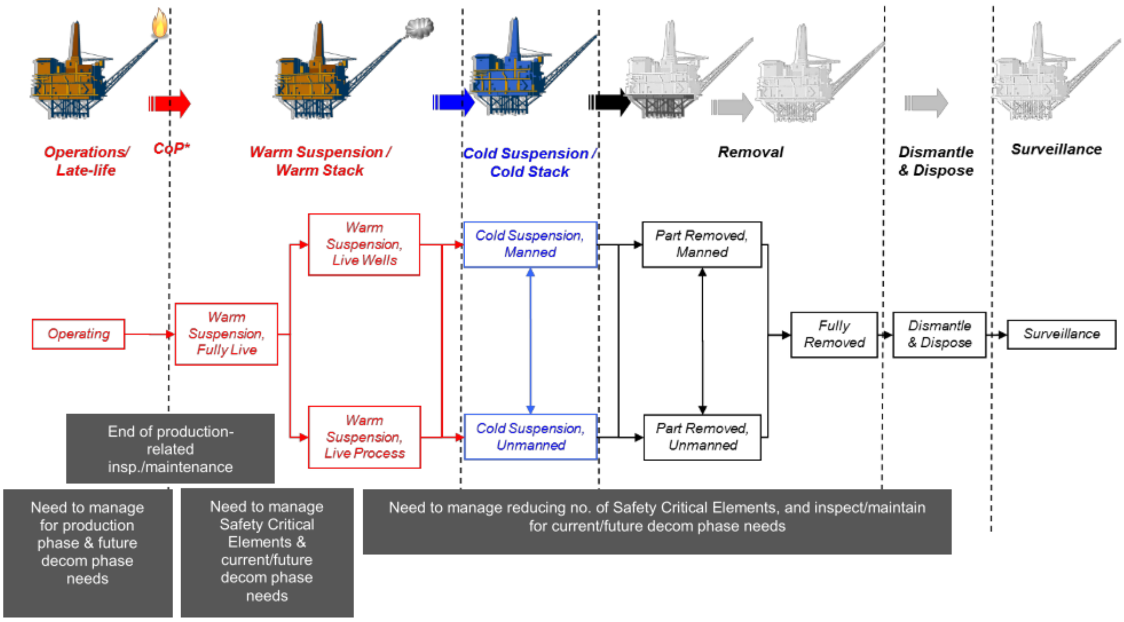


Figure 2-1: Summary of Decommissioning Workflow (OGUK, 2015)

Tan et al. (2021) reviewed the literature concerning decommissioning factors, estimation methodologies of decommissioning costs and environmental impact. Tan et al. (2021) conclude that there is currently a lack of data, and databases for estimating decommissioning cost and environmental impact are error-prone. This supports the work conducted by Ahiaga-Dagbui et al. (2017), which suggests that information and knowledge need to be more freely shared among operators and contractors. Together, these issues have the potential to combine and reduce the sustainability of the decommissioning process. Wilkinson et al. (2016) discuss the importance of communication between stakeholders and those responsible for planning the decommissioning process of an offshore installation. When tasks such as risk assessments are outsourced, it is difficult for stakeholders to judge the technically complex issues and have confidence in the final proposals. Walker and Roberts (2013) also raised a similar issue, stating the lack of knowledge sharing, trust issues and skills deficiency.

The decommissioning process produces waste that can be recycled, reused, or disposed of. The waste from offshore installations ranges from asbestos to equipment contaminated with NORM. Typical examples of hazardous waste are trapped gas or hydrocarbons, asbestos, residual diesel and oils, drill cuttings, mercury, and NORM. The correct identification of hazardous waste enables its safe handling and treatment. The changing regulations and different parties involved in the decommissioning process can result in a loss of clarity of liability.

With the current move towards a circular economy (Milios et al., 2019), ways to decommission an installation safely and sustainably need to be developed. Part of the decommissioning process must address how to handle hazardous waste materials from the installation. These hazardous materials must be identified, handled, transported, and processed per current legislation.

Existing literature tends to emphasise technical characterisation of hazardous waste streams rather than examining how these classifications influence operational decision-making during decommissioning. While the studies reviewed provide useful inventories and compliance references, few interrogate the reliability or completeness of reporting mechanisms that underpin such data. This lack of critical evaluation restricts understanding of how regulatory obligations translate into sustainable practice at the project level.

2.4 Decommissioning Waste Materials

Part of the decommissioning process is identifying and categorising the waste according to the European Union (EU) Waste Hierarchy (EU, 2008). From this, an active waste management plan can be formulated.

Waste is defined as "any substance or object which the holder discards or intends, or is required to discard" by the EU Waste Framework Directive (EU, 2008). The waste from offshore installations ranges from asbestos to equipment contaminated with NORM.

Akinyemi, Sun and Gray (2020) developed a data integration framework to estimate the costs of reusing and recycling waste items during decommissioning. This study focused primarily on the volume of steel present within the structure. The presence of hazardous waste materials and potential decontamination requirements is not considered. Engelseth (2016) highlights that waste should be referred to as "a resource" to ensure that it is valued, to create more transparent supply chain management initiatives, and not to be viewed as something that is simply going to be disposed of. This is key to moving towards the sustainable management of hazardous waste.

2.4.1 Drill Cuttings

OGUK (2019) states that the most significant volume of waste is the drill cuttings. These contain different potentially hazardous contaminants such as heavy metals, NORM, hydrocarbons and additives from the drilling mud used.

There have been several studies on the sustainability and processing of drill cuttings, mainly while the installation is still operational. Glickman, Piper and Ivan (2008) produced a waste management toolbox for Chevron. This involves the screening of the drilling fluids prior to their discharge in order to identify an environmental solution with the aim of meeting legislation and reducing impact. de Almeida, Araújo and de Medeiros (2017) compare and outline methods for drill cutting management. They conducted a sustainability analysis of existing technologies and suggested reinjection and microwave treatment as sustainable methods. Marinho et al. (2019) indicates that there is still a lack of knowledge of the onshore destination for drill cuttings. They have worked with Petrobras to research ways to assist the development of legislation on the discharge of drill cuttings.

2.4.2 Naturally Occurring Radioactive Materials

There have also been studies into the impact of NORM. NORM scale and sludge build up in equipment and components over time. This must be removed prior to any resale or recycling of the equipment. The injection of seawater to increase production increases the concentration of NORM (Heaton, Wade and Brodie, 2012). The removal of NORM scale is traditionally through high-pressure jet washing or sandblasting. Complications arise when the NORM scale and sludge contain other hazardous materials, such as mercury. The level of activity and composition must be determined in order to decide on the method of decontamination. Cowie et al. (2012) highlight the potential hazards to workers and the environment through the improper handling and disposal of NORM waste. Continuous surveying and testing must be conducted throughout the decommissioning process.

Valeur (2011) reviewed the legislation for the North Sea and concluded that the waste was not always handled correctly due to differences in legislation and practices between countries. The introduction of the strategy for the management of NORM (DECC, 2014) in the UK aims to combat this, but also highlights the issue of predicting the volumes of NORM waste. Abidin and Mahasan (2019) also conclude that estimating the volumes of NORM waste is critical to the decommissioning process.

While these studies address the technical and environmental aspects of waste characterisation, they offer limited discussion of how data uncertainty or regulatory inconsistencies influence operational decision-making. Most approaches focus on classification and treatment technologies, rather than on how waste data are integrated into planning and risk management. There is also little examination of how differing national regulations affect cross-border waste handling or reporting accuracy. This highlights the need for analytical models capable of linking waste identification, legislative context and decision outcomes across the decommissioning process.

2.5 Human and Cultural Factors

Communication and knowledge sharing are critical to the success of any project. Many historical processes involve tacit knowledge, knowledge, skills, and abilities that individuals gain through experience (Pulanyi, 1966). This knowledge is often difficult to convey verbally and can be lost when incidents such as staffing changes occur. Knowledge may be related to activities or processes that contain hidden assumptions (Turner 2012), resulting in some individuals being able to perform an activity whilst others may not. During the decommissioning phase, whether an activity is taking place offshore or onshore, subcontractors or personnel not customarily associated with the normal operating mode of the installation may be involved. Incident rates associated with subcontractors are higher than those of regular operational personnel (Valluru et al. 2017). Sharing knowledge, particularly previous lessons learned, is essential regardless of whether it is positive or negative (Mitchell, 2017). They must be shared on all levels. The loss of tacit knowledge strategically impacts decommissioning as the oil and gas industry is a knowledge-based business (Gagilan, 2019). It depends highly on the personnel's accumulated knowledge. Critical knowledge must be identified, captured, and disseminated. Knowledge sharing across decommissioning stakeholders is not always forthcoming, as individuals wish to hold on to their specialisms and originality to keep their position in the market.

Younes (2017) discusses the human factors and cultural issues that arise during decommissioning. This study highlighted that potentially serious incidents could arise from the mishandling of waste materials, as the perception was that it didn't matter if the materials, or their containers, were broken or damaged during removal. White and Adams (2012) outlined the successes of decommissioning the Northwest Hutton installation. The key was to ensure clarity on the hazard management processes and integrated contractor workforce. Wilkinson et al. (2016) discuss the importance of communication between stakeholders and those responsible for planning the decommissioning process of an offshore installation. When tasks such as risk assessments are outsourced, it is difficult for stakeholders to judge the technically complex issues and have confidence in the final proposals. Ahiaga Dagbui et al. (2017) echo this and suggest that information and knowledge must be more freely shared among operators and contractors.

Although the literature highlights the importance of communication and human factors, much of it remains descriptive and does not explore the systemic causes of poor knowledge transfer. Few studies analyse how organisational structures, contractual boundaries or incentive mechanisms shape stakeholder behaviour during decommissioning. This limits understanding of why lessons learned are not effectively institutionalised and why similar incidents recur despite detailed guidance. There is, therefore, a clear gap for research that connects cultural and procedural factors within an integrated analytical framework.

2.6 Circular Economy & Sustainability

Older installations currently considered for decommissioning were not designed per the circular economy concept. Circular economy considers reuse and regeneration, which are considered during the early stages of asset design and construction. Three fundamental principles drive the circular economy:

i. Eliminate waste and pollution.
ii. Circulate products and materials.
iii. Regenerate nature (Ellen MacArthur Foundation, 2024).

Before the current thinking of a circular economy, a linear economic model was the norm (Aggeri, 2021). This was based on extracting new raw materials and disposing of waste in landfills. Moving from a linear model to a circular one involves rethinking the lifecycles of materials so that materials never become waste. New offshore wind projects adopt this whole system approach (Velenture et al., 2021). Offshore wind projects require large volumes of foundation materials such as steel and concrete. This is in line with current government guidelines. The EU circular economy action plan was first introduced in 2015 and then further adapted and developed in 2020. The Global Alliance on Circular Economy and Resource Efficiency (GACERE) was launched in 2021 as part of the UN Sustainable Development Goals with several suggestions, including the phasing out of single-use plastics and increasing the use of recycled content.

Turning waste into a resource must be considered to close the loop in circular economy systems. Although the materials lifecycle in an ageing offshore installation cannot be mapped out retrospectively according to the 10 Rs and the 25-year environmental plan (DEFRA 2020), moves could be made to reduce and reuse waste materials as much as possible.

One way is through the remanufacturing and recertification of equipment. This practice is currently widespread within the automotive and aviation industries. (Waihab et al. 2018). Issues surrounding the reliability and safety of these productions may act as barriers to this technique. There is also a lack of expertise and awareness of these circular economy principles (Diganian et al 2024). There is also the issue that not everything can be repaired or remanufactured, particularly electrical waste (Alkouh et al., 2023), resulting in these materials being sent to landfill.

Engelseth (2016) highlights that waste should be referred to as "a resource" to ensure that it is valued, to create clearer supply chain management initiatives, and not to be viewed as something that is simply going to be disposed of. Engelseth (2017) goes on to suggest that waste management be viewed as a "reverse supply chain". Zhang et al. (2019) assessed the current maintenance strategies of offshore installations using data mining to propose suitable strategies. de Almeida, Araújo and de Medeiros (2017) assessed waste management in offshore oil and gas processes through the analysis of environmental, economic, safety and technical aspects. They used decision-making processes to suggest improvements to sustainability. Response to the Deep-Water Horizon accident led to a re-examination of asset maintenance and safety management (Sweeten, 2012).

Despite the importance of sustainability, there remains a paucity of evidence on the sustainable management of hazardous waste from the decommissioning of offshore structures. Lindauere et al. (2020) looked at both the global and European circular economy frameworks. They identified challenges to recycling items during decommissioning as being both technical and legal. Operators must have a clear understanding of their legal roles and responsibilities. Calder (2019) highlighted that when an installation is being transported to an onshore yard, it is no longer under the Health & Safety Executive (HSE) until it reaches the shore. Once an installation, or its parts, are brought onshore for dismantling, it is no longer under the permissioning regime but an inspection-led one. This reiterates Adetero (2009), who also stated that identifying obligations and liabilities is a concern. OGUK (2008) discussed the lack of and limited disposal routes for installations and the loss of as-built information. This issue had been previously identified by Parente et al. (2006), who highlighted the difficulty in the tracking of responsibilities as a project changed hands.

Although the concept of a circular economy has been widely discussed in policy and sustainability literature, its application to offshore oil and gas decommissioning remains largely theoretical. Most studies focus on material recovery and recycling technologies but give limited attention to the organisational, regulatory, and economic barriers that constrain circular practices once dismantling begins. Few authors examine how end-of-life decisions are influenced by conflicting objectives between waste minimisation, safety, and cost. The literature therefore provides little empirical evidence on how circular-economy principles can be operationalised within existing decommissioning frameworks, leaving a clear opportunity for integrative and decision-based approaches.

2.7 Safety

Robinson and Cowie (2003) highlighted the importance of the duty of care with regard to the transportation of hazardous waste. This duty of care flows across the entire waste chain but is dependent on awareness, planning, and management strategies regarding hazardous waste. It is influenced by the correct identification of the waste and proper disposal procedures. Khan and Amyotte (2002) stressed the need for early hazard identification and inherently safer practices in offshore operations. Du et al. (2018) underlined the importance of tracking and decontaminating hazardous materials, reinforcing the role of proper waste identification and handling. Akinyemi et al. (2020) pointed to the benefits of data integration in maintaining traceability and ensuring compliance across the waste chain. Similarly, Babaleye and Kurt (2020) demonstrated that well-informed planning and risk awareness are essential for safe transportation and dismantling. Efthymiou (2022) highlighted the logistical challenges of transporting hazardous waste to shore, noting the importance of coordinated management throughout. Janjua and Khan (2023) emphasised that effective planning and environmental approvals are central to ensuring safety during dismantling. MacIntosh et al. (2022) drew attention to the need for hazard awareness during disposal to prevent improper handling. Vidal et al. (2022) observed that unclear responsibilities can undermine the duty of care, particularly when subcontractors are involved. Watson et al. (2023) noted that onshore processing and treatment require sustained attention to duty of care to avoid environmental impacts. Most recently, Ramos and Pereira (2025) highlighted the handling of radioactive materials such as NORM as a key area where correct identification and disposal procedures are essential.

Although the reviewed studies emphasise the importance of hazard identification and the duty of care, most adopt a procedural rather than analytical focus. There is limited examination of how safety failures emerge from interactions between regulatory interpretation, contractor behaviour, and data uncertainty. Few authors attempt to quantify the relationship between information quality and risk outcomes, meaning that safety management is often treated as a static requirement rather than a dynamic process. This reveals an opportunity for approaches that model interdependencies between hazard awareness, waste traceability, and decision-making under uncertainty.

2.8 Rigs to Reefs

The OSPAR Decision 98/3 (OSPAR, 1998) prohibits disused offshore installations from being left in place either as whole or partial structures. There are exceptions for steel structures greater than 10,000 tonnes in air, gravity-based, floating concrete installations and concrete anchor bases whose removal would interfere with other legitimate uses of the sea. There is currently much debate as to whether this is still relevant and best practice.

The use of disused offshore installations as artificial reefs is widespread in the USA, and since the 1980s, parts of the subsea structure of US offshore installations have been converted to artificial reefs to support marine life. By 2018, 532 platforms had successfully been reefed in the Gulf of Mexico (BSEE, 2020).

Currently, all five Gulf states have incorporated decommissioned platforms into their artificial reef programme (BSEE, 2020). The advantages include a reduction in greenhouse gas emissions and decommissioning costs, as the platform does not require transportation to shore, enhanced fisheries and development of marine habitat.

OSPAR (2010) prevents this for installations within the North Sea following the decommissioning of the Brent Spar. The Brent Spar decommissioning project caused controversy as it was initially planned to be disposed of at sea instead of on land. This caused disagreement between the stakeholders and the general public, in particular environmental groups, as the UK government and Shell favoured deep-sea disposal. Strong opposition driven by the concerns over potential marine pollution and increasing public pressure led to the abandonment of the deep-sea disposal plan. OSPAR still states that rig-to-reef is not an option and that all non-virgin material must be removed where possible (OSPAR, 2010).

Jørgensen (2012) suggests that OSPAR reassess their guidelines to allow for artificial reef creation from deep-water disposal of disused installations. Jørgensen argues that it would be a sustainable way of dealing with subsea structures as they are already subject to marine growth and suggests that this would have a positive effect on fish conservation in the North Sea. Fowler et al. (2018) agree that this will enable biodiversity enhancement through the provision of reef habitat and protection from bottom trawling. Fowler et al. (2018) argue that leaving any chemical contamination undisturbed is more advantageous than the risk of it spreading over a large area during its removal.

Ounanian, van Tatenhove and Ramírez-Monsalve (2020) call for more flexibility in OSPAR decisions to allow for a case-by-case assessment. Ounanian, van Tatenhove and Ramírez-Monsalve (2020) discuss how existing installations have been shown to be habitats for the North Sea threatened species. Through rig-to-reef programmes, marine restoration could be assisted in line with the EU Biodiversity Strategy. This is in line with the current trend of switching environmental management from conservation to restoration.

To date, several studies have examined the environmental effects of decommissioning, focusing specifically on ecology and marine habitats. Fowler (2019) highlights a lack of consideration and knowledge about the biodiversity around the structures prior to decommissioning. Similarly, Sommer (2019) found that the environmental criteria examined in relation to the effects on habitats and ecosystems vary depending on the area of jurisdiction applied. Together, these studies indicate that this is an area of research that has been identified already as critical and is currently being pursued.

Despite the range of environmental and ecological studies on rigs-to-reefs, the discussion remains largely polarised between ecological benefit and regulatory constraint. Few analyses attempt to balance the ecological advantages of in-situ reefing with the long-term uncertainties over liability, contamination, and public perception. Much of the literature treats the debate as a policy dilemma rather than an integrated technical, legal and social issue. This narrow framing overlooks how decision-making frameworks could support evidence-based assessments of reefing options under different regulatory scenarios, suggesting an opportunity for a more holistic and quantitative approach.

2.9 Roles and Responsibilities

Calder (2019) outlined the role of the HSE in the decommissioning process. Calder highlighted the importance of the safety case revisions and the changing of the risk profile during the decommissioning process. Once an installation, or its parts, are brought onshore for dismantling, it is no longer under the permissioning regime but an inspection-led one. Operators must have a clear understanding of their legal roles and responsibilities. Calder

(2019) also highlighted that when an installation is being transported to an onshore yard, it is no longer under HSE until it reaches the shore. These issues had previously been raised by Parente et al. (2006), who highlighted the difficulty in the tracking of responsibilities as the project changed hands.

Adetoro (2009) also stated that identifying obligations and liability are a concern. OGUK (2008) discussed the lack of and limited disposal routes for installations and the loss of as-built information due to changes in staffing. Ahiaga-Dagbui et al. (2017) state that many installations built prior to 1998 OSPAR "were not designed with decommissioning in mind". The information available about the installation exists in different formats, and there is often a limited budget for inspection, surveys and familiarisation visits. Walker and Roberts (2013) also raised a similar issue, stating the lack of knowledge sharing, trust issues and a skills deficiency.

Collectively, these studies highlight that responsibility in decommissioning is often fragmented across regulatory, contractual and organisational boundaries. However, the literature offers little empirical analysis of how such fragmentation affects decision quality or compliance outcomes. The discussion of roles and liability remains largely descriptive, focusing on who holds responsibility rather than how accountability can be maintained across multiple interfaces. This gap suggests the need for structured tools that can trace responsibility throughout the waste stream and clarify obligations at each stage of the decommissioning process.

2.10 Classification of Chemicals

Anderson et al. (2018) outline the classification of chemicals under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and OSPAR schemes. This study highlighted the lack of data available within the REACH database and the different classifications of certain chemicals. For example, OSPAR may deem a substance toxic, whilst the REACH criteria may not. They also highlight the issue of polymers, which may not be classed as a risk onshore but may become a risk under offshore conditions as they begin to breakdown. Sühring et al. (2019) identified the issue of the handling and removal of hazardous chemicals. Due to changing legislation, legacy chemicals may not appear on permit applications for the installation. Chemicals that had been in use prior to the OSPAR may not be recorded in sufficient detail within the installation's inventory. During the decommissioning process, the contractor responsible for the chemical processing and decontamination will not have detailed information on the composition of these chemicals and the nature of their reactions. Sühring et al. (2019) describe the current approach, which is to use a surrogate chemical on which to base the risk assessments. If the incorrect surrogate is chosen, issues arise when the legacy chemical is more hazardous. This was an issue that had also been raised by La Védrine et al. (2015) in their study on the substitution of chemicals under the introduction of the REACH regulations.

These studies reveal that regulatory compliance in chemical classification remains reactive rather than predictive. The literature tends to describe inconsistencies between schemes such as REACH and OSPAR but rarely quantifies how these differences influence decommissioning risk or waste-handling decisions. The lack of harmonised data standards and the reliance on surrogate chemicals introduce uncertainty at the point of risk assessment. This gap highlights the need for integrated approaches that can model uncertainty in chemical classification and support consistent interpretation of hazardous materials across regulatory regimes.

2.11 Decommissioning Waste Summary

Through the analysis of available literature, it has become apparent that there is a gap between the sustainability of the decommissioning of offshore installations and the management of hazardous waste materials. The decommissioning process produces waste that can be recycled, reused or disposed of. The correct identification of hazardous waste enables its safe handling and treatment. The changing regulations and different parties involved in the decommissioning process can result in a loss of clarity of liability. Together, these issues have the potential to combine and reduce the sustainability of the decommissioning process.

While some research has been carried out on the decommissioning of offshore installations, no single study has been conducted into the sustainability of the decommissioning activities and management of hazardous waste. The issue concerning the legislation and regulations surrounding decommissioning has been identified but not pursued. A search of available literature has revealed that there are no studies that connect these significant issues.

The literature therefore exposes a fragmented understanding of how regulatory interpretation, information quality, and organisational behaviour interact to influence sustainability outcomes in decommissioning. Existing research isolates environmental, economic, or technical aspects but does not integrate them within a single analytical framework. This absence of systemic analysis provides the rationale for developing a probabilistic model that can capture the interdependencies between legislation, knowledge transfer, and waste-management performance. Addressing this gap is essential to move from descriptive accounts of decommissioning practice toward predictive, evidence-based approaches that support decision-making under uncertainty.

2.12 UK Offshore Industry Background

The UKCS comprises an area of seabed and subsoil over which the UK exercises sovereign rights. These rights include exploration and exploitation of natural resources. The boundary came into effect following the Continental Shelf Act 1964. This allowed for the exploration and development of oil and gas fields within the area. Figure 2-2 shows the area of the UKCS based on Oil and Gas Authority (OGA) data (OGA, 2020c).

Figure 2-2: Map of the UKCS, shown in blue, based on OGA data (OGA, 2020c).

The following sections provide essential technical context to define the physical scope of decommissioning activities within the UK Continental Shelf. This contextual foundation supports subsequent discussion of waste generation, regulatory control, and sustainability challenges.

2.12.1 Types of Installation

An offshore structure is one which has no fixed access to dry land and is required to stay in position in all weather conditions. They may be fixed to the seabed or floating structures. There are various types of offshore structures, and their design depends on their operating requirements and operating conditions. For the purpose of this report, fixed structures which are primarily concerned with production, storage and offloading of hydrocarbons are discussed.

Traditionally, installations are fixed steel structures. These consist of a welded steel tubular framework or jacket that supports a topside structure. The topside structure can consist of a helideck, power-generating equipment, hydrocarbon processing equipment, accommodation and hotel services. The structure is held in place by piles that are driven into the seabed. An example of the main sections of a fixed steel installation is shown in Figure 2-3. Fixed steel structures are traditionally used in UK waters. There are currently 260 fixed steel structures in place (Martins et al., 2023).

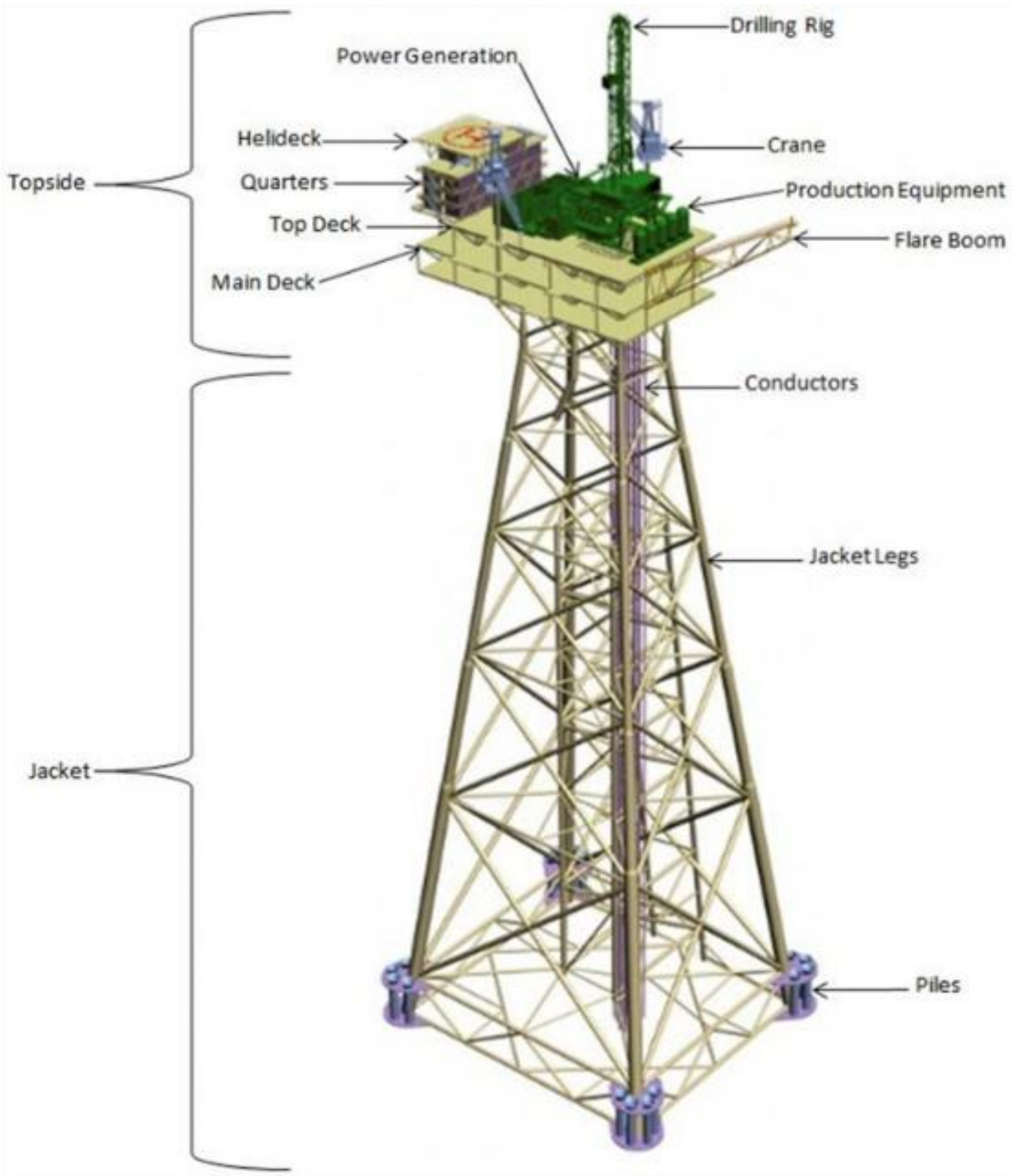


Figure 2-3: An example of a fixed steel structure. (Scarborough - Bull and Love, 2019)

Concrete gravity-based structures consist of a base constructed from reinforced concrete. The void space within this structure may be used for the storage of hydrocarbons or may be filled with ballast. An example of a concrete gravity-based structure is shown in Figure 2-4. Concrete gravity-based structures are more prevalent in Norwegian waters due to the deeper water and more exposed metocean conditions (Arup, 2014).

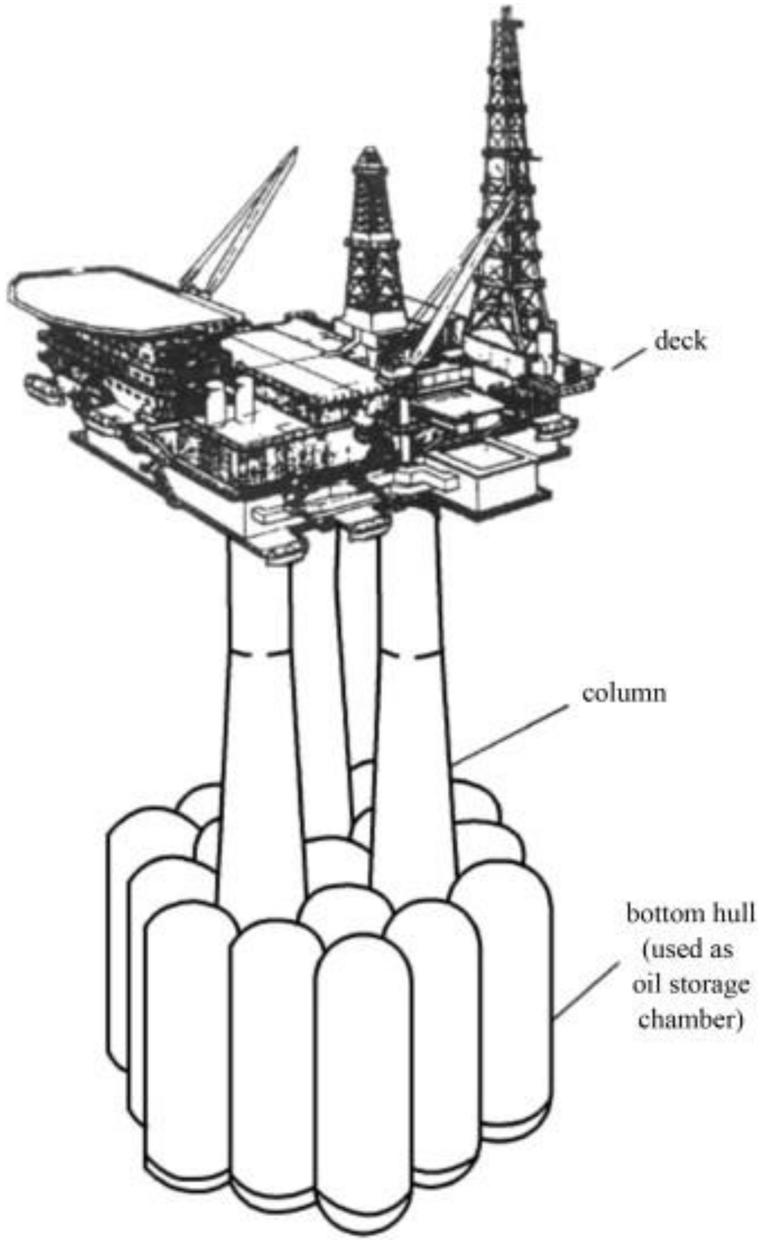


Figure 2-4: An example of a concrete gravity-based structure. (Fang and Duan, 2014)

An alternative to the fixed steel structure is the tension leg platform. An example of a tension leg platform is shown in Figure 2-5. The topside is a floating system that is tethered to the seabed by several tensioned legs. These are secured to foundation plates that are piled into the seabed, whilst the other end is connected to the topside structure. The first tension leg platform installed in the UK was in the Hutton field in 1984. This installation was decommissioned and removed in 2001 (Chakrabarti, Halkyard and Capanoglu, 2005).

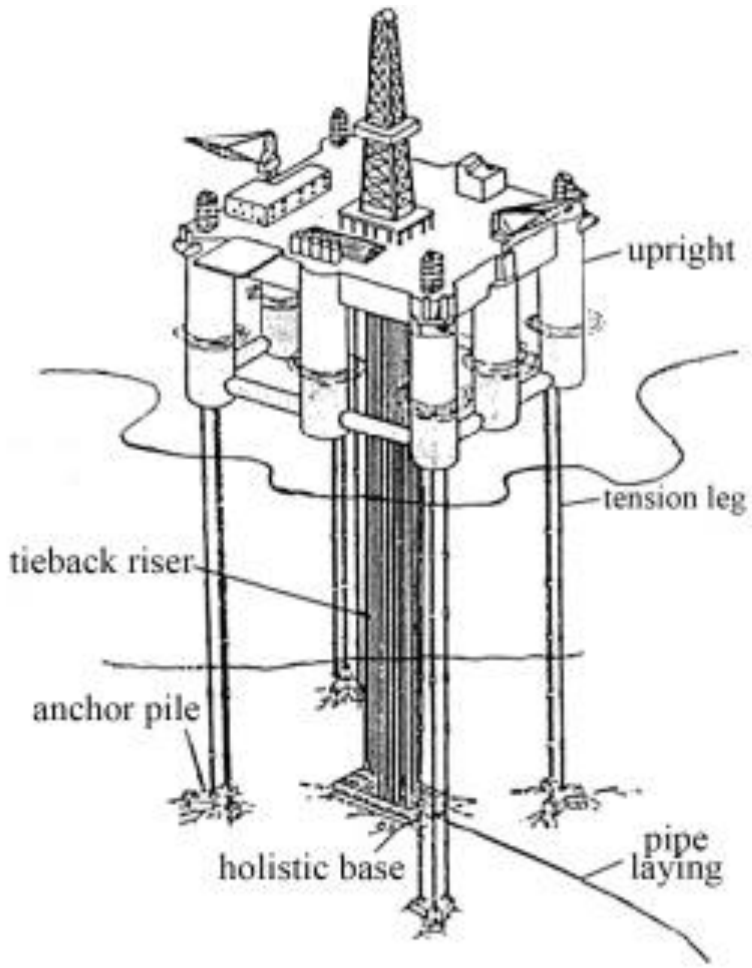


Figure 2-5: An example of a tension leg platform. (Fang and Duan, 2014)

Offshore installations are very complex. Regardless of the individual type, they consist of several thousand tonnes of steel as well as different types of equipment for the production of hydrocarbons, power generation, hotel services and safety equipment. All these structures present individual challenges as they reach the decommissioning phase. The decommissioning process is influenced by the type of platform, its size and structural integrity.

2.12.2 Topside Structure

The topside structure of an offshore installation consists of a series of decks: drilling deck, wellhead/production deck and cellar deck (El-Reedy, 2012), as shown in Figure 2-6.

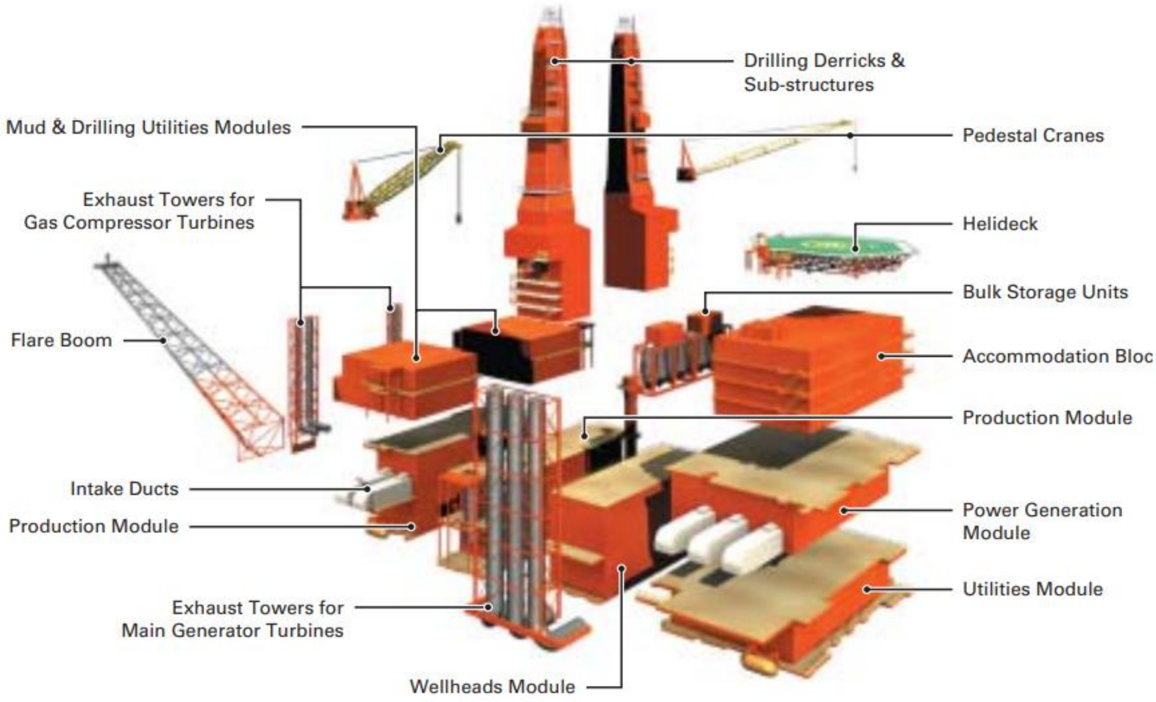


Figure 2-6: An example of the main components of a topside structure – North West Hutton Platform (BP, 2005)

The drilling deck may contain the drill rig, chemical storage tanks, communication systems, and accommodation. The production deck may contain oil and gas separation systems, processing systems, power generation systems and other utilities. The lower 'cellar' deck may contain manifolds and shutdown valves, utility systems such as cooling and freshwater systems (Arnold et al, 2005). An example of a layout of a cellar deck is shown in Figure 2-7.

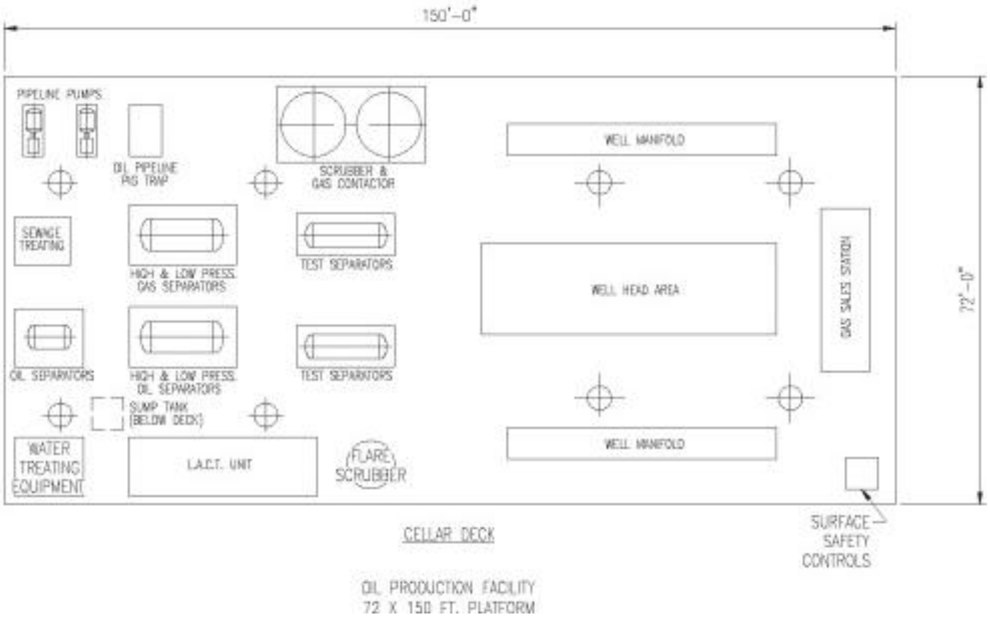


Figure 2-7: An example of the layout of a cellar deck (Arnold et al, 2005)

2.12.3 Jacket Structure

In a fixed steel jacket structure, the topside is supported by a steel jacket. As well as supporting the topside structure, the jacket may also provide support for conductors, risers and substructures such as boat docks (Efthymiou, 2022). The main components of a jacket structure are the jacket legs, brace, joints, and pile sleeves (Demir, 2005), as shown in Figure 2-8.

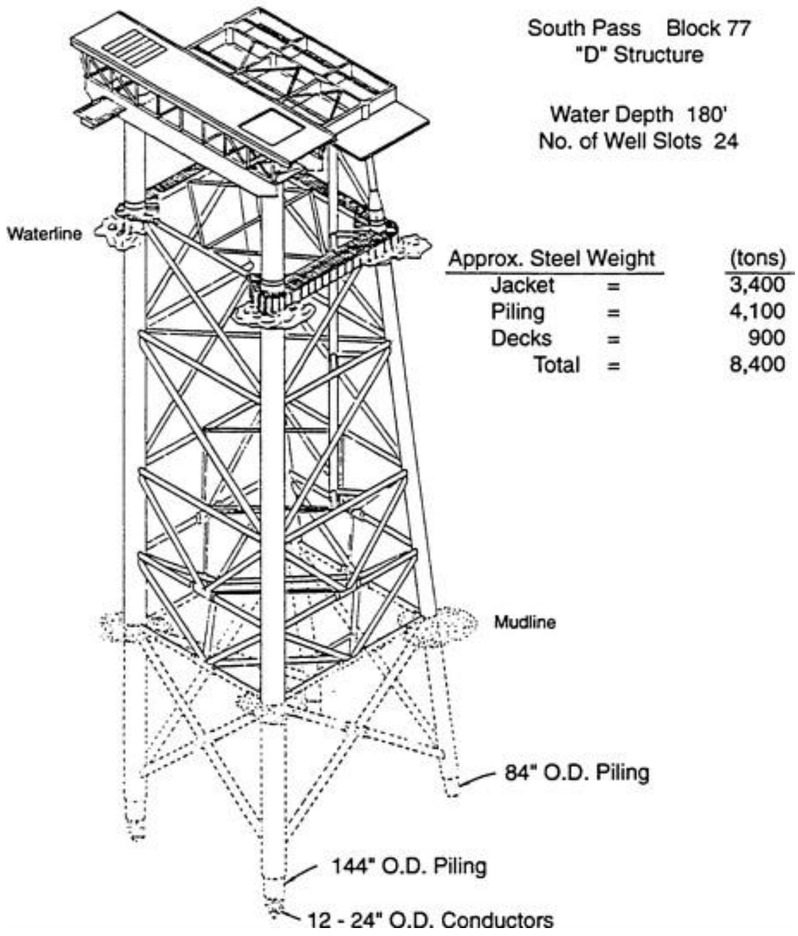


Figure 2-8: An example of a fixed steel jacket structure (National Research Council, 1996).

2.12.4 Lifecycle of Offshore Installations

Oil and gas installations have a complex lifecycle with many different phases. It can be simplified to upstream, midstream and downstream. Upstream is concerned with exploitation and production, midstream is concerned with transportation and processing, and downstream is the sale and distribution to end users Chakrabarti, Halkyard and Capanoglu, 2005. This thesis focuses on the decommissioning stage of the upstream phase. An overview of the upstream phase is shown in Table 2-1.

Table 2-1: Overview of the stages of the upstream phase.

Stage	Overview
Exploration	This phase takes many years and involves geological surveys, including magnetic, gravity, seismic, 2d/3d/4d to determine the presence of hydrocarbons. The process is a high-risk investment, as the reserve found may not be economically viable for production. During exploration, test wells may be drilled as part of the process.
Appraisal	If a site has been deemed to be potentially viable, further development may begin. Further exploration wells may be drilled.
Develop	The site is prepared for production, and the drilling of production wells takes place, as well as the installation of infrastructure.
Production	Extraction and transportation of hydrocarbons. This stage lasts for most of the installation's life. It may include late-life extension activities and a change of operating phase.
Close-Out	Once the installation and its wells are no longer economically viable, the decommissioning process begins.
Decommissioning	The wells are plugged, and the installation is removed.

During each stage of an installation's life, various hazardous materials are used. These could be part of the construction, installation, operation and production of hydrocarbons. The hazardous materials range from asbestos in gaskets and older insulation to NORM scale in production pipes and equipment (Cowie et al., 2012; Valeur, 2011). During the life of the platform, UK legislation and regulations have changed, as well as the materials that can be used (SEPA, 2018; Sühring et al., 2019). This can lead to issues as chemicals that were once allowed to be used without permits are now classed as hazardous (La Védrine et al., 2015).

Decommissioning of an installation begins with the plugging and abandonment of the wells. This process ensures that the well is permanently closed, and it must be carried out in such a way that all recoverable equipment is removed. Pipelines and their associated subsea infrastructure can be cleaned and recovered to shore. In some instances, they may remain in situ depending on their size, extent of burial and integrity (OSPAR, 2010; OGUK, 2015).

The removal of the topside structure is dependent on the size and availability of vessels to remove it. Methods for removal include:

i. Small piece – small sections are dismantled and shipped ashore.
ii. Heavy lift – through reverse installation, modules are removed onto crane vessels or barges for removal to shore.

iii. Reverse float over – the topside is cut from the jacket structure and taken ashore in one piece in a process that is a reversal of a float over installation.
iv. Single lift – the topside and jacket are removed and transported in one piece.

The topside structure and its equipment must be purged of any residual hydrocarbons and other drilling materials or fluids prior to their removal. Hazardous materials may be removed or secured to prevent accidental release during the removal of the structure.

Once the installation has been removed, the site must be cleared. This involves the removal of debris on the seabed. This is identified through survey and trawling activities. Post-decommissioning environmental surveys are carried out to ensure that levels of containment do not exceed allowed levels. The results are compared with the surveys showing the status of the seabed around the structure before decommissioning began. Ongoing monitoring of the site continues in order to assess the extent of the disturbance caused by the decommissioning activities.

2.12.5 General Decommissioning Process

The decommissioning options depend on several different factors: the location of the installation, the current structural integrity of the installation, and the requirements of local and international laws and legislations (UN, 1982; OSPAR, 2010).

Decommissioning can be split into three main groups: total removal, partial removal, and leave-in-situ. Generally, the decommissioning process results in the removal of the topside structures and all or part of the jacket structure. This is to ensure that there is no pollution or hazards to other users of the sea (MacIntosh et al., 2022). The decommissioning of an offshore installation can be split into the following phases: planning, preparation, dismantling and recovery, recycling/reuse or disposal, and monitoring and completion (Efthymiou, 2022; Vidal et al., 2022). Once all the relevant decommissioning plans have been submitted and approved, the decommissioning process follows the general format, as shown in Figure 2-9.

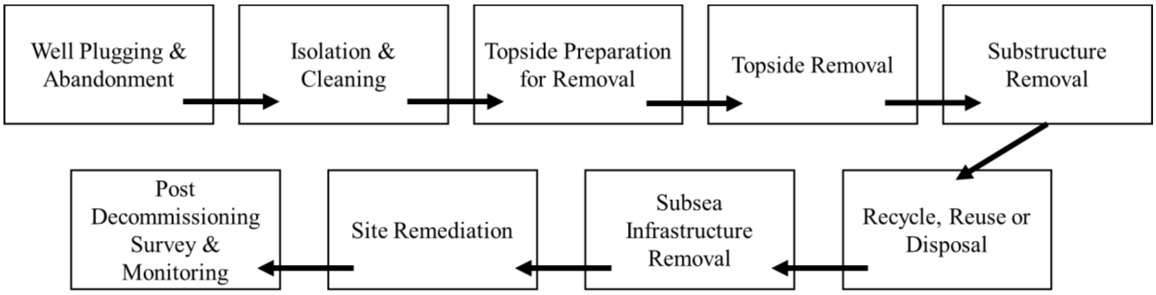


Figure 2-9: General Decommissioning Process

Once the installation has ceased operating, the decommissioning activities begin in earnest. Initially, any wells are decommissioned. A well-plugging and abandonment (P&A) program is carried out in line with the governing legislations and regulations when the well reaches the end of its lifetime. A key part of the process is to ensure well integrity after abandonment. This process can be split into three distinct phases: phase 1 – reservoir abandonment, phase 2 – intermediate abandonment, and phase 3 – wellhead and conductor removal (OGUK 2015).

Following the completion of the well P&A, permanent isolation and cleaning of the facilities and pipelines are carried out. This typically involves the shutdown procedure of the installation as laid out by the operator. It includes depressurisation, draining, purging, venting, cleaning, and purging of machinery and pipework (Sweeten, 2012; Brady, 2022).

The topside is prepared for removal. The removal method is selected on a case-by-case basis for individual installations. In the instance that the lowest deck is in poor condition, a large amount of remedial work is required to structurally strengthen it and prepare it for removal from the jacket structure. Once preparation is complete, the topside is removed via the chosen method, for example, using a semi-submersible crane or a single lift vessel. Once removed, it is transported to an onshore site for recycling, reuse, or disposal (Efthymiou, 2022; Akinyemi, Sun and Gray, 2020).

The substructure is removed, and any remaining structures are identified so as not to become a hazard to other sea users. Any remaining debris is removed from the seabed, surveys are carried out, and post-condition monitoring is conducted (Walker and Roberts, 2013; MacIntosh et al., 2022).

2.12.6 Different Removal Processes

Total removal can be applied to both the topside and the jacket, the topside only or the jacket only. Total removal involves separating the topside structure from the jacket structure and foundations and transporting it to an onshore location for recycling, reuse, or disposal. It is often carried out as a reverse engineering operation of the installation.

The topside structure can be removed via a single lift using a heavy lift vessel, multiple lifts of smaller modules via a smaller lift vessel or via dismantlement offshore and removal in smaller pieces (Shell, 2015; Turner, 2015).

Partial removal involves the removal of the topside structure and the top 85ft of the jacket structure. The jacket legs are removed with explosives and tugs (Janjua and Khan, 2023).

Leave in situ follows a similar process to that of total removal, but the chosen part of the jacket structure is left or towed to a new location to be used as part of a rig-to-reef program (BSEE, 2020; Jørgensen, 2012).

2.12.7 Common Parties Involved in the Decommissioning Process

The decommissioning process involves several different stakeholders, and despite their international location, many of them are common to the decommissioning process. Examples of common parties that are involved in the decommissioning process are as follows:

- Regulatory Bodies
    - International
    - Government
    - Local Authority
    - Environmental Agencies
- Operator
    - Onshore Personnel
    - Offshore Personnel
    - Contractors – Underwater, transport, topside
    - Contractors - Engineering, preparations, removal, and disposal
- Public Stakeholders
    - Sea Users
    - Disposal & Decommissioning Yards
    - Suppliers & Equipment Vendors

2.12.8 Basic Requirements for the Decommissioning Process

The basic decommissioning process remains the same regardless of the international location of the installation due to the governing international laws and the nature of the decommissioning process. The main purpose of decommissioning an installation is to return the seabed to a clear state (BEIS 2018).

Decommissioning involves prior planning and approval prior to the decommissioning activities commencing. The planning phase involves the creation of a decommissioning plan that details the chosen decommissioning process, environmental considerations, costs and scheduling. In some countries, it is a requirement to consult stakeholders and agencies (Watson et al., 2023).

Decommissioning involves well plugging & abandonment. Once this has been completed, the facilities and pipelines must be decontaminated and isolated to prevent any pollution of the surrounding area whilst in transit and when returned to shore (Sweeten, 2012; SEPA, 2018). Site remediation takes place to ensure that no debris or navigational hazards remain.

2.12.9 UK Offshore Industry Summary

The decommissioning of an offshore installation is a complex process, as they contain numerous different materials that must be removed and decontaminated from equipment to prevent incidents, such as pollution (Sühring et al., 2019; OGUK, 2015). Following the removal of the installation, the seabed must be cleared and the site must continue to be monitored (Walker and Roberts, 2013; MacIntosh et al., 2022).

Collectively, the literature describing the UK offshore industry provides a detailed technical understanding of installations and decommissioning procedures, but offers limited integration with sustainability or policy analysis. The emphasis on structural typologies and operational phases highlights the engineering complexity of decommissioning, yet few studies translate this technical knowledge into frameworks for improving waste management or regulatory coordination. This reinforces the need for a systems-based approach that connects engineering practice with environmental and governance considerations, a connection developed in the subsequent chapters of this thesis.

2.13 United Kingdom Statutory Background

The 1959 discovery of the Groningen field in the Netherlands triggered interest in North Sea oil and gas (Kemp, 2011). Previously, oil and gas exploration was limited to onshore sites. Seismic investigation of the British coast started soon after, with Shell commencing works in 1961 (Kemp, 2011). This increase in interest sparked debate on current laws and regulations as to who governed which area of the sea. The International Law of the Sea

Conference was held in Geneva in 1958 (Zacharias, 2014). The aim of this conference was to examine the main issues relating to the Law of the Sea (UNCLOS) and produced the following conventions:

i. Convention on the Territorial Sea and Contiguous Zone
ii. Convention on the High Seas
iii. Convention on Fishing and Conservation of the Living Resources of the High Seas
iv. Convention on the Continental Shelf.

The Convention on the Continental Shelf consisted of 15 articles. Article 1 define the continental shelf as *"(a) to the seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 metres or, beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources of the said areas; (b) to the seabed and subsoil of similar submarine areas adjacent to the coasts of islands" (United Nations, 1958).*

Article 2 stated "*The coastal state exercises over the continental shelf sovereign rights for the purpose of exploring and exploiting natural resources,"* (United Nations, 1958). These articles gave the coastal state power to construct and maintain installations for exploration and production purposes. These installations require the establishment of a safety zone around them. These safety zones must take measures to protect any living resources or the sea against any harmful agents associated with the exploitation of the national resource.

The United Kingdom government responded by the writing of the Continental Shelf Act. This introduced the requirement of obtaining a licence from the UK Secretary of State for anyone who wishes to explore and produce oil and gas (Continental Shelf Act 1964 (c.29)). The legislation governing the United Kingdom Continental Shelf has evolved with changes to, or the introduction of, new legislation, having historically been reactive.

The current statutory regime in the UK is designed to meet the international obligations, including OSPAR, UNCLOS and the Geneva Convention. UK legislation sets out how these will be met. Regulatory bodies enforce these legislations and issue guidance on how they can be met. Figure 2-10 shows a general overview of their hierarchy.

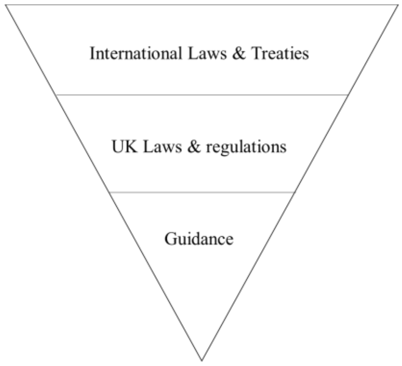


Figure 2-10: Hierarchy of Laws.

The current statutory regime is influenced by international law and OSPAR conventions. A goalsetting approach is used with operators developing their own ways of achieving safety and environmental objectives and convincing regulators that they are meeting them.

The following subsections outline the multi-layered legal and regulatory landscape governing offshore decommissioning in the United Kingdom. Establishing this context is essential to understanding the complexity and interdependencies that later influence hazardous-waste management, compliance and sustainability performance.

2.13.1 International Laws & Treaties

The UK is a signatory to the United Nations Convention of the Law of the Sea 1982 (UNCLOS). This is the principal convention regulating dumping and pollution at sea. It requires the signatory states to ensure the removal of offshore installations in their exclusive economic zone (EEZ) as opposed to abandonment or dumping.

Article 194 of UNCLOS outlines the requirements of preventing, reducing and the control of pollution of the marine environment (Convention on the Law of the Sea, 1982). Measures must be taken to minimise the pollution from the installations and devices operating in that marine environment. States must ensure that any laws and regulations are not less effective than the international ones (Convention on the Law of the Sea, 1982).

The 1989 Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in Exclusive Economic Zones were established by the International Maritime Organisation (IMO). These guidelines require the removal of abandoned or disused offshore installations (Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone, 1989).

The UK is also a signatory to the Convention on Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and London Protocol 1996. The

London Protocol was agreed in 1996 and amended in 2006. This prohibits dumping waste at sea including platforms or other man-made structures.

The Convention for Protection of the Marine Environment of the North-East Atlantic, also known as the OSPAR Convention, is designed to protect the marine environment of the North-East Atlantic. It came into force in 1992 and has undergone several amendments since its publication. OSPAR Decision 98/3 states that the dumping or leaving in place of disused installations is prohibited (Kirk, Warbrick and McGoldrick, 1999).

2.13.2 European Union Laws & Regulations

Following Brexit, retained European Union Law was created with future relationship agreement applied on provisional basis (Evers, 2021). The EU does not have any specific framework for decommissioning but does have the Waste Framework Directive 2008. The framework, in conjunction with the EU Waste Shipment Regulation 2006, reflect the principles of both OSPAR and the London Convention. It applies offshore and to any waste brought onto land for treatment or disposal (Brady, 2022).

The EU Environmental Liability Directive 2004 outlines the strict liability regime on operators to prevent environmental damage. It is based around the principle of the polluter pays (EU Environmental Liability Directive, 2004). This was amended by the Offshore Safety Directive 2013 which extended the liability to include oil and gas operations in maritime waters. This was in response to the Deepwater Horizon incident (Radovich, 2016).

2.13.3 United Kingdom Regulatory Framework.

The Petroleum Act 1998 (amended by Energy Act 2008) controls the decommissioning of offshore installations and pipelines on the UK continental shelf. Part IV of the Petroleum Act 1998 allows the Secretary of State to:

- Make regulations relating to decommissioning.
- Require the submission of costed decommissioning programs for each offshore installation and pipeline.
- The persons who submit the decommissioning programme have a duty to ensure it is carried out.
- Impose penalties for failure to comply with notices and can undertake any decommissioning programme if the relevant persons failed to ensure it is completed.

The current guidelines issued by the BEIS states that the UK follows the OSPAR 98/3 decision and that the waste hierarchy will be met. It is expected that the reuse of facilities is carried out wherever possible and the generation of waste is reduced (Brady, 2022)

The Decommissioning Strategy 2021 was published by the North Sea Transition Authority (NSTA). The NSTA was formerly known as the Oil and Gas Authority (OGA) but changed its name on 21 March 2022 (NSTA, 2022). The Decommissioning Strategy outlines how decommissioning can be part of the UK's energy transition to net zero. The NSTA is an independent regulator with the Secretary of State powers and functions under the Petroleum Act 1998. The environmental regulatory functions were not transferred to the NSTA.

Following Brexit, the Marine Environment Regulations 2018 aimed to ensure that the UK will continue to develop strategy in line with OSPAR. This would ensure marine strategy, planning and environment protection continue to function.

In England, the Environmental Agency (EA) regulates waste management and pollution. It is also responsible for the environmental permitting regime. In Scotland, this role is filled by the Scottish Environmental Protection Agency (SEPA). In Wales, it is national resources Wales and in Northern Ireland it is the Department of Agriculture Environmental and Rural Affairs. In the marine environment, the Marine Management Organisation (MMO) is responsible for the management, regulation and controlling of activities. It licenses marine activities in waters adjacent to England and UK offshore waters except those adjacent to Scotland. OPRED is the environmental regulator all offshore oil and gas operations.

2.13.4 Health and Safety

The health and safety legal regime imposes statutory duties imposed by the Health and Safety at Work Act 1974, Offshore Safety Act 1992 and Offshore Installations (Safety Case) Regulations 2005. These are based on risk-based regulations requiring operators to assess hazards and to mitigate them by reducing risk level to as low as reasonably practical (ALARP).

The Mineral Workings (Offshore Installations) Act 1971 was introduced in response to the Sea Gem Jack-up Rig disaster that resulted in the loss of 13 lives. This act required offshore installations to be certified as fit for purpose. The Health and Safety at Work Act 1974 was extended to include the offshore sector.

The inquiry into the Piper Alpha Disaster in 1988, when 167 men were killed, led to an overhaul of the offshore legislation. Following the publication of the Cullen Report in 1990, all 106 of the recommendations were put into place including new goal setting safety regulations. The Offshore Installations (Safety Case) Regulations 1992 required all offshore installations to submit safety cases for approval. Several other legislations followed and are summarised in Table 2-2.

Table 2-2: Summary of legislations introduced after the Cullen Report.

Legislation	Overview
PFEER 1995	Focus on identifying and preventing fire and explosion hazards.
DCR 1996	Requires installations to be designed, constructed and kept in a sound structural state. It also deals with the installation of the structure.
MAR 1995	Requires demonstration that management systems are adequate and comply with health and safety provisions.
PUWER 1992	Ensures safe provision and use of work equipment.
PSR 1996	Duties of pipeline operators relating to design, construction, operation, maintenance, and decommissioning.

2.13.5 European Union Waste Framework Directive 2008.

The EU Waste Framework Directive (WFD) 2008 defines waste, the waste hierarchy and waste a duty of care. This forms the basis of waste law through the retained EU law following the Brexit transition period (Radovich, 2016). The WFD aims to conserve raw materials, prevent waste and where waste cannot be prevented, used as a resource.

The UK government utilises the waste hierarchy as part of its regulations and guidance. The waste hierarchy is part of the European Union Waste Framework (EU, 2008). It defines waste as "any substance or object which the holder discards or intends or is required to discard". Throughout the decommissioning process, several types of waste are produced and must be disposed of safely. The waste hierarchy is shown in Figure 2-11.

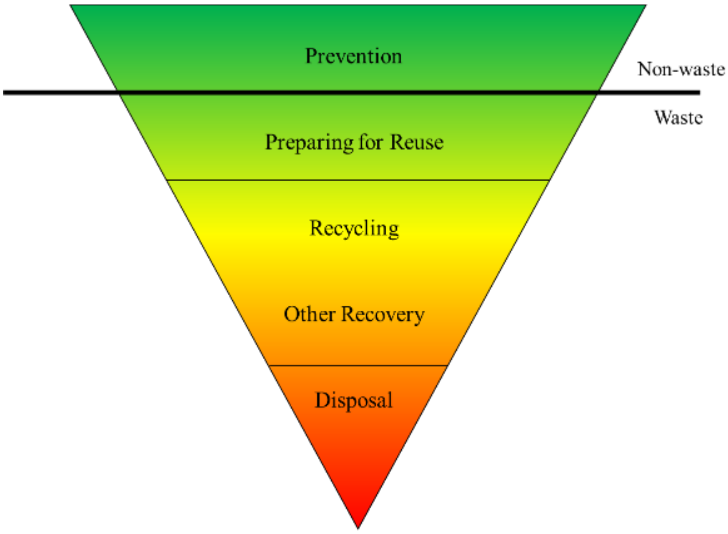


Figure 2-11: Waste Hierarchy

This definition of waste is implemented in England and Wales as part of the Environmental Protection Act 1990.

If waste has undergone a recovery operation, for example, recycling, then it ceases to become waste and achieves end of waste status. It will no longer be regulated as waste. The EA makes any formal regulatory decision whether waste has achieved this status following a formal application being submitted (Radovich, 2016).

2.13.6 Duty of Care.

Those handling controlled waste, for example, producers, carriers and disposers, have a duty of care to ensure that the waste is:

- not unlawfully disposed of.
- is only transferred to an authorised waste collection agency, registered carrier or licence disposer.
- not misplaced or escaped from a person's control (Perks, 2012).

If the waste is transferred, it must be transferred only to an authorised person and accompanied by waste transfer notice. The waste transfer note must contain sufficient information to allow it to be identified and to ensure that the person receiving the waste knows enough about the waste to deal with it appropriately. The waste transport notes form part of an audit trail along the waste stream.

The most preferred option is the prevention of the production of any waste materials but due to the nature of decommission, the age of the installations and the hazardous materials involved, this is not always possible. In order to prevent the production of waste, steps should be taken to reuse or to extend the life of equipment and materials used. Any materials or equipment that may be prepared for reuse includes any material or equipment that will be reused for the same purpose they were conceived. These items are not considered waste but must be prepared through thorough checking, cleaning and repairing so they can be successfully reused without any other pre-processing. Materials that are to be recycled includes the reprocessing of the materials or equipment to be used for other purposes. Waste that falls under the other recovery category includes any waste that would be used to replace other materials which are otherwise used for a particular function, for example construction aggregate. If none of these options can be fulfilled and the waste cannot be recovered, then it must be disposed of.

The duty of care was introduced under the Environmental Protection Act 1990 and has been further extended by regulations including the Controlled Waste Regulations 1992, the Special Waste Regulations 1996 and the Special Waste Amendment (Scotland) Regulations 2004. The duty of care states that all reasonable and applicable measures must be taken to ensure:

1. Waste is stored, transported and secured appropriately so that it does not leak or escape.
2. Waste is only transported by those companies and individuals licensed to do so.
3. Waste is only transferred to companies and individuals that are licensed to store, treat, process or dispose of it.
4. Waste consignment notes for non-hazardous waste must be completed and retained for a minimum of 2 years.
5. Waste consignments notes for hazardous waste must be completed and retained for a minimum of 3 years.

These apply not just to the operators, but anyone who imports, produces, carries, keeps, treats or disposes of waste. The purpose of these regulations is to ensure a clear audit trail of waste materials. Many operators appoint waste management companies to manage the waste streams during the decommissioning process.

There are 3 classifications for waste: hazardous, non-hazardous and inert. All waste during the decommissioning process must be classified and designated codes in accordance with the European Waste Catalogue (EU, 2008). In some instances, materials must be tested to determine if they are hazardous through specialist analytical testing. A simple overview of the waste classification system is shown in Figure 2-11.

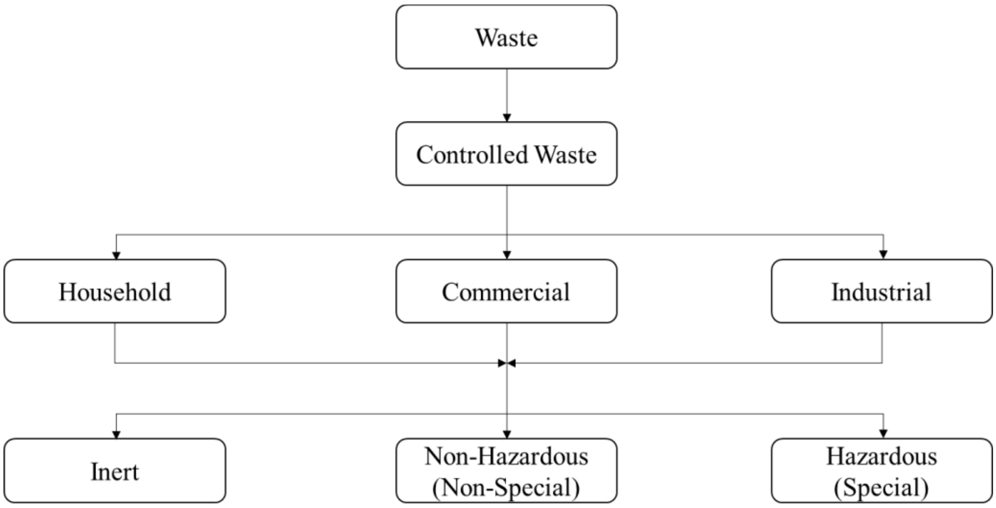


Figure 2-12: Waste Classification System

2.13.7 Active Waste Management Plans

Active waste management plans are required in order to demonstrate the duty of care of the operators and to allow for the monitoring of the waste handling. The active waste management plan should include the intentions for the waste, how compliance will be monitored, identification of the waste streams and a process for advising of the change of location or change in volume of waste.

The active waste management plan should be supported by an inventory of materials and wastes. This must contain a summary of waste, other materials and must be fit for purpose. It forms part of the decommissioning programme. The waste inventory is developed over three stages:

> Stage 1 – at the initial comparative assessment as part of the decommissioning programme. It may include weight, chemicals, material safety data sheets and asbestos register.
>
> Stage 2 – completed near cessation of production with the aim to refine and improve.
>
> Stage 3 – final inventory prior to dismantling and should include all information required for safe dismantling.

2.13.8 Oil & Gas Authority Strategy

The Maximising Economic Recovery (MER) Strategy (OGA, 2015) was introduced to promote the maximum economic recovery of UK petroleum. The Energy Act 2016 gave OGA the powers to enforce the MER Strategy through issuing enforcement notices, penalties, and loss of licences. MER supports decommissioning activities by setting out obligations stating that owners and operators must ensure that:

i. all alternative viable options for the installation have been explored.
ii. the decommissioning of the installation will be cost effective.
iii. new technology has been deployed to optimum effect to ensure maximum economic recovery from the installation and its wells.

Following a consultation in 2020, the OGA published a revised version of the MER Strategy now entitled the OGA Strategy, in 2021 (OGA, 2021). This revised document included changes designed to aid in meeting the 2050 net zero carbon target as laid out in the revised Climate Change Act 2008 (Thomson Reuters, 2020). It is still a requirement that all alternative viable options for the installation have been explored, but it now includes the consideration of alternative use of a carbon capture and storage facility.

2.13.9 Decommissioning Obligations

Decommissioning activities begin at least 3 years before the planned decommissioning of an installation. The first step is to consult with the Department for Business, Energy and Industrial Strategy (BEIS) to discuss the decommissioning programme. Table 2-3 shows a timeline of events leading up to the decommissioning activities. It shows the different stages and requirements that must take place prior to the decommissioning plan being approved.

The decommissioning programme is required as outlined in the Petroleum Act 1998. It must contain the following:

i. Items of equipment, infrastructure and materials that have been installed or drilled must be identified and a decommissioning solution included for each.

ii. Comparative assessment of decommissioning options considering energy usage and emissions.

iii. Detailed decisions on how the solutions chosen are compliant with the waste hierarchy.

iv. Details on consultations with stakeholders, interested parties, cost breakdowns and programme management.

v. An environmental appraisal that assesses the impact of the programme.

The decommissioning programme cannot be executed until approval has been granted by the UK Secretary of State. The environmental appraisal must assess the impact of the programme and consider energy usage and emissions. Approval is only granted once these requirements have been satisfied and it has been publicised for stakeholder and public consultation. Following the completion of the decommissioning, a detailed close-out report must be submitted that includes seabed surveys, waste transfer receipts and findings from the activities.

Collectively, the legislative and regulatory framework for offshore decommissioning demonstrates a mature but highly fragmented governance structure. The UK regime aligns with international conventions such as OSPAR and UNCLOS, yet the overlap of domestic and transboundary requirements can create uncertainty for operators and regulators alike. The literature suggests that while these instruments ensure high environmental standards, their complexity can hinder efficient implementation and waste-stream traceability. This underlines the importance of the framework developed in this thesis, which seeks to translate statutory obligations into a coherent, operational process for managing hazardous waste sustainably.

Table 2-3: Pre-decommissioning Activities

3-5 Years	3 Years	24 Months	21 Months	18 Months	16 Months	12 Months	4-6 Months	4 Months	6 Weeks	Decommissioning	Post Decommissioning
Initial meeting with BEIS.	Identify options & decommissioning routes.	Submit 1^{st} draft to BEIS.	Feedback from BEIS.	Submit 2^{nd} draft.	Feedback from BEIS.	Submit final draft.	Written approval from BEIS.	Submit Decommissioning Operating Application for any chemicals to be used or discharged.	Provide notice of change of status to UK Hydrographic Office for pipelines and installations.		Ensure segregation of waste and records of waste disposal retained.
	Carry out comparative environmental assessment of options	BEIS consults with other government departments.		Circulate 2^{nd} draft to Statutory Consultees, publicise in press and internet.		Submit OPPC Permit.					Independent verification of removal of debris from seabed.
	Identify impacts and any designated habitats.			Carry out baseline environmental survey if required.		Submit Disposal of Material under FEPA.					Seabed sampling to monitor levels of contaminants.
	Prepare 1^{st} draft.										Submit copies of debris clearance and survey reports to BEIS.

2.13.10 Discussion

Lindøe, Baram and Paterson (2013) discuss the robustness of the UK regulatory regime in comparison with the US and Norwegian sectors. They highlight how change in legislation is accident driven and that although UK legislation is a benchmark, it lags behind the Norwegian sector. Hale (2014) states that the Norwegian scheme is the most explicit and articulated. Engen and Lindøe (2019) question the goal setting approach of UK legislation, stating that companies and operators must justify their decisions to the regulatory bodies for approval. This requires a high level of understanding of the legislation.

Calder (2019) states that one of the key issues with the legislation surrounding the offshore industry, and in particular, decommissioning is the boundary between offshore and onshore. Operators must also be clear on when an installation ceases to be classed as operating under offshore legislation and switches to marine regulations. SEPA (2019) also highlight the issue of boundaries and areas of jurisdiction. Figure 2-13 shows a simple overview of areas that each authority and agency operate. The limit for onshore waste regulations extends only to the low water line.

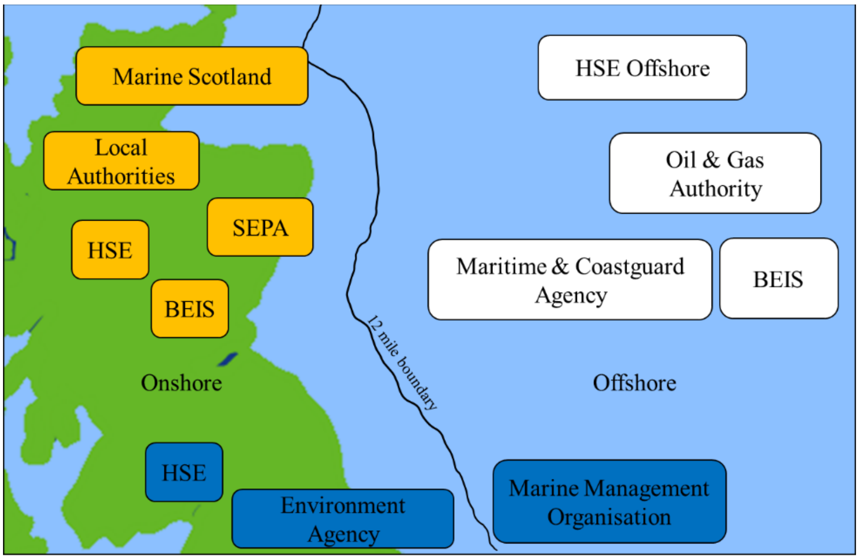


Figure 2-13: Areas of Jurisdiction of Regulatory Bodies and Authorities (based on SEPA (2018)).

Calder (2019) highlights that operators must recognise all activities associated with decommissioning include work undertaken by other vessels such as support vessels. Onshore activities do not follow the same permissioning scheme as the offshore activities. Contractors, waste handlers, dismantlers and recycling companies must already be registered with relevant body and be licensed to handle specific waste products. It is the operator's duty of care to audit any onshore work to ensure that this is the case. Throughout this process of identification to disposal, it must be clearly identified, tracked and handled correctly. There is a possibility that it may get lost or not processed by the correct operators.

2.13.11 UK Statutory Regime Summary

Prior to decommissioning activities taking place, a decommissioning plan must be submitted for approval to OPRED. This must include environmental appraisals and a waste management plan. Waste materials must be identified in accordance with the EU Waste Framework, classified and details of how they will be processed included in the waste management plan.

Publicly available decommissioning close-out reports highlight the issue of identifying the volume of hazardous waste present, the effectiveness of cleaning and decontamination prior to removal

The decommissioning of offshore installations is subject to rigorous legislation and regulations. A key issue in complying with legislation and ensuring the traceability of waste whilst being transported, is the understanding of the legislation both offshore and onshore. To ensure operators meet their duty of care, they must confirm that waste is identified, labelled, stored, transported and processed in accordance with regulatory requirements. This includes ensuring all waste has a waste transfer note that is held for a minimum of two years.

Overall, these observations suggest that the UK regulatory framework is comprehensive but administratively fragmented. Much of the legislative progress has been reactive, driven by incidents rather than proactive policy development. Comparative studies, particularly those examining the Norwegian and US systems, indicate that regulatory clarity and early integration of decommissioning planning can enhance safety and environmental performance. The UK's goal setting approach allows for flexibility but relies heavily on the operator's interpretation of compliance, which can lead to inconsistency in implementation. These systemic features reinforce the need for a structured decision support framework, such as that developed in this thesis, to bridge the gap between regulatory intent and operational execution.

2.14 Common Decommissioning Practices Between ASEAN Countries, UK, and Gulf of Mexico

Worldwide, there are estimated to be currently over 1200 operational offshore installations (Lockman & Brauch, 2022). Each country has established its own set of regulations and guidelines concerning the decommissioning of ageing installations.

The decommissioning of offshore installations incurs significant costs. Each Association of Southeast Asian Nations (ASEAN) country, the UK, and the Gulf of Mexico (GoM) have established methods to ensure these costs are met and decommissioning activities are completed.

In the UK, the Energy Act 2016 dictates that the operator or owner covers the decommissioning costs. OGUK acts as an independent regulator with the power to impose sanctions. In the GoM, the Bureau of Ocean Energy Management (BOEM) serves as the regulatory authority overseeing a structured finance program. Bonds are required to cover the entire lifecycle of an installation, from exploration to production and decommissioning. Decommissioning expenditure must be reported within 120 days of completing each activity, including pipelines and structures. In Malaysia, a decommissioning budget must be approved by Petroliam Nasional Berhad (PETRONAS), and a cessation fund was created after 1998, contributed to by operators. Indonesia has a post-operation fund for financing decommissioning activities, which is tax-deductible for operators. Thailand mandates financial security from co-ventures, assigners, and assignees to ensure proper decommissioning and post-decommissioning monitoring. Vietnam requires operators to establish a financial guarantee fund for decommissioning activities based on an approved plan within a year of production commencement. In Brunei, all duty holders must provide a cost estimation methodology, and the decommissioning and remediation submission should contain a cost estimate of proposed methods.

It is evident that all the considered countries have financial plans or guarantees in place to ensure the completion of decommissioning activities, emphasising the responsibility of operators. Transparency is crucial, and the involvement of an independent party in monitoring activities is vital.

In the UK, the decommissioning planning phase begins approximately three to five years before decommissioning, allowing for thorough consideration of all operations. The operator, regulatory body, and other stakeholders engage in discussions during the submission of a draft decommissioning plan, which includes a comparative assessment of various options and environmental impact assessments. The draft plan is made publicly available for stakeholders to evaluate.

Similarly, in the GoM, the pre-decommissioning stage involves the circulation of a draft environmental impact report as part of the required execution plan. These documents must be approved before commencing decommissioning activities. Malaysia follows PETRONAS technical standards, requiring the submission of an environmental impact assessment, environmental management plan, data, and a decommissioning options assessment. Risk assessment is conducted to identify and assess risks associated with the chosen decommissioning strategy.

Indonesia mandates a work plan and budget or plan of development, submitted three to five years before the execution of decommissioning production facilities. Thailand utilises the best practical environmental option tool to select suitable decommissioning options, considering environmental impact, public health, safety, technical feasibility, and cost. Vietnam requires an environmental monitoring report as part of the decommissioning plan, while Brunei requires a decommissioning and restoration (D&R) submission covering the cessation of production to the end of decommissioning activities, including site monitoring.

Prior planning of decommissioning activities is integral to commence the decommissioning process. It enables the evaluation of various options' feasibility, potential costs, time frames, and environmental considerations, while also involving stakeholders through public consultations.

Following the planning and approval stages, the technical execution of decommissioning can begin, including well plugging and abandonment, pipeline and subsea structure removal, topside structure and facility removal, debris removal, site remediation, surveys, and post-decommissioning monitoring.

Research on well plugging and abandonment has been conducted extensively in the UK, where regulations and guidelines inform the process to ensure post-plugging and abandonment integrity and prevent environmental incidents. In the GoM, technical details of permanent well plugging are specified, with exceptions in special circumstances. Malaysia requires the total removal of the wellhead and well plugging, verified and submitted to PETRONAS. Thailand sets well plugs at critical intervals to prevent fluid migration and confines hydrocarbon resources, cutting wellheads off 15ft below the mudline. Vietnam maintains the integrity of abandoned wells, leaving casings intact but cutting and removing wellheads at least 3m below the seabed. Brunei assesses the subsurface isolation requirement and well integrity for abandonment, confirming isolation and restoring the well location to a final declared state, marked with visible signage.

The removal of topside structures and facilities varies across all countries, with removal options considered on a case-by-case basis. All countries agree that structures must not be left to degrade and become environmental hazards. In the UK, structures are generally removed except in special cases, while the GoM considers rigs to reef as an option. Malaysia allows partial or total removal as well as reuse as an artificial reef. Indonesia and Thailand also determine removal options on a case-by-case basis, with Thailand requiring decontamination prior to removal. Vietnam specifies cleaning and decontamination before removal, and Brunei assesses each offshore structure on a case-by-case basis.

It is evident that good practice involves evaluating each installation's removal options on a case-by-case basis. The base case should be total removal, but a comparative assessment should be conducted to fully evaluate potential removal or reuse options.

In the UK, a close-out report must be submitted, publicly available and containing waste volumes, costs, and remedial monitoring. Debris removal and seabed clearance are verified through independent seabed surveys. The GoM doesn't explicitly mention post-decommissioning processes, but issued permits must be closed with reports detailing removal and waste methods, and a post-decommissioning survey to ensure site clearance and seabed mapping.

The current legislative requirements are summarised in Table 2-4, whilst the similarities in decommissioning requirements are shown in Table 2-5.

Table 2-4: Laws and Legislations of UK, GoM and ASEAN Countries

International Laws	UK	Gulf of Mexico	Malaysia	Indonesia	Thailand	Vietnam	Brunei
1958 Geneva Convention of the Continental Shelf	Y	Y	Y	Y	Y		
International Maritime Organisation (IMO) Guidelines and International Convention for the Prevention of Pollution from Ships (1973)	Y	Y	Y	Y *(Not mandatory)*	Y		
Modifying Protocol 1978 (MARPOL)	Y	Y	Y				
United Nations Convention Law of the Sea 1982 (UNCLOS)	Y	Y	Y	Y	Y	Y	Y
Basel Convention 1992	Y	Y	Y	Y	Y	Y	Y
COBSEA Regional Seas (ASCOPE)	Y	Y	Y	Y	Y	Y	Y
London Convention and London Protocol	Y	Y			Y		
National Government Bodies & Agencies	Department for Business, Energy and Industrial Strategy Oil & Gas Authority Health & Safety Executive Environment Agency Scottish Waste Authorities Northern Ireland Environment Agency Department for Environment, Food & Rural Affairs Marine Scotland Department for Transport Maritime & Coastguard Agency Ministry of Defence HM Treasury/HM Revenue & Customs The Crown Estate/Crown Estate Scotland Joint Nature Conservation Committee Natural England Scottish Natural Heritage Countryside Council Wales		PETRONAS Malaysia Petroleum Management (MPM) Division	Ministry of Environment Ministry of Energy and Mineral Resources (Directorate General of Oil and Gas) Ministry of Transport (Directorate General of Sea Transportation) Ministry of Ocean and Fishery	Department of Mineral Fuels Pollution Control Department Revenue Department Office of Natural Resources and Environmental Policy and Planning Petroleum Institute of Thailand	Ministry of Industry and Trade	Ministry of Energy and Industry of Brunei

	Council for Nature Conservation & Countryside						
National Laws & Acts			1. Section 485A of Merchant Shipping Ordinance (1952) 2. Section 6 of Continental Shelf Act (1966) 3. Section 23 of the Economic Zone Act 4. Environmental Quality Act 1974 5. Environmental Impact Assessment 6. Guidelines for Petroleum Industries Environmental Guideline for Decommissioning of O&G Facilities in Malaysia 2019 - DOE	Main statutory is Oil and Gas Act No. 22 of 2001, Clause 11 Article (3) which states that postproduction liability is one of mandatory clause in Oil and Gas Contract. Statuary in lower hierarchy is: * Minister of Energy and Mineral Resources Regulation No. 15 of 2018 about Postproduction Activities in Upstream Oil and Gas	1. Decision No. 40/2007/QD-TTg on decommissioning of fixed petroleum installations, equipment, and facilities (valid from 4/4/2007 to 11/2/2018). 2. Decision No. 49/2017/QD-TTg on decommissioning of petroleum installations, equipment, and facilities (valid since 12/2/2018 to replace Decision No. 40/2007/QD-TTg). 3. Decision No. 41/1999/QD-TTg on safety management in oil and gas activities (valid from 23/3/1999 to 15/3/2015) 4. Decision No. 04/2015/QD-TTg on safety management in oil and gas activities (valid since 16/3/2015 to replace Decision No. 41/1999/QD-TTg) - Well plugging & abandonment in particular 5. Decision No. 37/2005/QD-BCN on the protection and abandonment of oil and gas wells (valid from 29/12/2005 to 9/9/2020) 6. Decision No. 10/VBHN-BCT on the protection and abandonment of oil and gas wells (valid since 23/2/2014) Circular No. 17/2020/TT-BCT on the protection and abandonment of oil and gas wells (valid since 10/9/2020 to replace Decision No. 37/2005/QD-BCN)	1. Petroleum Act B.E. 2514 (1971), Petroleum Act (No.6) B.E. 2550 (2007) 2. Ministerial Regulations No. 1-20 (B.E. 2354) - concession agreement: Clause 40 of Ministerial Regulation No.12 B.E.2524 (1981), Clause 15 (4) of Model Concession, DMF/P 2, annexed to Ministerial Regulation No.17 B.E.2532 (1989) (Fam et al, 2018) Petroleum Income Tax Act 1971, Thailand – Malaysia Joint Authority Act B.E. 2533, 1990, Act on Offences Relating to Offshore Petroleum Production Places, 1987 (International Association of oil & gas Producers_584, 2017) Petroleum Act (No. 6) B.E. 2550 (A.D. 2007) in which the Department of Mineral Fuels (DMF) acts as the governing body & must regulate the decommissioning process under international & domestic laws & regulations. After the enactment of this Petroleum Act in 2007, the amendments included the imposition of decommissioning obligations & placement of financial security obligations. Yet, it does not provide specific detailed decommissioning requirements. Ministerial regulation-Designation of rules, procedures, conditions, schedules of submission & placement of financial security. The new ministerial regulation to be issued will add more realistic timeframes & specific details (as the Petroleum Act before its re-enactment was not realistic or specific enough on decommissioning methods). According to Fam et al. (2018), in the updated Petroleum Act (No. 6) B.E. 2550 (2007), Section 80 requires a decommissioning program inclusive of estimated decommissioning costs for the approval of the Director-General before decommissioning begins.	The Mining Act (Revised 1984) Chapter 44: The Petroleum Mining Act (Revised 1984) Chapter 45: The Petroleum (Pipe- Lines) Act (Revised 1963) Chapter 138: The Territorial Waters of Brunei Act (Revised 2002) Chapter 189: The Land Code (Strata) Act (Revised 2000)

Table 2-5: Similarities in decommissioning requirements for each country.

		UK	Gulf of Mexico	Malaysia	Indonesia	Thailand	Vietnam	Brunei
	Funding of Decommissioning	Owner/ Operator	Operator Bonds	Cessation Fund (Since 1998) – contribute to by operators	Post-Operation Fund – contribute to by operator	Financial Security or Surety placed by individual or combination of	Financial Guarantee Fund set up by Operator	Duty Holders must provide cost estimation as part of D&R activities
Pre-Decommissioning	Decommissioning Plan	Draft 3-5 years prior	Y	*Y*	3-5 years prior to execution schedule	2-5years prior (dependent on remaining reserves)	Y	*Y*
	Comparative Assessment	Y		*Y*		*Y*		*Y*
	Environmental Appraisal	Y	Y	*Y*		*Y*	Y	
	Costs	Y		*Y*	Y	*Y*		
	Materials Inventory	Y	Y		Y			
	Description of items to be decommissioned	Y	Y		Y			
	Consultation with interested parties	Y	Y	*Y*	Y			
	Schedule	Y	Y	*Y*	Y			
	Project Management	Y	Y	*Y*	Y			
	Debris Clearance	Y			Y			
	Post-decommissioning monitoring & maintenance	Y						*Y*
	Supporting studies	Y						
	HSE Risk Assessment	Y	Y	*Y*	Y	*Y*	Y	*Y*
	Circulated for Public Consultation	Y	Y		Y			
Decommissioning Execution	Cessation of Production	Y	Y					
	Venting/Flaring	Y						
	Well Plugging & Abandonment	Y	Y	*Y*	Y	*Y*	Y	*Y*
	Cleaning, discharging, emissions	Y	Y	*Y*	Y	*Y*	Y	*Y*
	Oil Spill Planning	Y	Y	*Y*				
	Seabed deposit management	Y	Y			*Y*		*Y*
	Pipelines & Associated Structures	Y	Y	*Y*		*Y*	Y	*Y (draft document)*
	Explosive Use	Y	Y				Y	
	Debris Removal Options	Y	Y					
	Waste Handling	Y	Y	*Y*	Y	*Y*	Y	*Y*

	Waste Shipment (across borders)	Y	Y	*Y*				
	Safety Zones	Y						
	Equipment & materials brought ashore	Y						
	Export of installations and equipment	Y						
	Export & import	Y						
Post-Decommissioning	Site Survey	Y	Y	*Y*			Y	
	Monitoring Schedule	Y		*Y*		*Y*		*Y*
	Close-Out Report	Y (within 4 months of completion)	Y (Reports required for each permit within 30 days)	*Y (environmental report within 1 month of completion)*		*Y*	Y (within 9 months of completion)	

2.14.1 Discussion of Global Decommissioning Practices

The regulation of offshore decommissioning varies significantly between the UK, the Gulf of Mexico and ASEAN countries, reflecting differences in financial responsibility, environmental obligations, and regulatory enforcement (Watson et al., 2023; Lockman et al., 2023). Each region has developed its own framework based on historical practices, industry needs, and international commitments (Adetoro, 2009; Ahiaga-Dagbui et al., 2017a). While there are similarities in overarching objectives, key differences exist in planning requirements, cost allocation, waste management, and long-term monitoring (Kumar et al., 2021; Fowler et al., 2019).

2.14.1.1 *Regulatory Approach and Compliance*

The UK follows a goal-setting approach, where operators are required to demonstrate compliance with regulatory objectives rather than follow a strictly defined set of procedures (Lindøe et al., 2013; OGA, 2020b). This method provides flexibility but also places greater responsibility on operators to justify their decommissioning plans (Walker and Roberts, 2013). In contrast, the GoM follows a prescriptive regulatory framework, where operators must adhere to predefined procedures and financial security requirements set by regulatory bodies such as the BSEE (BSEE, 2020). The approach taken by ASEAN countries varies, with some nations adopting elements of both systems. For example, Malaysia and Thailand require structured decommissioning plans, while Brunei and Vietnam assess projects on a case-by-case basis (Kumar et al., 2021).

One of the key differences between the UK and other regions is the approval process for decommissioning. In the UK, a detailed decommissioning programme must be submitted and approved before work begins. This includes a comparative assessment of removal options, stakeholder consultations, and an environmental appraisal (Shell, 2015; OGA, 2020a). The GoM requires similar approvals, but there is a greater emphasis on ongoing financial security throughout an installation's lifecycle, ensuring that operators have the necessary funds to carry out decommissioning (Parente et al., 2006). In ASEAN countries, approval processes vary, with some nations requiring pre-approved financial security plans and others relying on government oversight during decommissioning execution (Kumar et al., 2021; Khan et al., 2025).

2.14.1.2 *Financial Responsibility and Cost Allocation*

Funding decommissioning activities is a critical challenge for operators, and different regions have adopted varying approaches to ensure financial security.

- UK: Under the Energy Act 2016, the financial responsibility for decommissioning falls on the operator or owner, with tax relief mechanisms available to offset some costs. There is no requirement for upfront financial security unless an operator is deemed financially at risk (OGAUK, 2015; OGUK, 2019).
- GoM: Operators must provide financial bonds to cover decommissioning costs. This ensures that even if a company becomes insolvent, funds remain available for decommissioning (Parente et al., 2006; Lockman et al., 2023).
- ASEAN: Some ASEAN nations, such as Malaysia and Indonesia, have introduced cessation funds, where operators contribute throughout an installation's lifecycle. Thailand and Vietnam require operators to submit financial guarantees at the start of production, ensuring costs are covered when decommissioning occurs (Kumar et al., 2021).

The GoM's bonding system ensures that decommissioning costs are accounted for from the outset, reducing the risk of financial shortfalls. The UK, in contrast, relies on the financial strength of operators, which has raised concerns about potential liabilities if an operator ceases to exist before decommissioning obligations are met (Ahiaga-Dagbui et al., 2017b). The cessation fund approach used in Malaysia and Indonesia provides an alternative model, ensuring a reserve of funds is available while spreading costs over time (Kumar et al., 2021).

2.14.1.3 *Environmental Compliance and Waste Management*

A key component of decommissioning is ensuring compliance with environmental regulations, particularly regarding waste disposal and seabed clearance.

- UK: The UK adheres to OSPAR Decision 98/3, which generally requires the complete removal of offshore structures unless an exemption is granted (Kirk et al., 1999; Efthymiou, 2022). Waste management follows strict regulations under the Waste Framework Directive (2008), with operators required to track and audit waste from offshore removal to onshore disposal (SEPA, 2018; Akinyemi et al., 2020).
- GoM: The GoM has a more flexible approach, allowing for the Rigs-to-Reefs program, where decommissioned structures are repurposed as artificial reefs. This reduces removal costs and provides environmental benefits but differs from the UK's strict removal requirement (BSEE, 2020; Jørgensen, 2012).
- ASEAN: ASEAN countries take a mixed approach, with some nations requiring full removal while others permit in-situ decommissioning under certain conditions. Malaysia and Thailand mandate decontamination before removal, while Vietnam and

Brunei assess removal options on a case-by-case basis (Khan et al., 2025; Kumar et al., 2021).

The UK's strict adherence to OSPAR guidelines ensures a high level of environmental protection, but it may limit flexibility in cases where partial removal could be a viable alternative. The Rigs-to-Reefs approach used in the GoM demonstrates an alternative strategy that some ASEAN nations, such as Malaysia, have started to explore (Fowler et al., 2018; Ounanian et al., 2020).

2.14.1.4 *Stakeholder Engagement and Public Involvement*

Stakeholder involvement in decommissioning decision-making also differs significantly between regions.

- UK: Public consultation is a mandatory part of the decommissioning approval process, with decommissioning plans made available for review and feedback. Close-out reports are also publicly accessible (Shell, 2024a; OGA, 2020a).
- GoM: The GoM requires environmental assessments, but there is less emphasis on public involvement compared to the UK. While operators must submit decommissioning reports, they are not always made publicly available (Pazandak, 2020).
- ASEAN: Public involvement in ASEAN countries varies. Malaysia and Thailand have formal consultation processes, whereas Brunei and Vietnam primarily involve government regulators in decision-making (Kumar et al., 2021; Al-Najjar, 2021).

2.14.2 International Statutory Regime Conclusion

The UK's transparency in decommissioning planning and execution is a notable difference compared to other regions. In contrast, the GoM and ASEAN countries focus more on regulatory approval rather than public consultation (Walker and Roberts, 2013).

The comparison of decommissioning legislation across the UK, Gulf of Mexico, and ASEAN countries highlights the different approaches taken to regulatory enforcement, financial security, and environmental obligations (Kumar et al., 2021; Adetoro, 2009). The UK's goal-setting framework allows for flexibility but requires strong industry oversight, whereas the GoM's prescriptive approach ensures financial readiness but may limit operator decision-making (BSEE, 2020; Parente et al., 2006). ASEAN countries adopt a range of policies, often influenced by economic priorities and evolving environmental commitments (Khan et al., 2025; Kumar et al., 2021).

One of the key takeaways is the difference in financial security mechanisms. The GoM ensures funds are available throughout an installation's lifecycle, whereas the UK relies on operator responsibility, potentially creating future liabilities (Lockman et al., 2023). The cessation funds used in Malaysia and Indonesia offer a middle-ground solution, balancing cost distribution with financial assurance.

The environmental trade-offs between strict removal (UK) and alternative approaches (GoM's Rigs-to-Reefs program) also demonstrate different regulatory priorities. While OSPAR ensures minimal seabed impact, other regions explore reuse options to reduce costs and environmental disturbances.

Overall, while the UK maintains high regulatory standards and public transparency, there are lessons to be learned from alternative financial and environmental approaches used in other regions. Future research could explore how a hybrid model incorporating financial assurance and sustainable removal options could improve global decommissioning practices (Watson et al., 2023; Vidal et al., 2022).

In summary, international comparison shows that decommissioning governance is shaped as much by political economy and regulatory culture as by technical capability. Prescriptive regimes such as those in the Gulf of Mexico provide certainty but can stifle innovation, whereas the UK's goal-setting framework encourages adaptive management but demands high regulatory literacy and trust between stakeholders. The emerging hybrid approaches in parts of ASEAN, combining financial assurance with flexibility in waste and structure management, illustrate how regulatory learning can evolve through cross-regional dialogue. These findings reinforce the rationale for a structured decision support framework that can integrate legal, environmental and operational factors within a single analytical model. This approach is developed and applied in the later chapters of this thesis.

2.15 Research Gap

The literature review has provided an in-depth analysis of the key factors influencing offshore decommissioning, with a particular focus on regulatory frameworks, sustainability considerations, waste management practices, and financial security mechanisms. The review has highlighted the complexity of decommissioning operations, emphasising the need for structured planning, stakeholder engagement, and adherence to evolving legislative requirements (OGA, 2020a; SEPA, 2018; Babaleye and Kurt, 2020).

A comparison of UK, Gulf of Mexico and ASEAN decommissioning practices revealed significant differences in regulatory enforcement, financial responsibility and environmental obligations (Kumar et al., 2021; Lockman et al., 2023; Khan et al., 2025). The UK follows a goal-setting regulatory framework, requiring operators to demonstrate compliance with sustainability and safety objectives, while the Gulf of Mexico adopts a prescriptive approach that ensures financial readiness through mandatory bonding requirements. ASEAN countries exhibit regulatory variability, with some nations implementing cessation funds and structured approval processes while others rely on case-by-case evaluations.

The review has also identified critical challenges in waste management, particularly regarding hazardous waste identification, knowledge sharing and legislative compliance. Issues such as unclear liability, inconsistent regulatory interpretations and limited knowledge transfer across the waste stream present barriers to achieving sustainable decommissioning outcomes (Du et al., 2018; Robinson and Cowie, 2003; Akinyemi et al., 2020). The need for a unified regulatory approach and improved waste tracking mechanisms has been emphasised across multiple sources.

Existing decommissioning models have primarily focused on cost reduction and operational efficiency, with limited emphasis on the interaction between regulatory compliance, waste management and sustainability factors. This gap in the literature highlights the absence of an integrated analytical tool that can model the interdependencies among these variables. Addressing this gap requires a data-driven, systems-based framework capable of linking legal, operational and environmental dimensions of offshore decommissioning. The framework developed in this thesis directly responds to this need by combining empirical data and expert judgement to evaluate how these factors collectively influence sustainability and compliance outcomes.

2.16 Concluding Remarks

The following summarises the key points from this chapter and outlines its role in building the foundation for the research:

- Offshore decommissioning is governed by a complex mix of international, European, and UK legislation. This includes environmental protection directives, waste regulations, and health and safety frameworks.

- There is evidence of fragmentation between offshore and onshore regulatory regimes. This contributes to uncertainty over legal responsibilities, particularly at the boundary between offshore installations and land-based waste handling.
- Regulatory overlap and inconsistency can lead to compliance gaps, unclear duty of care obligations, and poor traceability of hazardous materials.
- The chapter demonstrates that the UK follows a goal-setting approach to regulation. While this allows for flexibility, it requires a strong understanding of responsibilities across all stakeholders involved in the waste stream.
- These findings support the need for a more structured decision-making framework to guide operators in aligning waste management practices with current legislation and sustainability targets.

CHAPTER 3: RESEARCH METHODOLOGY AND TECHNIQUES

3.1 Introduction

This chapter outlines the methodology adopted in this study. It explains how expert engagement, decision-support techniques, and analytical modelling were combined to develop a framework for the sustainable management of hazardous waste generated during offshore oil and gas decommissioning. The approach integrates qualitative and quantitative methods to ensure that expert knowledge and data analysis contribute jointly to the framework's design.

A research framework (Figure 3-1) was developed to guide the process and maintain a logical structure for the study. The framework defines the main stages of the work: identifying key issues in offshore decommissioning, engaging industry experts through discussions and interviews, prioritising factors using the Analytic Hierarchy Process (AHP), and modelling the relationships and uncertainty between these factors using Bayesian Networks (BN). The results from these stages were used collectively to inform the development of the integrated decision-support framework presented later in this thesis.

Experts working within regulatory, operational, and environmental roles in the offshore sector were contacted to participate in unstructured interviews. Their insights helped refine the list of factors influencing hazardous-waste management and guided the design of the AHP questionnaire. The outputs from the AHP and BN stages were then synthesised to produce a comprehensive methodology linking expert judgement with probabilistic analysis for improved decision-making in offshore decommissioning.

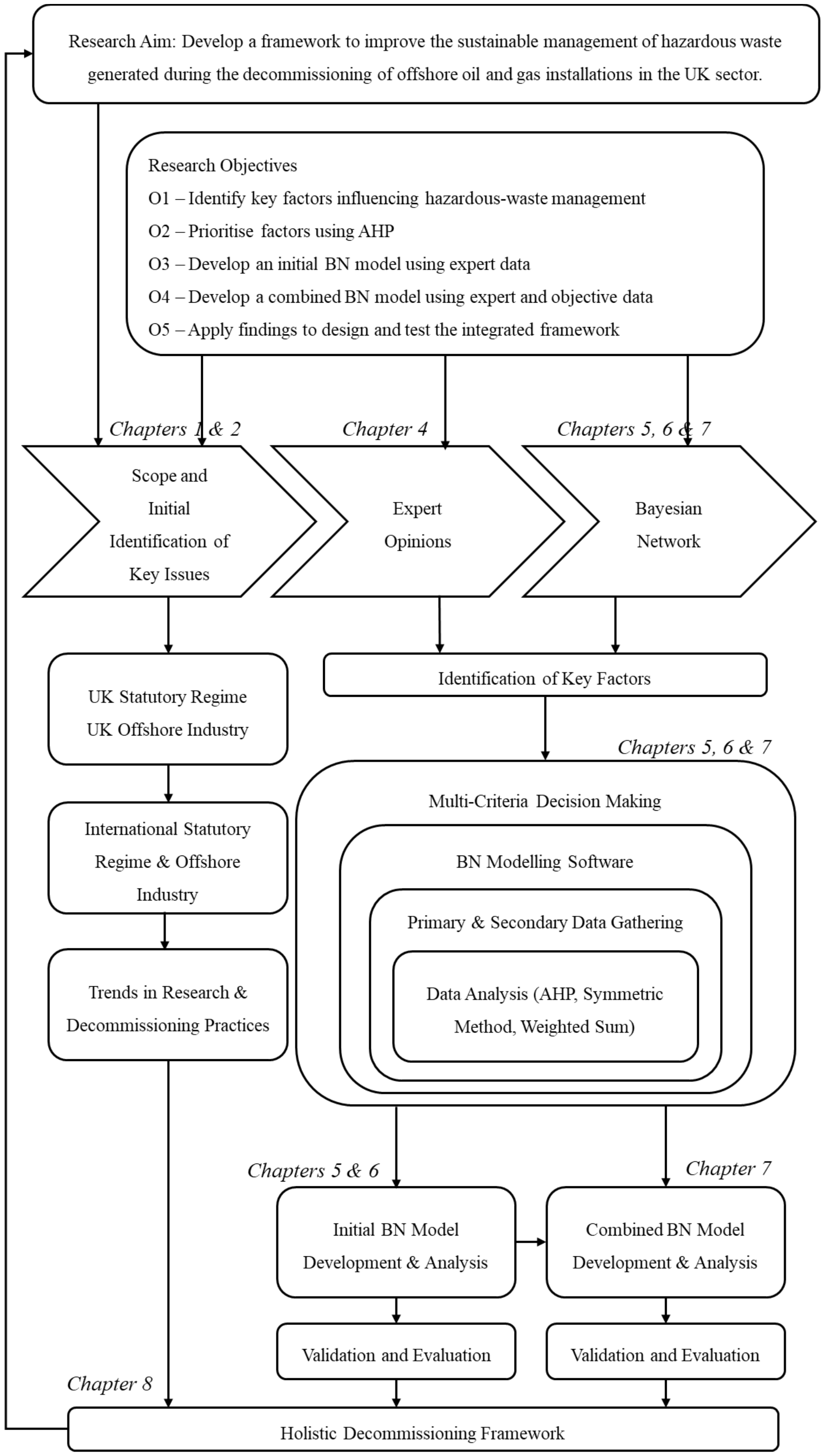


Figure 3-1: Proposed research framework.

Offshore decommissioning involves a combination of environmental, regulatory, and operational factors that interact in complex and uncertain ways. Capturing these interdependencies requires both qualitative and quantitative techniques. Therefore, this study integrates expert elicitation, the AHP, and BN modelling. Expert elicitation and AHP were used to identify and prioritise the key factors influencing hazardous-waste management, while BN modelling was applied to represent their probabilistic relationships and examine how uncertainty propagates through the system. Together, these complementary methods form an integrated framework that directly supports the research aim of improving the sustainable management of hazardous waste in offshore decommissioning.

3.2 Advocacy Discussions

Interviews can be defined as "conversations between a researcher and those being researched" (Hammond & Wellington, 2020). The goal of an interview is to find out what cannot be directly observed or measured (Greener & Greener, 2016). Interviews can be classified into three types:

i. Structured
ii. Semi-structured
iii. Unstructured

Prior to them being conducted, consideration must be made as to the relation of the aims of the research project and the aims of the interview (Hammond & Wellington, 2020).

Structured interviews consist of a series of prepared questions that are asked to each respondent in the same order. The responses can be coded to allow for further analysis and comparison. The highly structured nature of these interviews limits the flexibility in responses and the relationship between the interviewer and interviewee.

Semi-structured interviews are used when a researcher wishes to know specific information for comparison with information gathered from other interviews. Semi-structured interviews are the most common type used for qualitative research (Dawson, 2009). To ensure continuity between interviews, the interviewer must produce a schedule or list of questions to be asked. These questions are often open-ended to enable discussion to take place. The disadvantage of this process is that salient topics may be omitted (Dawson, 2009).

The third type of interview is the unstructured interview. During an unstructured interview, the questions asked are not predetermined, allowing for discussion to take place. For these to be successful, the interviewer must build a rapport with the interviewee to provide detailed, honest responses. Unstructured, expert interviews are widely used and aim to gain information about a very specific field (Doringer, 2020). Due to the nature of the interview, the responses obtained are varied, causing analysis and comparison between interviews to be difficult.

An unstructured approach was chosen to allow the interviewee to talk freely and at length about aspects of the research project they deemed important. The key findings would be used to develop criteria and alternatives for the AHP.

Experts were approached to take part in the semi-structured interviews. Franz and Larson (2002) noted that in group discussions, experts are more likely to mention relevant information than other respondents. The background of an expert enhances their knowledge, abilities and expertise that are relevant to the discussion. An expert can be defined as "a person who is very knowledgeable about or skilful in a particular area" (Stevenson, 2010). The ability to be classified as an expert depends on the experience and skills gained over the years (Finkbeiner, 2017). Through the experience that they possess from working within the decommissioning sector, the experts are more likely to recall relevant information and distinguish it from irrelevant information (Franz & Larson, 2002). The aim of each advocacy discussion was to establish what each expert identified as the key issues for decommissioning and the management of hazardous waste.

3.3 Multi-Criteria Decision Making

Decision analysis methods have been a focus of research since the 1960s. Decision analysis "seeks to apply logical, mathematical, and scientific procedures to decision problems that are characterised by uniqueness, importance, uncertainty, long run implications and complex preferences." (Howard, 1968)

In the instance when single attribute decision making may not be sufficient, a multiple attribute method may be applied. Multicriteria decision making (MCDM) is a complex decision-making tool involving both quantitative and qualitative factors (Mardani, 2015). MCDM has been applied to marine and offshore scenarios, including wind farm site selection, sustainability analysis. This is due to the ability of MCDM methods to break down complex decision-making problems and several subproblems (Zhang & Balakrishnana, 2021). Alternatives based on each subproblem can be analysed and then assessed to choose the best alternatives among the alternative options. An advantage of this is the ability to incorporate subjective information.

There are a variety of different MCDM methods which differ by the ways that the weights for each criterion are applied and the methods for which uncertainty are handled.

In this study, a multi-criteria decision-making approach was adopted to manage the combination of qualitative expert judgement and quantitative evaluation required for sustainable offshore decommissioning. Among available methods, AHP was selected because it allows expert-driven prioritisation of the key factors identified in Chapters 1 and 2 and provides a structured input to the subsequent Bayesian-Network modelling.

The most common methods include:

i. AHP
ii. TOPSIS
iii. VIKOR
iv. ELECTRE (Mardani, 2015).

3.4 Analytical Hierarchy Process

The methods described in Sections 3.4 to 3.12 were selected in direct response to the research gaps identified in Chapters 1 and 2. The literature review highlighted uncertainty in hazardous-waste management and limited integration between regulatory, environmental, and operational factors. To address these issues, a combined methodological approach was adopted. Expert elicitation was used to capture practical insight from industry specialists; the AHP structured these qualitative judgments into measurable priorities, and BN modelling allowed these relationships to be analysed quantitatively. Together, these approaches provide a coherent framework that links expert understanding with data-driven analysis, aligning with the study's overall aim of improving sustainable hazardous-waste management in offshore decommissioning.

The analytical hierarchy process was first proposed by Thomas Saaty during the 1970s as a tool for multicriteria decision-making. This method relies on pairwise comparisons of alternatives and aggregation to calculate overall priorities. AHP allows for a degree of inconsistency due to the input of human judgment.

In this study, AHP was applied to structure and quantify expert judgements on the factors influencing hazardous-waste management during offshore decommissioning. AHP was selected because it enables qualitative assessments from industry experts to be expressed as numerical priorities, creating a transparent and repeatable process for comparing environmental, regulatory, and operational criteria. The resulting priority weights formed the input parameters for subsequent Bayesian-Network modelling, linking the qualitative expert analysis to quantitative system evaluation.

AHP is based on four steps: problem modelling, weight valuation, weight aggregation and sensitivity analysis (Alessio, 2009). It is a hierarchal method that involves the development of a hierarchal structure between an overall goal, criteria and alternatives. The alternatives are compared with criteria to create a pairwise comparison table.

AHP has been shown by França et al. (2020) that it can be used as part of a decision-making process. They used AHP to identify key issues of a risk assessment process. AHP has the advantage of being flexible and able to be applied to a wide variety of problems. Oguztimur (2011) outlines some of the advantages and disadvantages of using AHP. The key advantage is that AHP relies on the judgements of experts, which allows for the problem to be evaluated easily and for priorities to be identified, but this can also be viewed as a disadvantage. The model must be designed within a boundary that allows the alternatives to be identified. If a new alternative is identified, the model must be adjusted to include this. This increases the amount of computation required as the size of the model increases. AHP has its strengths in its usability and universality (Karthikeyan, 2016). The hierarchal structure allows for a focus on criteria.

3.5 Alternatives to AHP

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was introduced by Hwang and Yoon in 1981 as a multi-criteria decision-making method that ranks alternatives based on their geometric proximity to an ideal solution (Hwang & Yoon, 1981). The fundamental principle of TOPSIS is that the chosen alternative should have the shortest distance from the positive ideal solution and the furthest distance from the negative ideal solution (Kolios et al., 2016). It involves normalisation of a decision matrix, calculation of the ideal and anti-ideal solutions, and computation of Euclidean distances to rank options accordingly.

TOPSIS is well-suited for problems involving quantifiable data and where trade-offs between benefit and cost criteria are required. However, it requires precise numerical data and cannot directly accommodate qualitative inputs or expert judgement in the same way as AHP. For this reason, the use of TOPSIS was deemed unsuitable for this project, which relies on both qualitative and expert-based assessments for complex offshore decommissioning scenarios.

VIKOR (Vlsekriterijumska Optimizacija I Kompromisno Resenje) was developed by Opricovic in 1998 (Opricovic & Tzeng, 2004). It is a multi-criteria decision-making method designed to identify a compromise solution that provides maximum group utility and minimum individual regret. VIKOR introduces a ranking index based on the distance of each alternative from the best solution using weighted and normalised deviations (Mardani et al., 2015).

This method is particularly applicable when decision-makers need to reach a consensus or resolve conflicts among stakeholders and is often applied in socio-technical problems or public decision-making. However, the method assumes a certain degree of decision-maker consensus or preference structure, which was not available in this study due to the divergent views of the stakeholders interviewed. Therefore, VIKOR was not considered appropriate for this research, which required individual expert input to be treated equally without enforced compromise.

ELECTRE (Elimination Et Choix Traduisant la REalité) is a family of outranking methods developed in the 1960s (Roy, 1968). It compares alternatives using concordance and discordance indices to eliminate less desirable options. The ELECTRE approach is more focused on identifying outranked alternatives rather than providing a full ranking and is suitable for problems with non-compensatory decision contexts (Zhang and Balakrishnan, 2021).

ELECTRE is advantageous when decision-makers cannot or do not want to assume full trade-offs between criteria. However, it can become computationally complex as the number of criteria and alternatives increases and may not provide the clear prioritisation required in this research. Given the hierarchical nature of the problem being explored and the need for full ranking of criteria, ELECTRE was not selected for use in this project.

A key strength of AHP lies in its capacity to integrate subjective judgements systematically and transparently (Martins et al., 2020). This is especially critical in decommissioning operations, where decision-making must reconcile conflicting priorities between environmental protection, cost, regulatory compliance, and legacy infrastructure (Li, 2023; Butschek et al., 2023). For example, Eke (2023) used AHP in stakeholder conflict resolution within decommissioning projects, demonstrating its practical effectiveness in eliciting and reconciling expert views.

In contrast, methods such as TOPSIS and VIKOR often assume the availability of normalised datasets and numerical performance scores for all alternatives, a condition often unmet in early-stage decommissioning where qualitative judgements dominate (Wei & Zhou, 2024; Mahmudah et al., 2024). AHP excels in such cases by converting these qualitative inputs into quantitative priorities through its well-established pairwise comparison approach.

From a usability standpoint, AHP's intuitive process, comparing two criteria or alternatives at a time, enhances accessibility and reduces cognitive load, which is important when involving industry professionals who may not be decision-analysis experts (Zhou & Wei, 2024; Ismail & Sum, 2023). Cognitive science supports the practical limit of comparing 7 ± 2 items at once (Mu & Pereyra-Rojas, 2017), aligning with AHP's design structure.

Furthermore, the consistency check ($CR < 0.1$) provided by AHP offers an objective measure of judgement coherence, improving the reliability of stakeholder input compared to other methods that lack such diagnostic tools (Saaty & Vargas, 2013; Oguztimur, 2011).

Recent literature further supports the use of the Analytical Hierarchy Process in contexts directly related to offshore decommissioning and hazardous waste management. Li and Hu (2022) developed a multi-attribute decision-making framework incorporating AHP to evaluate offshore infrastructure removal strategies, noting the method's effectiveness in addressing conflicting economic and environmental criteria. Martins et al. (2020) concluded that AHP's structured, pairwise comparison approach was particularly suitable for contexts marked by high stakeholder uncertainty and the presence of legacy infrastructure, where other techniques, such as TOPSIS, may prove less intuitive. Butschek et al. (2023) further illustrated AHP's flexibility by applying it to geospatial prioritisation within marine energy planning, demonstrating its adaptability to environmental decision-making involving regulatory and risk-based considerations. In addition, Sum and Ismail (2023) applied AHP to evaluate managerial competence in offshore settings, reaffirming the method's value in expert-led qualitative assessments where quantitative scoring is not always appropriate.

AHP was selected as the most appropriate method for handling the complex, multi-stakeholder decision-making processes inherent in offshore decommissioning and hazardous waste management. While several multi-criteria decision-making techniques were reviewed, including TOPSIS, VIKOR, and ELECTRE, AHP was chosen based on its unique suitability for contexts involving expert judgement, qualitative-to-quantitative translation, and limited datasets.

3.5.1 Overview of Analytical Hierarchy Process

The analytical hierarchy process is a technique developed by Thomas Saaty during the 1970s. It is a multicriteria decision-making method that allows for a degree of inconsistency due to the input of human judgment. The process follows a framework that breaks down a problem into hierarchal levels to allow them to be compared, ranked and aggregated for a solution (Saaty and Kearns, 1985). Figure 3-2 shows a simplified flow chart of the steps to complete an analytical hierarchy process.

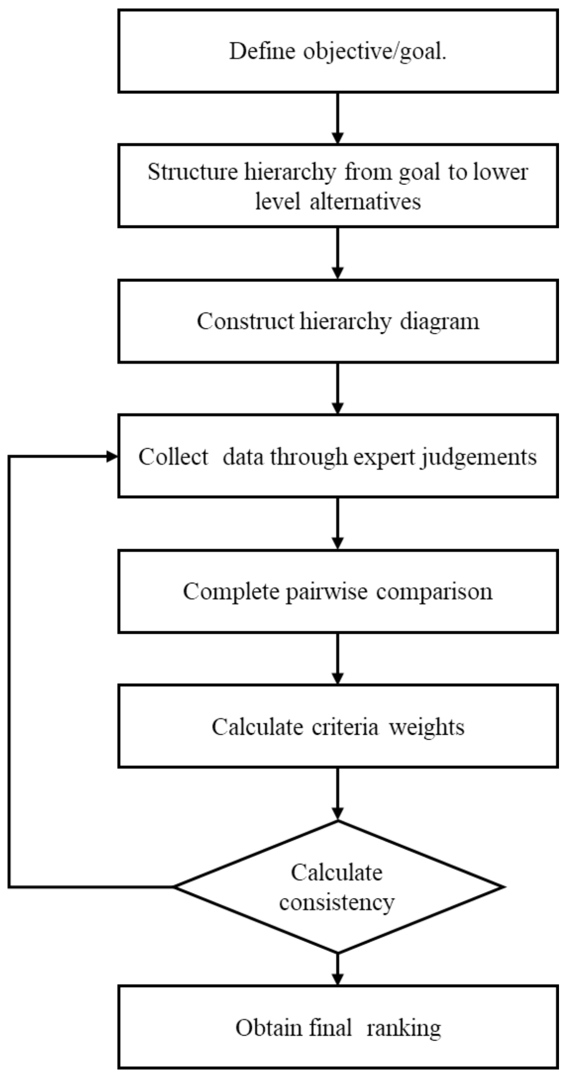


Figure 3-2: Summary of steps for analytical hierarchy process (based on (Saaty and Kearns, 1985))

The first step in the AHP process is to define the problem and identify the goals or objectives. This enables a hierarchal structure to be developed from the top goal to sub-criteria to alternatives. The hierarchal structure is shown in Figure 3-3.

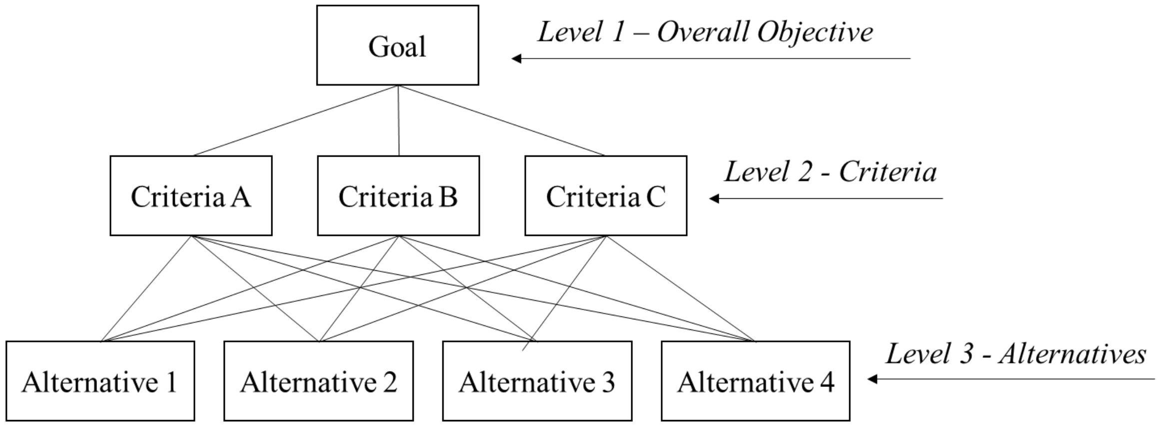


Figure 3-3: Example of the hierarchal structure.

Once the hierarchy has been determined, a questionnaire can be developed to allow for each alternative and the criteria to be compared. A questionnaire is developed to allow the comparison of the alternatives. The results of the questionnaire enable a pairwise comparison matrix to be produced.

The questionnaire requires the respondent to compare alternatives and to rank their importance using the Saaty Scale. The Saaty Scale is shown in Table 3-1. This is a scale of relative importance that Saaty recommended to enable subjective pairwise comparisons (Saaty and Kearns, 1985).

Table 3-1: Scale of Relative Importance (Saaty and Kearns, 1985)

Important		Unimportant	
Intensity of importance	Definition	Intensity of unimportance	Definition
1	Equal importance	1	Equal importance
3	Moderate importance	1/3	Moderate unimportance
5	Strong importance	1/5	Strong unimportance
7	Very strong importance	1/7	Very strong unimportance
9	Extreme importance	1/9	Extreme unimportance
2,4,6,8	Intermediate importance values	1/2,1/4,1/6,1/8	Intermediate unimportance values

The alternatives can be presented to the chosen expert respondents through a simple questionnaire. For example, the comparison between three alternatives, A1, A2 and A3 may be required. Table 3-2 illustrates a section of the questionnaire and the comparisons of three alternatives, A1, A2 and A3.

Table 3-2: Section of example questionnaire highlighting the comparisons of three alternatives.

	Unimportant								Equally important	Important								
A1	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	**3**	4	5	6	7	8	9	A2
A1	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	**7**	8	9	A3
A2	1/9	1/8	1/7	**1/6**	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9	A3

Table 3-2 shows A2 is three times more important than A1, A3 is seven times more important than A1, but A3 is 1/6 times less important than A2. Using these rankings, a pairwise matrix is constructed. The pairwise matrix is a *nxn* dimensional square matrix as shown in (3-1). The diagonal of the matrix, when *i*=*j*, are equal to the value 1.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ {}^{1}/_{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ {}^{1}/_{a_{1n}} & {}^{1}/_{a_{2n}} & \cdots & 1 \end{bmatrix} \tag{3-1}$$

The completed matrix using the example responses from Table 3-2 gives matrix A.

$$A = \begin{bmatrix} 1 & 2 & 7 \\ \frac{1}{2} & 1 & \frac{1}{6} \\ \frac{1}{7} & 6 & 1 \end{bmatrix} \tag{3-2}$$

The next step is to normalise the matrix. This is required in order to produce dimensionless data, in order to allow the alternatives to be ranked. Each column within the pairwise matrix is summed.

$$a_{ij} = \sum_{i=1}^{n} a_{ij} \tag{3-3}$$

Then each element in the matrix is divided by its column total in order to generate the normalised pairwise matrix.

$$X_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nn} \end{bmatrix} \tag{3-4}$$

The weighted matrix is produced by dividing the sum of the normalised column by the number of criteria used.

$$W_{ij} = \frac{\sum_{j=1}^{n} X_{ij}}{n} \begin{bmatrix} W_{11} \\ W_{21} \\ \vdots \\ W_{n1} \end{bmatrix} \tag{3-5}$$

The consistency index is calculated to determine the consistency of the judgments.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3-6}$$

Where n is the number of elements being compared and λ_{max} is the maximum eigenvector of the matrix. Pairwise comparison matrices are positive and reciprocal, the principal eigenvector can be determined using (Liberatore and Nydick, 2003).

$$A_w = \lambda_{max}\, W_{ij} \tag{3-7}$$

The consistency index is then divided by the random consistency number of the matrix. These values, shown in Table 3-3, were suggested by Saaty and Kearns (1985) to determine if the consistency of the judgements are acceptable.

Table 3-3: Random consistency index (Saaty and Kearns, 1985)

Size of Matrix	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (RC)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The consistency ratio must be less than 10%. Saaty and Kearns (1985) suggests that in some cases, 20% may be tolerated. If the consistency ratio is exceeded, then the experts must revise their judgments.

$$CR = \frac{CI}{RC} \leq 10\% \tag{3-8}$$

The final priority matrix for each expert can be produced by finding the sum of the products of the weight for each criterion and weight for each alternative.

$$Final\ priority\ for\ Each\ Altenative\ = \sum_{i=1}^{n} W_{ij}\, W_{criteria\ i} \tag{3-9}$$

When there are multiple expert respondents, an aggregated response is required. A procedure is only considered satisfactory if it:

i. Reflects the collective judgments of the respondents
ii. Responds to changes in individual preferences
iii. Provides ranking for the alternatives presented (Saaty and Vargas, 2013).

If none of the respondents' opinions are considered greater than the others, then an aggregated response can be found using the geometric mean of the weights (Saaty and Vargas, 2013). The geometric mean method is also advocated by Liberatore and Nydick (2003) when a consensus cannot be made through discussion.

$$W^G = \left(\prod_{i=1}^{n} W_i\right)^{1/n} = \sqrt[n]{W_1 W_2 W_3 \ldots\ldots\ldots W_n} \tag{3-10}$$

3.5.2 Pearson Correlation Coefficient

Following the AHP analysis, the Pearson Correlation Coefficient, also known as the Product Moment Correlation Coefficient (Sedgewick, 2012), was calculated to determine if any relationships existed between each of the respondents. The Pearson Correlation Coefficient is used to measure the extent of two variables predicting each other and shows the relationship between them (Dana et al, 2015). It is used to establish the strength of the relationship between two numerical variables (Breman- Brown & Saunders, 2008). It is limited to testing linear relationships as significant curvilinear relationships can result in non-significant values (Armstrong, 2019).

The Pearson coefficient, denoted by r, is calculated using equation 3-11.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

(3-11)

Where r is the Pearson correlation coefficient, x_i are the values of the x-variable in the sample, $\bar{x}$ is the mean of the values of the x-variable, y_i are the values of the y-variable in a sample and $\bar{y}$ is the mean of the values of the y-variable.

The value of the person coefficient indicates the type and strength of the correlation. A positive correlation indicates that the values being analysed move in the same direction. Consequently, a negative correlation indicates the values being analysed move in the opposite direction as illustrated in Figure 3-4.

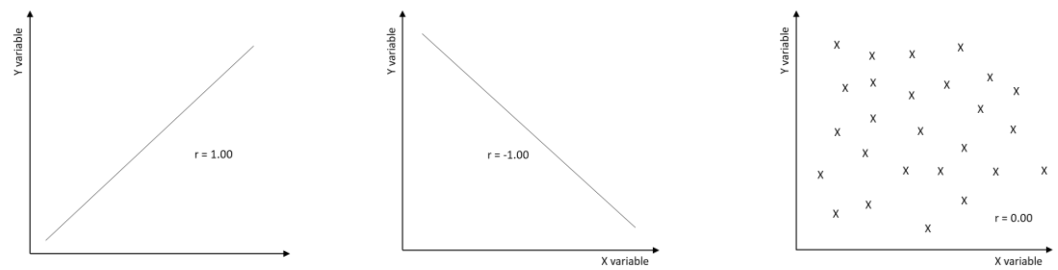


Figure 3-4: Examples of Pearson Correlation Coefficients

Table 3-4 indicates the strength of the correlation for each magnitude of the Pearson correlation coefficient. A magnitude of 1 indicates that the correlation is perfect and a value of zero indicates that there is no correlation.

Table 3-4: Pearson Correlation Coefficient Magnitude Strengths

Pearson correlation coefficient (magnitude)	Correlation strength
$0.8 \leq r \leq 1.0$	Very Strong
$0.5 \leq r \leq 0.8$	Strong
$0.3 \leq r \leq 0.5$	Medium
$0.0 \leq r \leq 0.3$	Low

3.6 Probability Theory

Probability is the measure of likelihood that an event will occur. It can be expressed as a percentage, decimal form or a fraction. The probability of an event A occurring is defined as:

$$P(A) = \frac{No. of\ outcomes\ favourable\ to\ the\ occurence\ of\ A}{Total\ number\ of\ equally\ likely\ outcomes} = \frac{n(A)}{n(S)} \quad (3\text{-}12)$$

Probability theory is governed by the following axioms:

Axiom 1: The probability of an event is a real number greater than or equal to zero.

$$P(A) \geq 0 \quad (3\text{-}13)$$

Axiom 2: The probability that at least one of all possible outcomes of an event will occur is equal to one.

$$P(A) = 1 \quad (3\text{-}14)$$

Axiom 3: If two events, A and B, are mutually exclusive, then the probability of either occurring is the probability of A occurring plus the probability of B occurring.

$$P(A \cup B) = P(A) + P(B) \quad (3\text{-}15)$$

Events are considered independent if the outcome of one event does not affect the outcome of the other.

$$P(B|A) = P(B) \quad (3\text{-}16)$$

Events are considered dependent if the outcome of one event affects the outcome of the other.

$$P(A\ and\ B) = P(A) \times P(B|A) \quad (3\text{-}17)$$

This basic probability leads to Bayes' Theorem, which is utilised in Bayesian Networks.

3.6.1 Bayesian Networks

Bayesian networks can be used to explore relationships between key factors and find outcomes for a system in a straightforward, visual manner. Bayesian networks are a type of directed acyclic graph that uses Bayes' Theorem (Neapolitan, 2004).

In this study, Bayesian Networks were used to model the probabilistic interactions between the key factors influencing hazardous waste management identified through the literature review, expert discussions, and the AHP analysis. The method was chosen because it allows the integration of expert-derived priorities with objective data to represent uncertainty in decommissioning decision-making. This enables the framework developed in later chapters to simulate how variations in regulation, knowledge sharing, and waste identification can influence sustainability outcomes across the decommissioning process.

Bayesian Networks were selected for this project due to their ability to model complex systems involving uncertainty, limited datasets, and interdependent variables. These characteristics are consistent with the nature of offshore decommissioning, where legacy data is often incomplete, and many of the risk factors are causally connected. Bayesian Networks allow for both qualitative and quantitative data inputs, making them suitable for applications where expert judgment must supplement empirical data (Babaleye, Kurt and Khan, 2019).

The use of Bayesian Networks in this project enables the integration of expert judgment obtained through AHP and semi-structured interviews. They model probabilistic dependencies among risk factors and waste-handling decisions. Bayesian Networks also allow for scenario-based reasoning, simulating how changes in certain variables affect outcomes. The structure allows for dynamic updating as new data becomes available or assumptions are refined.

Several alternative methods were initially considered. These include Fault Tree Analysis (FTA), Analytical Hierarchy Process as a stand-alone method, Monte Carlo Simulation (MCS), and Fuzzy Logic. Each has strengths, but none provided the full combination of uncertainty modelling, causal reasoning, expert integration, and adaptability required for this study.

Fault Tree Analysis was developed in 1962 by Bell Telephone Laboratories. It is widely used in safety-critical sectors for identifying root causes of system failures (Ericson, 2005). While FTA is useful for identifying fault propagation, it is deterministic and limited to binary outcomes. It cannot model uncertainty or interdependencies, which are central to offshore decommissioning (Animah and Shafiee, 2020).

The Analytical Hierarchy Process was introduced by Thomas Saaty in the 1970s. It structures decision-making using pairwise comparisons within a hierarchical framework (Saaty, 1980). Although it effectively captures expert judgment, it cannot account for probabilistic relationships or feedback loops. It was therefore used to inform the structure of the Bayesian Network, rather than as a primary tool (Martins et al., 2020).

Monte Carlo Simulation was formalised by Metropolis and Ulam in 1949. It is used to assess uncertainty by generating outcome distributions through repeated sampling (Metropolis and Ulam, 1949). MCS is suited to problems with well-defined data and known distributions.

However, it cannot model variable dependencies and is not suitable where expert opinion must replace empirical data (Shafiee and Adedipe, 2022).

Fuzzy Logic was proposed by Lotfi Zadeh in 1965. It is useful for systems with qualitative or vague inputs and has been applied in environmental decision-making. However, fuzzy logic does not provide probabilistic outputs or allow for causal inferences. It also lacks the ability to update with new data, which limits its utility in dynamic systems (James and Renjith, 2024).

Bayesian Networks were chosen because they address all these limitations. They represent causal relationships, incorporate uncertainty, and support both qualitative and quantitative inputs. The graphical structure enables communication with stakeholders and adaptation to specific decommissioning contexts. This method supports the complexity of hazardous waste management and the dynamic nature of offshore decommissioning environments.

Bayesian networks are constructed using nodes and links. Nodes represent variables which can either be discrete or continuous. The links between the nodes indicate causality. Each node can be classified as a parent or child node.

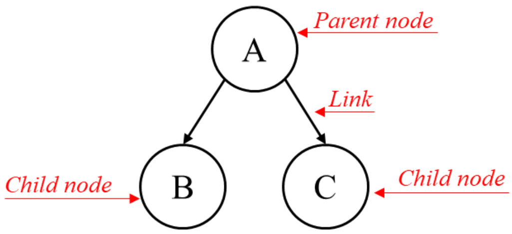
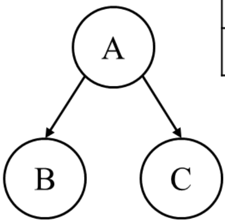


Figure 3-5- Example of a Simple Bayesian Network.

A simple BN is shown in Figure 3-5. In this example, A is a parent of the node of C and a parent node of B. Therefore, nodes B and C are child nodes of A. BN can be developed by the addition of further nodes and links, indicating their influences.

BN represents quantitative relationships among modelled variables. The probability distribution for each node is shown in a conditional probability table (CPT). These CPTs can be used to express the relationships between nodes. Figure 3-6 illustrates the conditional probability tables for a simple BN.

a_1	$P(a_1)$
a_2	$P(a_2)$



	a_1	a_2
b_1	$P(b_1 \mid a_1)$	$P(b_1 \mid a_2)$
b_2	$P(b_2 \mid a_1)$	$P(b_2 \mid a_2)$

	a_1	a_2
c_1	$P(c_1 \mid a_1)$	$P(c_1 \mid a_2)$
c_2	$P(c_2 \mid a_1)$	$P(c_2 \mid a_2)$

Figure 3-6- Example of a Bayesian Network with Conditional Probability Tables.

Bayes' Theorem was developed in the 18th century by Thomas Bayes (Weber and Simon, 2016). Previous (unconditional) probability represents the likelihood that an input parameter will be in a particular state. The conditional probability calculates the likelihood of the state of a parameter given the state of the input parameters affected.

Bayes' Theorem is represented using equation 3-18.

$$P(b|a) = \frac{P(a|b).P(a)}{P(b)} \tag{3-18}$$

BNs satisfy the local Markov property, which states that a node is conditionally independent of its non-decedents, given its parents. The BN uses Bayesian inference probability computation. This inference can come from known probabilities or through calculation through variable elimination. The network is solved when the nodes have been updated using Bayes' Theorem.

3.6.2 Formulating a Bayesian Network

In order to formulate a Bayesian Network, the following steps, shown in Figure 3-7, will be taken. This is based on the generic steps outlined by Neapolitan (2004) and Weber and Simon (2016).

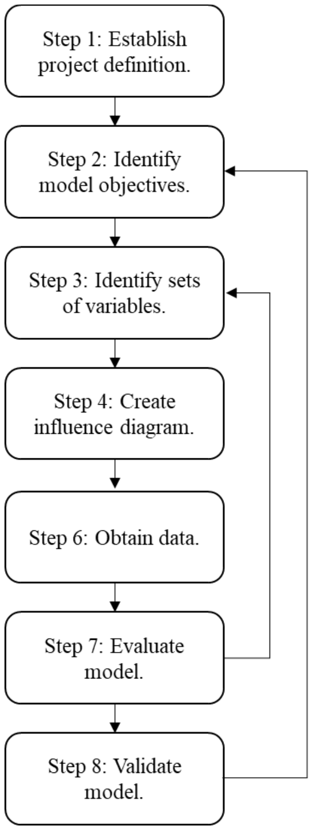


Figure 3-7 - Steps for Formulating a Bayesian Network.

Step 1 has been completed through the initial literature review for the project proposal and the literature review contained within this interim report. Step 2, the model objectives will be developed around research objective 4. The data will be obtained through questionnaires designed around the initial model. The remaining steps will be an iterative process, with the model being developed to reflect the key issues arising from the literature review and questionnaires. Once the data has been collected and the model completed, it will be analysed using Bayesian Network software.

3.6.3 Conditional Probability Tables

Generating the conditional probability tables for a Bayesian network can often be the most challenging part of the analysis. The aggregated priorities from the AHP analysis will be used to construct the tables for the nodes that correspond to the criteria and alternatives in the hierarchal structure shown in Figure 3-8.

When nodes that have more than one parent, their probabilities can be determined using the weighted sum algorithm proposed by Das (2008). This approach uses the results from the pairwise comparison and their relative weights.

The example in Figure 3-8 shows a child node, C, with two parent nodes.

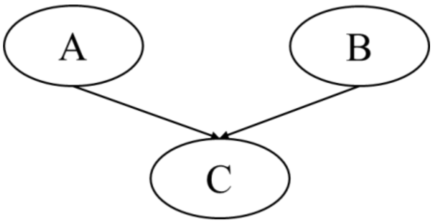


Figure 3-8- Simple Bayesian Network

If the parent nodes have the same number of states:

$$k_1 = k_2 = \cdots = k_n$$
$$where\ k_n = the\ number\ of\ states\ of\ the\ nth\ node$$

The compatible states for the parent's nodes are represented by

$$\{comp\ (A_i = a_s)\} \equiv \{comp\ (B_i = b_s)\}$$

Where '≡' indicates the sets are identical.

For Figure 3-8, the compatible parent combination is:

$$\{comp\ (A_i = s)\} \equiv \{comp\ (B_i = s)\} \equiv \{A = s, B = s\}$$

For child node C, the probability distribution will be:

$$P(C|\{comp(A = s)\}) = P(C|\{comp(B = s)\})$$

This leads to the weighted sum algorithm (Das 2008)

$$P(x^l|y_1^{s1}, y_2^{s2}, \dots \dots \dots . y_n^{sn}) = \sum_{j=1}^{n} w_j . P(x^l|\{Comp(Y_j = y_j^{sj})\}$$

Where: $l = 0, 1, \dots, m$ and $S_j = 1, 2, \dots, k_j$

This can be applied to the child node C show in Figure 3-8.

3.7 Concluding Remarks

This chapter explains how the chosen research methods support the overall aim of developing a framework for the sustainable management of hazardous waste during offshore decommissioning. Each method was selected to address a specific research objective and to close the gaps identified in Chapters 1 and 2. The expert discussions provided qualitative insight into regulatory and operational issues; the AHP converted these insights into ranked priorities; and the Bayesian Networks used those priorities to model how key factors interact and how uncertainty affects outcomes. Together, these approaches provide a clear link between qualitative understanding and quantitative analysis.

The following key points summarise the core methodology adopted and set the foundation for the analysis:

- AHP was selected to capture and rank expert judgement in a structured and accessible way, using pairwise comparisons and hierarchical modelling.
- Bayesian Networks were developed to explore causal dependencies and simulate decision scenarios using both qualitative and quantitative data.
- Advocacy-based discussions allowed the identification of key themes and expert concerns, shaping the decision criteria and model structure.
- The integration of AHP and Bayesian Networks supports a flexible approach capable of handling uncertainty, data gaps, and expert insight.
- The methodology is grounded in established academic techniques but tailored to the practical constraints and needs of offshore decommissioning.

This integrated approach directly addresses the research gaps identified in Chapters 1 and 2 by combining qualitative expert understanding with quantitative modelling to support sustainable and evidence-based offshore decommissioning.

CHAPTER 4: DETERMINATION OF KEY FACTORS IN DECOMMISSIONING THROUGH EXPERT OPINION

4.1 Introduction

This chapter outlines the process undertaken to gather expert input to identify key factors influencing offshore decommissioning and hazardous waste handling. It explains the rationale for using unstructured interviews and provides background on the selected participants. The chapter then presents the main themes that emerged from the discussions and links them to the development of a structured decision model.

4.2 Expert Discussions and Participant Justification

Experts were approached to take part in virtual interviews. An unstructured approach was chosen to allow for the interviewee to talk freely and at length, about aspects of the research project they deemed important. The key findings would be used to develop criteria and alternatives for the AHP. The backgrounds of each expert approached to take part are shown in Table 4-1. Each expert currently works within the decommissioning sector at manager or above level.

Four industry specialists were consulted through informal expert discussions arranged by the supervisory team. Each individual was selected because they hold senior positions directly involved in UK offshore decommissioning projects and possess extensive experience in regulatory compliance, waste management, or project delivery. The purpose of these discussions was to identify key operational and regulatory challenges in hazardous-waste handling rather than to gather personal opinions. The sessions were exploratory and not formally recorded, as they served to guide the design of subsequent structured analysis through the AHP and BN models.

Table 4-1: Background details of experts chosen for semi-structured interviews and discussions.

Expert	Role	Expertise Area
1	Project executive at an environmental protection agency with focus on decommissioning.	Oversees regulatory approval and waste-management compliance for multiple UKCS decommissioning projects.
2	Project manager at an environmental protection agency with focus on decommissioning.	Responsible for permitting and environmental impact review of offshore dismantling operations.
3	Business development director for regulator backed, not for profit trade body for energy decommissioning.	Leads industry collaboration and knowledge-sharing initiatives; experienced in cost-reduction and waste-stream optimisation.
4	Decommissioning manager, not for profit representative body for UK offshore oil and gas industry.	Coordinates operator engagement on decommissioning standards, duty-of-care compliance, and waste-routing strategies.

Although only four experts participated in these discussions, this was considered sufficient for the purpose and scope of this research. Offshore decommissioning and hazardous-waste management are highly specialised domains in which the number of professionals with direct regulatory, operational, and strategic responsibility is limited. The participants were purposefully selected to capture the perspectives of the principal stakeholder groups involved in UK decommissioning which include regulators, industry bodies, and operators. This aligns with accepted practice in expert-elicitation studies, where the focus is on depth and relevance of expertise rather than sample size (França et al., 2020; Babaleye and Kurt, 2020). Collectively, the four experts represented the full range of viewpoints required to identify key industrial challenges and inform the subsequent analytical stages of the study.

Each unstructured interview was conducted as a discussion using online video conferencing software. Each followed the format of introductions, project outline, findings from work completed and discussion on findings. This gave each expert the opportunity to voice what they felt as the most important issues affecting the decommissioning process. The results are summarised in Table 4-2.

Table 4-2: Summary of key points made during semi-structured interviews and discussions with industry experts.

Expert	Key Points
Expert 1	• High volumes of waste. • Lack of understanding of the waste management process. • Different values between environmental and safety regulations. • Length of waste stream – aim to reduce it.
Expert 2	• Lack of understanding of legislative compliance along the waste stream by operators. • Extent of conformity and discrepancies along the waste stream.
Expert 3	• Lack of understanding of waste management by operators. • Sector dismissive of waste and onshore costs. • Lack of knowledge sharing. • Duty of care and disposal of liability concerning onshore activities as part of the waste stream. • Misidentification/mislabelling of legacy chemicals.
Expert 4	• Lack of knowledge sharing. • Lack of understanding of CDM regulations with regards to decommissioning. • Lack of clarity of legal jurisdiction and duty of care across different stages of decommissioning. • Issues with mishandling, mislabelling and difficulty identifying older assets and equipment due to missing historical data.

4.3 Discussion

The emerging theme from the expert discussions was that of concern over the understanding of the legislative requirements along the waste stream. This is consistent with the findings from the previous study conducted. Several factors could explain this observation, firstly due to the length of the waste stream and the large number of stakeholders involved. Secondly, the lack of knowledge sharing amongst stakeholders. The lack of knowledge sharing would also account for the issues with the identification of legacy chemicals and old assets.

4.4 Summary

The key points raised in the discussions with the industry experts will be used to develop an AHP hierarchy and a pairwise questionnaire that can be distributed to a larger number of industry experts.

4.5 AHP Hierarchy Model

The key factors identified during the advocacy discussions and the literature review were used to produce a hierarchy of criteria and alternatives. The process follows a framework that breaks down a problem into hierarchical levels to allow them to be compared, ranked, and aggregated for a solution (Saaty and Kearns, 1985). The hierarchy structure is shown in Figure 4-1. The number of alternatives has been limited to seven as cognitive science that suggest that a person's working memory capacity is in the order of 7 ± 2 (Mu & Pereyra-Rojas, 2017).

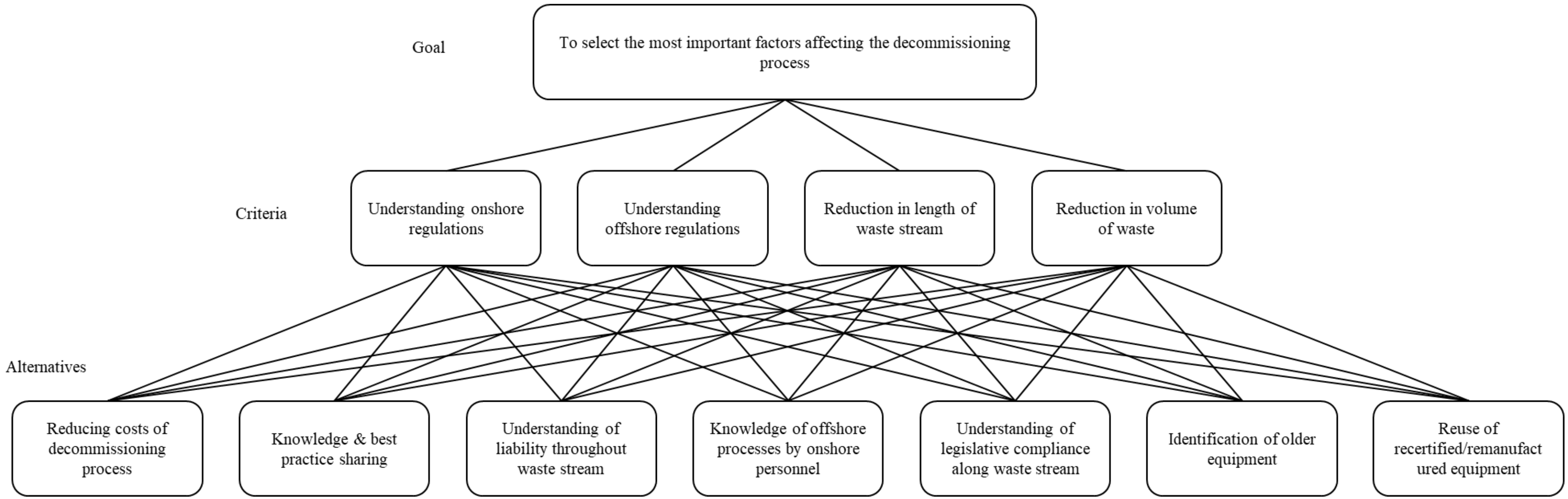


Figure 4-1: AHP Hierarchy Diagram.

The AHP hierarchy consisted of a top goal, four criteria and seven alternatives. The details of each are as follows:

Criteria 1 (C1): Understanding of onshore regulations - the understanding of the current, applicable onshore regulations during decommissioning activities.

Criteria 2 (C2): Understanding of offshore regulations - the understanding of the current, applicable offshore regulations during decommissioning activities.

Criteria 3 (C3): Reduction in length of waste stream - the reduction in the length of the waste stream during the decommissioning process.

Criteria 4 (C4): Reduction in volume of waste - the reduction in the volume of waste along the waste stream during the decommissioning process.

Alternative 1 (A1): Reducing costs of decommissioning process – methods to reduce the cost of the decommissioning process.

Alternative 2 (A2): Knowledge & best practice sharing – the knowledge and best practice sharing amongst parties conducting the decommissioning process.

Alternative 3 (A3): Understanding of liability throughout the waste stream – the understanding of the liability of individual stakeholders throughout the waste stream of the decommissioning process.

Alternative 4 (A4): Knowledge of offshore process by onshore personnel – the knowledge of the offshore decommissioning processes by the onshore personal that are conducting the decommissioning process.

Alternative 5 (A5): Understanding of legislative compliance along waste stream – the understanding of current legislative requirements along the waste stream during the decommissioning process.

Alternative 6 (A6): Identification of older equipment – the identification of older equipment that may be present onboard installations prior to the commencement of decommissioning.

Alternative 7 (A7): Reuse of recertified/remanufactured equipment – the reuse of recertified/remanufactured equipment that has been removed from installations during the decommissioning process.

4.6 Questionnaire Design

The questionnaire was developed using the hierarchical structure. The questionnaire required respondents to compare alternatives and rank their importance using the Saaty Scale (Saaty and Kearns, 1985). The questionnaire was distributed using onlinesurveys.ac.uk to allow for General Data Protection Regulation (GDPR) and Liverpool John Moores University ethics requirements to be met.

The questionnaire also gathered demographical data of the respondents in the form of years of experience, industry sector and educational background. The questionnaire is shown in Appendix E.

4.7 Application of Pairwise Comparison and AHP

The method outlined in section 2.4 was followed in order to complete the AHP calculations. The responses to the distributed questionnaire allowed for the formulation of pairwise comparison matrices. Table 4-3 shows the pairwise comparison matrix for the level 1 criteria for one individual expert's judgements.

Table 4-3: Pair-wise comparison matrix for level 1 criteria.

	C1	C2	C3	C4
C1	1	1	7	7
C2	1	1	7	7
C3	1/7	1/7	1	1
C4	1/7	1/7	1	1
SUM	**2.29**	**2.29**	**16.0**	**16.0**

Using the data from Table 4-3, a standardised matrix could be created. This is shown in Table 4-4. The matrix is created by dividing the ranking of each criteria by the sum of their column. If the standardisation is correct, the sum of each of the column will equal one.

Table 4-4: Normalised comparison matrix for level 1 criteria

	C1	C2	C3	C4	Criteria Weights
C1	0.44	0.44	0.44	0.44	0.44
C2	0.44	0.44	0.44	0.44	0.44
C3	0.06	0.06	0.06	0.06	0.06
C4	0.06	0.06	0.06	0.06	0.06
SUM	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Using Eq. (3), the maximum eigenvector can be determined.

$$\lambda_{max} = \left(\frac{1}{0.44} \times 0.44\right) + \left(\frac{1}{0.44} \times 0.44\right) + \left(\frac{1}{0.06} \times 0.06\right) + \left(\frac{1}{0.06} \times 0.06\right) = 4$$

This allows for the consistency index to be calculated using Eq. (3-6).

$$CI = \frac{4-4}{4-1} = 0.00$$

The consistency ratio is calculated using the random index shown in Table 4-3 and Eq. (3-8).

$$CR = \frac{0.00}{0.9} = 0.00$$

The final priority matrix can be calculated by combining the individual weights for each criteria and alternative.

4.8 Results & Discussion

The demographics for the respondents to the AHP questionnaire is shown in Table 4-5. Respondents two and three work in the education sector, whilst respondents one, three, four, five, six and seven work in industry. The majority have experience both onshore and offshore.

Table 4-5: Demographics of Respondents to AHP Questionnaire

Respondent	Area of Expertise	Number of Years' Experience	Current Role	Onshore or Offshore
1	Safety Engineering	More than 10	Supply chain	Both
2	Maritime Engineering	5 - 10 Years	Researcher	Both
3	Project Management	1-5 Years	Supply Chain	Onshore
4	Well Plugging & Abandonment	More than 10	Consultancy	Both
5	Waste Management	More than 10	Lecturer	Both
6	Subsea Engineering	More than 10	Supply chain	Both
7	Project Management	5 - 10 Years	Operator	Both

The selection of seven respondents reflects both industry and academic expertise across key domains of offshore decommissioning, including safety, waste management, subsea engineering, and project delivery. Given the specialised nature of decommissioning activities, this cross-section provides sufficient diversity to capture representative expert judgment. The group size also aligns with accepted practice in AHP studies, where panels of 5 to 10 experts are commonly considered adequate for achieving reliability while maintaining manageable consistency ratios (Saaty & Vargas, 2013).

Saaty states that consistency ratios should be less than 0.1 otherwise the responses are not consistent, although a ratio of 0.2 can be tolerable (Wedley, 1993). The initial results of the AHP analysis resulted in inadequate consistency ratios. These results justified including the calculation of the Pearson Correlation Coefficient to determine if there was any similarity in the responses.

A simple sensitivity check was also performed by varying selected pairwise comparison values within ±10 % to observe changes in criterion ranking. The overall priority order of key criteria remained consistent, indicating that the AHP results are robust to small variations in expert judgements.

Table 4-6 shows the criteria and alternatives that resulted in the highest weighting for each respondent for each objective. It can be seen that, although there are differing opinions, there is a small consensus. For the overall objective 1, to select the most important factors affecting the decommissioning process, the majority of respondents identified that an understanding of the offshore regulations as a key factor. This reflects the findings of the advocacy discussions and that of the literature review.

Table 4-6: Criteria and alternatives with the highest weightings for each respondent.

Respondent	To ensure sustainable and successful decommissioning of offshore installations	To ensure onshore legislation and regulations are understood.	To ensure offshore legislation and regulations are understood.	To reduce the length of the waste stream.	To reduce the volume of waste.
1	C2	A2	A2	A3	A7
2	C1	A1	A1	A2	A2
3	C2	A2	A1	A1	A1
4	C2	A3	A3	A3	A3
5	C3/C4	A1	A3	A1	A3/A5
6	C1/C2	A6	A6/A7	A1/A6/A7	A3/A5
7	C1/C2	A6/A5	A2/A5/A6	A2/A5/A6	A2/A5/A6

The weightings for each respondent for the level one criteria compared to the overall goal is shown in Table 4-7. It can be seen that the majority of respondents identified that criteria two – the understanding of offshore regulations is of the highest importance. The offshore industry is subject to several legislations and regulations. It is positive that the expert respondents identified that the understanding of these is of an importance. The fact that there is no consensus on what the most important factor reflects the findings of the literature review and previous research. Several key factors had been identified but there was no clear indication of which is most important.

Table 4-7: Criteria Weightings for Each Respondent (R) for the overall goal.

GOAL-To select the most important factors affecting the decommissioning process							
	R1	R2	R3	R4	R5	R6	R7
C1	0.23	0.57	0.32	0.10	0.17	0.42	0.44
C2	0.65	0.26	0.44	0.60	0.17	0.42	0.44
C3	0.04	0.13	0.11	0.15	0.33	0.08	0.06
C4	0.08	0.04	0.12	0.15	0.33	0.08	0.06

Table 4-8 shows the weightings for each respondent for each of the objectives. Again, there is no overall clear consensus on which alternative represents the key factor for each objective. The results reflect the findings of the literature review, previous expert discussions and the individual roles of each expert. For example, respondent 6 is currently involved with the supply chain and the reuse of equipment. They have identified that the alternatives associated with reusing equipment as the most important. Whereas respondent 5 who is involved with waste management, has selected the alternatives concerned with waste as being most significant.

Table 4-8: Criteria Weightings for Each Respondent (R) for each objective.

	Understanding onshore regulations						Understanding offshore regulations						Reduction in length of waste stream						Reduction in volume of waste					
	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6	R1	R2	R3	R4	R5	R6
A1	0.16	0.29	0.05	0.07	0.28	0.05	0.21	0.28	0.41	0.23	0.21	0.20	0.17	0.11	0.42	0.23	0.29	0.25	0.13	0.10	0.27	0.19	0.18	0.08
A2	0.38	0.17	0.26	0.10	0.03	0.15	0.41	0.17	0.21	0.07	0.04	0.13	0.18	0.25	0.18	0.08	0.07	0.13	0.15	0.42	0.25	0.06	0.02	0.07
A3	0.17	0.20	0.05	0.26	0.22	0.08	0.16	0.19	0.06	0.25	0.25	0.05	0.31	0.15	0.08	0.29	0.24	0.06	0.19	0.13	0.13	0.31	0.28	0.30
A4	0.08	0.12	0.14	0.17	0.08	0.03	0.04	0.12	0.11	0.18	0.06	0.03	0.03	0.09	0.07	0.16	0.04	0.02	0.01	0.15	0.07	0.14	0.04	0.03
A5	0.09	0.17	0.27	0.21	0.19	0.05	0.06	0.18	0.13	0.11	0.25	0.06	0.13	0.17	0.11	0.12	0.27	0.06	0.16	0.06	0.09	0.10	0.28	0.31
A6	0.06	0.02	0.09	0.08	0.10	0.38	0.02	0.02	0.04	0.08	0.10	0.26	0.01	0.13	0.09	0.06	0.05	0.24	0.05	0.05	0.09	0.10	0.10	0.09
A7	0.06	0.04	0.15	0.10	0.10	0.26	0.11	0.04	0.04	0.08	0.10	0.27	0.16	0.09	0.06	0.07	0.05	0.24	0.31	0.08	0.09	0.11	0.10	0.13

The criteria used in the AHP model were derived from the literature review and refined through expert discussions to ensure relevance and comparability. Each criterion represents a distinct yet interrelated aspect of sustainable decommissioning (regulatory understanding, waste-stream management, and volume reduction). The set was reviewed by two independent industry practitioners to confirm that no major dimensions were omitted before final inclusion in the AHP hierarchy.

Despite the consistency ratios of the AHP being higher than the required 0.1, the individual responses highlight the trends in what are perceived as the key factors in decommissioning process. Overall, the understanding of offshore regulations, reduction in costs, knowledge and best practice sharing and the understanding of liabilities throughout the waste stream are highlighted. This reiterates the findings of the literature review and the advocacy discussions. The complex, everchanging area of regulations and legislations are a key factor in decommissioning. Without a clear understanding of them, the risk of liability throughout the process and along the waste stream would increase. The concept of knowledge and best practice sharing has been raised in the literature review of the decommissioning closeout reports and advocacy discussions. The large number of stakeholders and ever-changing staffing of offshore installations results in loss of knowledge and also the reluctance to share amongst individual parties. It is thought that in the process of reducing costs, the decommissioning process would be carefully scrutinised and in turn, a greater understanding of the current statutory regime achieved.

The responses of each individual respondent reflect their own roles and areas of expertise. For example, the respondent with a background in waste management felt that the alternatives in the pairwise comparison questionnaire that dealt with waste management were the most important. Respondent 1, who deals with the supply chain identified that knowledge and best practice sharing were key. Despite their being consistency ratios less than 0.1, there are patterns in the responses of each respondent that were expected from the results of the literature review and the advocacy discussions with experts.

Further dissection of the individual responses identified a trend in the choice of responses. The respondents had a clear preference on what they saw as the key factors that could be linked back to their area of expertise and current roles.

4.9 AHP Summary

Despite the consistency ratios of the AHP being higher than the required 0.1, the individual responses highlight the trends in what are perceived as the key factors in decommissioning process. Overall, the understanding of offshore regulations, reduction in costs, knowledge and best practice sharing and the understanding of liabilities throughout the waste stream are highlighted. This reiterates the findings of the literature review and the advocacy discussions. The complex, everchanging area of regulations and legislations are a key factor in decommissioning. Without a clear understanding of them, the risk of liability throughout the process and along the waste stream would increase. The concept of knowledge and best practice sharing has been raised in the literature review of the decommissioning closeout reports and advocacy discussions. The large number of stakeholders and ever-changing staffing of offshore installations results in loss of knowledge and also the reluctance to share amongst individual parties. It is thought that in the process of reducing costs, the decommissioning process would be carefully scrutinised and in turn, a greater understanding of the current statutory regime achieved. Analysis of the individual responses showed clear trends linked to each respondent's area of expertise and current role

4.10 Further Work

Following on from the initial AHP analysis and the detailed look at the questionnaire responses, it became apparent that only a fraction of alternatives were being selected during the comparisons. Another questionnaire using only those alternatives is being developed and forwarded to the initial respondents for further consideration.

4.11 Pearson Correlation Coefficients

Pearson Coefficients were calculated in order to compare each respondent's opinions on each objective in the AHP analysis to determine if they are in agreement or disagreement.

4.12 Application of the Pearson Correlation Coefficient

Each of the respondents' responses to the AHP questionnaire are compared to each other in order to determine any agreements or disagreements for each objective. For example, respondent 1 is compared to respondent 2 for each of the 5 objectives. Table 4-9 shows the initial data taken from the AHP analysis for respondents 1 and 2 for objective 1. The mean values of each data set is then calculated.

Table 4-9: Initial data for respondents 1 and 2 for objective 1.

Respondent 1 x_i	Respondent 2 y_i
7.000	0.111
7.000	6.000
7.000	8.000
8.000	9.000
8.000	9.000
1.000	0.333
$\bar{x} = 6.333$	$\bar{y} = 5.407$

Using equation 1-1, the Pearson Correlation Coefficient is calculated. Table 4-10 shows the calculations for each stage.

Table 4-10: Calculations for each step of the Pearson Correlation Coefficient Equation.

$(x_i - \bar{x})$	$(y_i - \bar{y})$	$(x_i - \bar{x})^2$	$(y_i - \bar{y})^2$	$(x_i - \bar{x})\,(y_i - \bar{y})$
0.667	-5.296	0.444	28.051	-3.531
0.667	0.593	0.444	0.351	0.395
0.667	2.593	0.444	6.722	1.728
1.667	3.593	2.778	12.907	5.988
1.667	3.593	2.778	12.907	5.988
-5.333	-5.074	28.444	25.746	27.062
	Sum (Σ)	**35.333**	**86.683**	**37.630**

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

$$r = \frac{37.630}{\sqrt{35.333 \times 86.683}}$$

$$\underline{\boldsymbol{r = 0.680}} \qquad [1\text{-}2]$$

The Pearson correlation coefficient for respondents 1 and 2 for objective 1 is 0.680. This indicates a strong, positive correlation, meaning that the two respondents are in agreement that objective 1 is important with regard to decommissioning.

4.13 Results & Discussion

The results of these calculations are shown in Table 4-11 and Table 4-12.

Table 4-11: Pearson Correlation Coefficients for Each Respondent Pair

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
R1-R2	0.680	0.203	0.211	-0.220	-0.112
R1-R3	0.872	0.092	-0.115	-0.190	0.026
R1-R4	0.649	0.356	-0.032	0.236	-0.195
R1-R5	-0.965	-0.282	0.029	0.292	0.388
R1-R6	0.965	0.330	0.364	0.162	0.549
R1-R7	0.965	0.123	-0.258	-0.515	-0.410
R2-R3	0.603	-0.073	0.094	0.256	0.046
R2-R4	0.397	0.491	0.399	-0.126	-0.228
R2-R5	-0.680	0.138	0.238	0.163	-0.442
R2-R6	0.680	-0.445	-0.401	-0.443	-0.139
R2-R7	0.680	-0.117	-0.193	0.428	0.125
R3-R4	0.685	0.067	-0.206	-0.218	-0.185
R3-R5	-0.729	-0.248	-0.080	0.204	-0.042
R3-R6	0.729	0.326	0.061	0.102	-0.250
R3-R7	0.729	0.241	-0.037	0.170	0.073
R4-R5	-0.476	0.072	0.087	0.510	0.343
R4-R6	0.476	-0.116	-0.368	-0.403	-0.122
R4-R7	0.476	0.109	-0.400	-0.253	-0.324
R5-R6	-1.000	-0.374	-0.123	-0.180	0.785
R5-R7	-1.000	-0.332	0.056	-0.175	-0.078
R6-R7	1.000	0.135	-0.189	-0.183	-0.074

Table 4-12: Pearson Correlation Coefficients for Each Respondent Pair

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
R1-R2	Strong Positive	Low Positive	Low Positive	Low Negative	Low Negative
R1-R3	Strong Positive	Low Positive	Low Negative	Low Negative	Low Positive
R1-R4	Strong Positive	Medium Positive	Low Negative	Low Positive	Low Negative
R1-R5	Perfect Negative	Low Negative	Low Positive	Medium Positive	Medium Positive
R1-R6	Perfect Positive	Medium Positive	Medium Positive	Low Positive	Strong Positive
R1-R7	Perfect Positive	Low Positive	Low Negative	Strong Negative	Medium Negative
R2-R3	Strong Positive	Low Negative	Low Positive	Low Positive	Low Positive
R2-R4	Medium Positive	Medium Positive	Medium Positive	Low Negative	Low Negative
R2-R5	Strong Negative	Low Positive	Low Positive	Low Positive	Medium Negative
R2-R6	Strong Positive	Medium Negative	Medium Negative	Medium Negative	Low Negative
R2-R7	Strong Positive	Low Negative	Low Negative	Medium Positive	Low Positive
R3-R4	Strong Positive	Low Positive	Low Negative	Low Negative	Low Negative
R3-R5	Strong Negative	Low Negative	Low Negative	Low Positive	Low Positive
R3-R6	Strong Positive	Medium Positive	Low Positive	Low Positive	Low Negative
R3-R7	Strong Positive	Low Positive	Medium Negative	Low Positive	Low Positive
R4-R5	Medium Negative	Low Positive	Low Positive	Strong Positive	Medium Positive
R4-R6	Medium Positive	Low Negative	Medium Negative	Medium Negative	Low Negative
R4-R7	Medium Positive	Low Positive	Medium Negative	Low Negative	Medium Negative
R5-R6	Perfect Negative	Medium Negative	Low Negative	Low Negative	Strong Positive
R5-R7	Perfect Negative	Medium Negative	Low Positive	Low Negative	Low Negative
R6-R7	Perfect Positive	Low Positive	Low Negative	Low Negative	Low Negative

The AHP analysis resulted in varying consistency ratios. Consistency ratios that are less than 0.1 are deemed reliable. The expert respondent data that has been obtained indicated the consistency ratios varied across each objective for each respondent.

In order to determine if there was any correlation between respondents, the Pearson correlation coefficient was calculated in order to compare the pairwise comparisons between each respondent.

Objective 1: To select the most important factors affecting the decommissioning process

The results show that for objective 1, the majority of respondents were in agreement that the understanding of regulations is important, except respondent 5 who indicated the opposite. This echoes what has been identified from the literature review and also within the discussions with industry experts that sustainable and successful decommissioning of offshore installations are relevant and important.

The literature review highlighted the current importance and relevance of the decommissioning of offshore installations due to the number of installations requiring decommissioning. It is also important to obey the legislation and regulations as laid out by the UK government and internal law. During decommissioning, it is crucial to work towards net-zero targets. The advocacy discussion in section 3.1 backs up the importance of decommissioning; firstly, as the experts agreed to take part, they must feel that decommissioning is essential. Secondly, they held strong opinions on the current issues within the decommissioning sector.

The respondents are in agreement that understanding onshore and offshore regulations, reducing the waste stream and reducing the volume of waste are essential but have differing views on which factor is the most important.

They are in agreement it is important but not in agreement as to which is more important. This is due to the background of the respondents. Due to the small sample number, the results highlight their different views strongly. For example, respondent number 5 is from a waste management background so feels that waste is a higher importance in their role.

Objective 2: Understanding of onshore regulations

The results show that for objective 2, that none of the respondents are in a strong agreement or strong disagreement. There is a general medium to low agreement that this is important.

The Pearson correlation coefficient show a low to medium positive correlation whilst respondent three and five have a low to medium negative correlation. This shows that they are not all in agreement with each other.

The AHP results show that the knowledge and best practice sharing as well as the knowledge of liability are important in understanding the onshore regulations.

This makes sense as to fully understand onshore regulations with regards to decommissioning, knowledge and best practice sharing would be beneficial, as would an understanding of liability and legislative compliance. Again, the individual respondents' backgrounds are reflected in their responses.

In order to ensure compliance and maximise sustainability, it makes sense to have a good understanding of the legislations.

Objective 3: Understanding of offshore regulations

Objective 3 resulted in a mix of positive and negative low to medium correlations. This illustrates that each respondent recognises that offshore legislation and regulations are important but to differing degrees of importance. This highlights that this is still a relevant area for discussion in decommissioning.

During the advocacy discussion, the experts highlighted that a lack of understanding of legislations and regulations offshore. The Pearson correlation coefficient indicates low correlation strength. This shows it is still of importance but a detailed look at individual AHP questionnaire responses again highlight that respondents are not in total agreement as to which factor is the most important. The expert discussions highlighted the understanding of regulations as an important factor which is reflected in the Pearson correlation coefficient.

Objective 4: Reduction in length of waste stream

Objective 4, to reduce the length of the waste stream shows again, a mixture of correlations. Whilst all agreed with respondent 5, they did not necessarily agree with each other.

Responses are mixed, those with positive correlations are the top end of the low strength positive correlation, whilst the negative correlation are also top of the low strength. The differing opinion could be due to the roles of each respondent. If they completed the AHP questionnaire purely thinking about their current role, the reduction of the length of the waste stream may or may not seem important to them individually.

Again, knowledge and understanding is highlighted as being potentially important as well as reduction in costs, and identification of older equipment. This makes sense as knowledge of good practice, commonly present waste materials and machinery, would aid the reduction of the waste stream and help to reduce costs.

Objective 5: Reduction in volume of waste

Objective 5, to reduce the overall volume of waste shows that the majority of respondents do not agree on the level of importance.

4.14 Summary Pearson Coefficient Assessment

The Pearson correlation coefficient is used to determine correlations between sets of values. The calculated coefficient represents the strength of the relationship and the nature of the correlation. A value of zero indicates no correlation and a value of 1 indicates a perfect correlation.

For each objective, the respondents were compared using the Pearson correlation coefficient. The results indicated that all the respondents identify that decommissioning is important and that there are key factors involved. When combined with the results of the AHP, it is shown that the key factors for each objective are reduced to the following:

i. Reduction in costs
ii. Knowledge and best practice sharing,
iii. Liability throughout the waste stream.

This echoes what has already been identified in the literature review and the advocacy discussions. So, the findings come down to the knowledge of legislation and regulations. This underlines the need for a holistic framework that can be used throughout the decommissioning process. If a framework is developed using the knowledge and best practice of current/past stakeholders, this would aid in the understanding of legislations, regulations and liabilities which would have a knock-on effect on the cost reduction and sustainability of the decommissioning process.

It was anticipated that there would be agreement between the respondents from similar backgrounds, for example, the respondents involved in the education sector would hold similar views but this has not been the case. Each respondent has a different level of expertise which has resulted in their different opinions of importance of each factor associated with decommissioning. Although a consensus was not reached, this initial research highlights that each of the factors is still important factor of decommissioning that needs to be addressed. How this would be addressed still need to be identified and would involve a higher level of discussion and involvement from industry experts but due to the almost secretive nature of the industry and the reluctance to cooperate, this is not the case.

4.15 Concluding Remarks

This chapter presented the findings from expert discussions and confirmed the importance of stakeholder insight in identifying key decommissioning issues.

- There is a widespread lack of understanding across stakeholders regarding legal responsibilities, particularly along the waste stream.
- Poor identification of legacy materials and limited knowledge sharing continue to present operational and compliance risks.
- Although perspectives varied, experts consistently emphasised the need for clearer accountability and traceability across offshore and onshore stages.
- The key points raised directly informed the development of the AHP structure and demonstrated the value of expert opinion in shaping a robust decision-making framework.

CHAPTER 5: INITIAL BAYESIAN NETWORK MODELLING OF KEY FACTORS IN DECOMMISSIONING

5.1 Introduction

This chapter describes the development of a Bayesian Network model designed to represent the complex interactions influencing hazardous-waste management during offshore oil and gas decommissioning. The model integrates subjective data obtained from the literature review, advocacy discussions, and the Analytic Hierarchy Process to quantify relationships between the key factors identified in earlier chapters.

Offshore decommissioning involves multiple stages and stakeholders, extending from early engagement with the Department for Energy Security and Net Zero (formerly BEIS) to the final close-out report. These activities involve numerous interacting factors that affect the success and sustainability of the process. In particular, the identification of influential factors and the determination of their relative impact on waste-handling performance are critical to meeting environmental, safety, and regulatory targets.

The Bayesian Network approach enables these factors to be represented within a single probabilistic model, allowing relationships to be visualised and uncertainties to be quantified. Test cases were developed to evaluate model performance, and a sensitivity analysis was undertaken to assess the influence of each variable. The outcomes from these analyses provided the foundation for refining the structure and validating the framework developed later in this thesis.

5.2 Background

It is anticipated that a large number of offshore installations will undergo decommissioning operations over the coming years (SEPA 2022). The decommissioning process is subject to a series of legislations based on national and international requirements. Meeting these requirements and conducting decommissioning operations sustainably and safely incurs huge costs. Current UK recommendations aim to reduce the overall cost by 35% whilst still maintaining sustainable decommissioning operations (OGUK 2015).

The decommissioning process begins with discussions with BEIS and the production of a draft decommissioning plan. This is circulated to stakeholders for comment and discussion. Once this has been approved by BEIS, decommissioning can commence.

The literature review, detailed in Chapter 1, showed that key factors in the decommissioning process are:

i. A gap between the sustainability of the decommissioning of offshore installations and the management of hazardous waste materials.
ii. Loss in clarity of liability due to the changing regulations and different parties involved in the decommissioning process.
iii. A lack of knowledge sharing, trust issues, and a skills deficiency.
iv. Issues surrounding incomplete or insufficient inspection, surveys, and familiarisation visits.
v. Understanding of duty of care across the entire waste chain.
vi. Identification of hazardous waste and proper disposal procedures.

Advocacy discussions with industry experts have identified the following key points:

i. Lack of knowledge sharing across the waste stream.
ii. Lack of understanding of legislative compliance.
iii. Volumes of waste produced.
iv. Costs associated with the decommissioning process.

5.3 Sequence of Events

In order to determine the interaction of the key factors, a Bayesian Network would be developed. The BN would be based on the identified key factors and would be built using a sequence of events. This sequence of events is based on the decommissioning process timeline and the anticipated order of activities, as shown in Figure 5-1

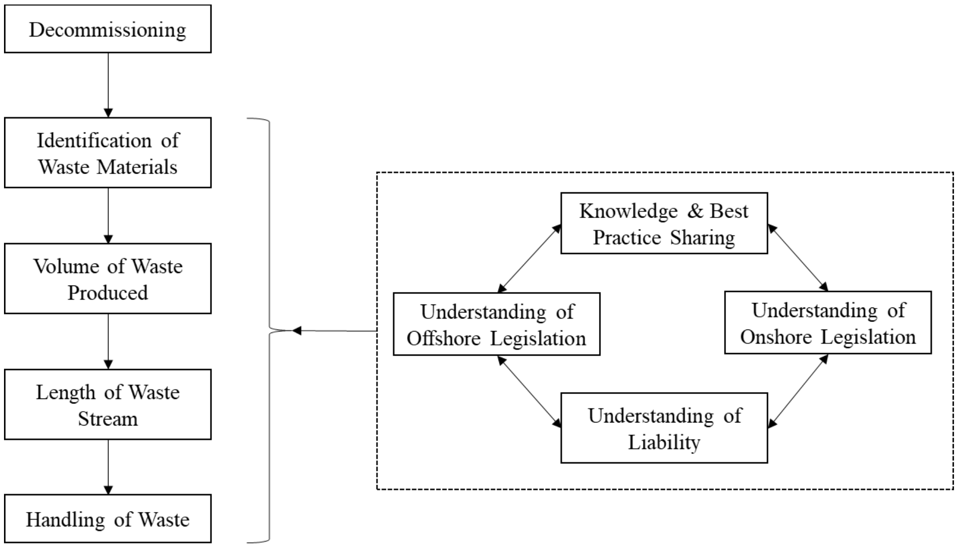


Figure 5-1: Interaction between key factors and sequence of events.

Figure 5.1 shows how the main stages of offshore decommissioning link with the regulatory, operational and knowledge-based factors identified in the earlier chapters. The layout reflects the sequence of activities that normally take place in a UKCS decommissioning project and how they influence one another.

The process begins with decommissioning, which represents the formal decision to stop production and begin project planning. This leads to the identification of waste materials, which relies on accurate surveys, testing and the review of historical inventories. The correct identification of materials at this early stage is very important because it directly affects both the volume of waste produced and the length of the waste stream. When waste materials are properly identified and separated, they can be processed or reused in the right way. This reduces the total amount of waste and the chance of materials being sent to landfill. It also shortens the waste stream because fewer treatment and transport stages are needed, which means fewer stakeholders are involved and there is less risk during handling.

The handling of waste represents the operational end of the process and includes all physical and administrative controls for managing materials safely and sustainably. Its success depends on the earlier stages, especially the identification of materials, routing and communication between stakeholders.

The second group of elements in Figure 5.1 represents the factors that influence all stages of the process. Knowledge and best practice sharing helps ensure consistency between operators, contractors and regulators. Understanding both offshore and onshore legislation helps to make sure that every stage of the process meets the required regulations. These factors directly influence the understanding of liability because limited knowledge sharing or poor understanding of legislation can lead to uncertainty over who is responsible if something goes wrong. The flow of knowledge and awareness of legal duties between stakeholders has a direct impact on accountability and overall performance.

This sequence follows typical UKCS practice. Materials are identified through surveys, testing and inventories, which then inform the estimated waste volumes and types. These factors, along with routing decisions, affect the length of the waste stream and the likelihood of escalation through environmental or liability events. The sequence provides the basis for the causal links that are used to develop the initial Bayesian Network model in the next section.

5.4 Scenarios

In order to determine a possible sequence of events, several scenarios would have to be considered. This was achieved by looking at timelines produced in decommissioning plans and closeout reports. This enabled the key events to be selected in line with the key points that had been previously identified. The potential escalation events have been identified as environmental and liability events. In the event of mishandling of hazardous waste, there is the potential for an environmental event to occur such as a spill or unauthorised discharge. If waste is not transported by approved carriers with the correct paperwork, there is the possibility of escalation to a liability event where the stakeholder is liable for not adhering to legal requirements.

5.5 Initial BN Model

5.5.1 Assumptions and Limitations.

In order to ensure the model's validity and comprehension, the underlying assumptions and limitations must be defined:

- The model has been built for the situation where an offshore installation is undergoing decommissioning within the UKCS. The installation considered is of a fixed steel jacket type. There are several different types of installations within UKCS, each one presenting its own unique decommissioning requirements. Fixed steel installations account for the majority of aging installations in UK waters hence why they have been chosen as the basis for this model.
- The model has been developed based on the key factors that have been previously identified in Chapter 2. There are many different factors in play during the

decommissioning process and their significance varies depending on the role and target of the individual expert. This model is concerned with the sustainability of the decommissioning process and the handling of generic hazardous waste materials. Its purpose is to determine the interaction of the identified key factors to enable a decommissioning framework to be developed.

- The model assumes that the decommissioning process follows a standard sequence of events as outlined in regulatory guidelines, though, in practice, variations may occur due to project-specific challenges.
- Additionally, the model was constructed using expert opinions and subjective data, which, while valuable, introduces a degree of uncertainty and potential bias. The limited availability of objective failure data and historical decommissioning records further constrained the accuracy of probability distributions within the model. Another key assumption is that all stakeholders involved in the decommissioning process have access to and correctly interpret legislative requirements, whereas, in reality, regulatory complexities often lead to varying levels of understanding.
- Finally, the model is specific to installations within the UKCS and may not fully capture the nuances of other offshore structures or international decommissioning practices. Despite these limitations, the model provides a valuable framework for assessing the interactions between key factors in offshore decommissioning and can be refined with additional data and industry feedback.

5.5.2 Nodes and Structure

The initial model is shown in Figure 5-2. This has been developed using the feedback from the advocacy discussions and the AHP questionnaires. This model aims to determine how the key factors identified by industry experts, influence the sustainable and safe handling of hazardous waste materials.

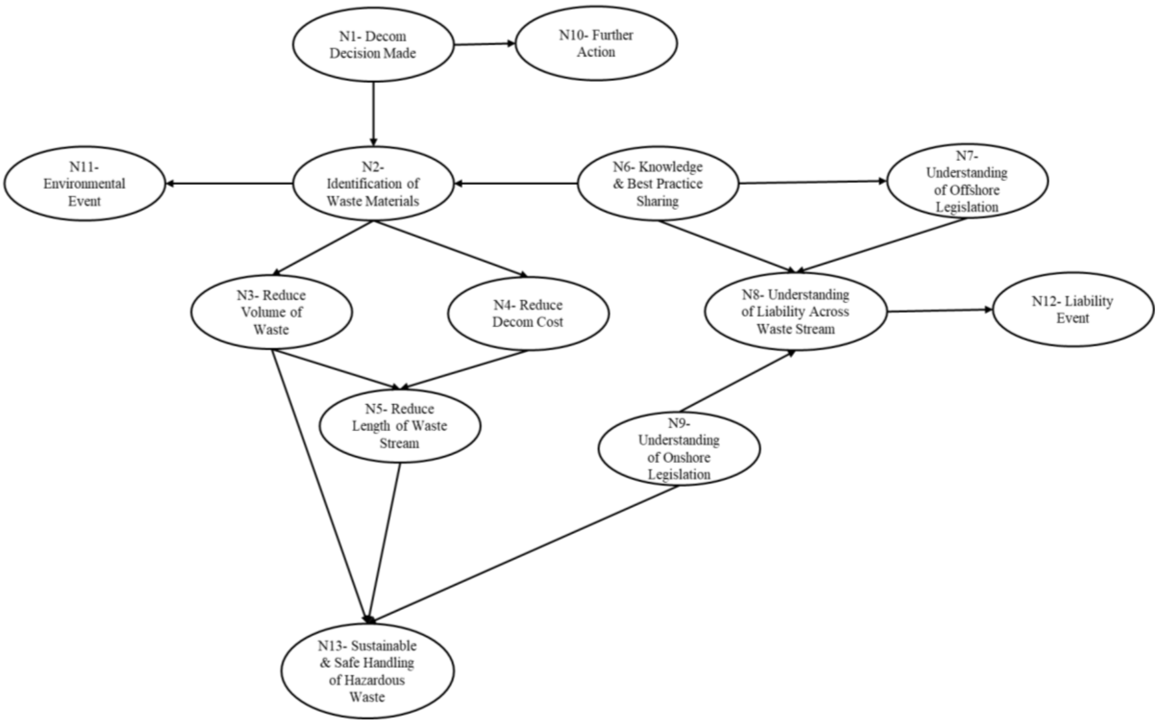


Figure 5-2: Initial BN model illustrating the key factors in the decommissioning process.

The network in Figure 5.2 represents the logical sequence of cause and effect in the decommissioning process, focused specifically on hazardous-waste management. The process begins with the decision to decommission, which acts as the initiating event. If this decision has not been made, no further decommissioning activity takes place. Once decommissioning has begun, the identification of waste materials becomes critical. Correct identification determines what happens next in the process and directly affects safety, cost and environmental outcomes. If waste materials are not correctly identified, there is an increased likelihood of an environmental event such as a spill, leak or exposure incident.

The accuracy of waste identification is influenced by the level of knowledge and best-practice sharing between stakeholders. Where knowledge on historical materials, equipment and processes is shared, the likelihood of correct identification improves. Knowledge and best-practice sharing are closely linked to understanding of offshore legislation and understanding of liability across the waste stream. These connections reflect the fact that better awareness of legal and procedural responsibilities supports safer and more compliant operations. When liability is not fully understood, there is potential for a liability event to occur, for example through incorrect documentation, unauthorised transport, or mishandling of hazardous materials.

Identification of waste materials also links to reductions in waste volume and decommissioning cost. When the type and characteristics of waste are fully understood, materials can be processed, reused or recycled appropriately, lowering both total waste volume and disposal cost. This also shortens the length of the waste stream, as fewer parties are involved in handling and transfer. All of these factors contribute to the final outcome of sustainable and safe handling of hazardous waste. The understanding of onshore legislation further influences this outcome, since materials crossing from offshore to onshore environments become subject to different regulations. Correct understanding of these requirements ensures that the waste continues to be managed safely and in compliance with statutory obligations.

The relationships between nodes therefore represent how early decisions and information quality cascade through the process, influencing later outcomes and the overall sustainability of decommissioning operations.

The individual nodes are described in the following section:

Initiating Circumstance

1. Decommissioning Decision Made [States: Yes, No] – This is the root node representing the initiating event, has a decision been made about decommissioning? The data within this node represents the initiation of the decommissioning process.

Intermediate Events

2. Identification of Waste Materials [States: Yes, No] – This chance node represents the probability of the correct identification of the waste materials present during the decommissioning process.
3. Reduce Volume of Waste [States: Yes, No] – This chance node represents the probability of the reduction of the volume of waste materials produced during the decommissioning process.
4. Reduce Decommissioning Costs [States: Yes, No] – This chance node represents the probability of the reduction in the cost of the decommissioning process.
5. Reduce Length of Waste Stream [States: Yes, No] – This chance node represents the probability of the reduction in the length of the waste stream.
6. Knowledge and Best Practice Sharing [States: Yes, No] – This chance node represents the probability of knowledge and best practice sharing occurring during the decommissioning process.
7. Understanding of Offshore Legislation [States: Yes, No] – This change node represents the probability of the understanding of offshore legislation by stakeholders involved in the decommissioning process.

8. Understanding of Liability across the Waste Stream [State: Yes, No] – This chance node represents the probability of the understanding of individual liability by stakeholders across the waste stream.
9. Understanding of Onshore Legislation [States: Yes, No] – This chance node represents the probability of understanding of onshore legislation during the decommissioning process.

Final Events

10. Further Action [States: Yes, No] – This chance node represents if further action is required.
11. Environmental Event [States: Yes, No] – This chance node represents an environmental event occurring if the waste materials have not been correctly identified.
12. Liability Event [States: Yes, No] – This chance node represents a liability event occurring if the individual liabilities during the decommissioning process are not understood.
13. Sustainable and Safe Handling of Hazardous Waste Materials [States: Yes, No] – This chance node represents the probability that the hazardous waste materials present are handled correctly and in a sustainable manner.

5.6 Data for the Initial BN Model

It's crucial to emphasise that the numerical outcomes of the model do not represent absolute values; instead, they illustrate the model's practicality. As the model receives a complete dataset for verification, it enhances confidence levels in planning and decision-making amid uncertainty. Data for the initial model was obtained from the AHP questionnaire responses. This data is limited due to the difficulty encountered in obtaining the responses, partially due to the small pool of expert respondents and also due to the lack of willing respondents. For some nodes, data is limited or not available. For cases where hard data are absent, CPTs must be completed through subjective reasoning or the application of expert judgment. Despite the limited availability of data, the model serves to demonstrate the interactions between the identified key factors.

5.7 Limitations and Assumptions

The development of the Bayesian network was based on several assumptions and limitations. The model assumes that the decommissioning process follows a standard sequence of events as outlined in regulatory guidelines, though, in practice, variations may occur due to project-specific challenges. Additionally, the model was constructed using expert opinions and subjective data, which, while valuable, introduces a degree of uncertainty and potential bias. The limited availability of objective failure data and historical decommissioning records further constrained the accuracy of probability distributions within the model. Another key assumption is that all stakeholders involved in the decommissioning process have access to and correctly interpret legislative requirements, whereas, in reality, regulatory complexities often lead to varying levels of understanding. Finally, the model is specific to installations within the UK Continental Shelf and may not fully capture the nuances of other offshore structures or international decommissioning practices. Despite these limitations, the model provides a valuable framework for assessing the interactions between key factors in offshore decommissioning and can be refined with additional data and industry feedback.

5.8 Application of Pairwise Comparison Technique and AHP

The data for the bayesian network model was obtained from a several sources as shown in Table 5-1. The AHP analysis produced a weighting for the parent nodes. These weightings were then used with symmetric method to complete the conditional probability tables.

The questionnaires and respondents were as detailed in Chapter 2. Comparison matrices were constructed from the responses in order to obtain the criteria weights and consistency ratios. The differing consistency ratios meant that aggregated responses could not be used. The responses that were within the required consistency ratio were used for the initial bayesian network in order to determine its suitability and to determine initial interactions between the identified key points.

Table 5-1: Details the number of states for each node, the number of parent nodes, and the data source.

Node Name	Data Source	Number of States	Parent Nodes
N1 – Decom decision made	Yes/No question	2 (Yes, No)	0 (None)
N2 – Identification of waste materials	Expert opinion	2 (Yes, No)	1 (N1)
N3 – Reduce volume of waste	Expert opinion	2 (Yes, No)	1 (N2)
N4 – Reduce decom cost	Expert opinion	2 (Yes, No)	1 (N2)
N5 – Reduce length of waste stream	Expert opinion	2 (Yes, No)	2 (N3, N4)
N6 – Knowledge & best practice sharing	Expert opinion	2 (Yes, No)	0 (None)
N7 – Understanding of offshore legislation	Expert opinion	2 (Yes, No)	1 (N6)
N8 – Understanding of liability across waste stream	Expert opinion	2 (Yes, No)	2 (N7, N9)
N9 – Understanding of onshore legislation	Expert opinion	2 (Yes, No)	0 (None)
N10 – Further action required	Expert opinion	2 (Yes, No)	2 (N5, N8)
N11 – Environmental event	Expert opinion	2 (Yes, No)	2 (N2, N5)
N12 – Liability event	Expert opinion	2 (Yes, No)	2 (N7, N8)
N13 – Sustainable & safe handling of hazardous waste	Expert opinion	2 (Yes, No)	3 (N10, N11, N12)

The number of states refers to the possible conditions of each node, which in this model are expressed as “Yes” or “No”. This binary structure was chosen to simplify probability assignment and maintain consistency with the qualitative expert data obtained from the AHP and interviews. Using two states also prevents the conditional probability tables from becoming excessively large, since the number of permutations increases exponentially with the number of parents and states per node (Fenton & Neil, 2013; Neapolitan, 2004). More detailed multi-state modelling (e.g. “Low/Medium/High”) would require extensive numerical data that are not currently available for offshore decommissioning. The “Parents” column shows how many nodes directly influence the selected node based on the causal relationships described earlier. For example, the “Understanding of Liability Across the Waste Stream” node has two parents because it depends on both “Understanding of Offshore Legislation” and “Knowledge and Best Practice Sharing”. The “Expert Opinion” entries indicate where subjective probability values were derived from AHP results and expert elicitation rather than empirical datasets.

5.9 Application of the Symmetric Method

The conditional probability tables were propagated using the method outlined in Chapter 2. The priorities obtained from the AHP analysis were used to construct the tables for the nodes that correspond to the hierarchical structure shown in Chapter 2. In the event that a node had more than one parent, the symmetric method and the weighted sum algorithm proposed by Das (2008) was used. In order to illustrate how this method was applied, part of the bayesian network model is considered, as shown in Figure 5-3. The notation for the nodes that will be used throughout this section are shown in Table 5-2.

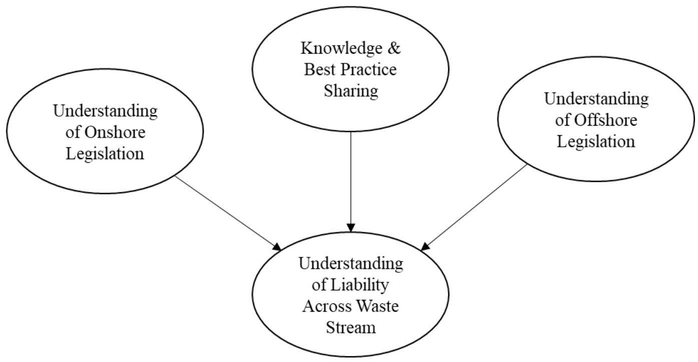


Figure 5-3: Part of initial bayesian network model used to demonstrate propagation of conditional probability tables.

Table 5-2: Notation for parent nodes.

Parent Nodes	**Notation**
Understanding of Onshore Legislation	Q
Knowledge & Best Practice Sharing	R
Understanding of Offshore Legislation	S
Child Node	
Understanding of Liability Across Waste Stream	T

The partial network shown in Figure 5-3 contains a child node that has 2^3 different parental configurations as it has three parents that each have two states (yes and no). The corresponding conditional probability table for the child node will contain 2^3 different probability distributions. This requires a great deal of effort and cooperation of the industry experts to generate. Conditional probability tables grow exponentially with the number of parent nodes, for example n parents would require 2^n distributions. The symmetric method enables the conditional probability table to be simplified.

Applying the method described in Chapter 2, the compatible parent configuration for the partial network shown in Figure 5-3 is demonstrated by Equation 5-1.

$$\begin{aligned}\{comp(Q = q^s)\} &\equiv \{comp(R = r^s)\} \equiv \{comp(S = s^s)\} \\ &\equiv \{(Q = q^s, R = r^s, S = s^s)\} \\ &where\ the\ set\ contains\ two\ states\ s = yes, no\end{aligned} \tag{5-1}$$

Hence the probability distribution over the child node T will be:

$$\begin{aligned}P(T|\{comp(Q = q^s)\}) \equiv P(T|\{comp(R = r^s)\}) \equiv P(T|\{comp(S = s^s)\}) \\ where\ the\ set\ contains\ two\ states\ s = yes, no\end{aligned} \tag{5-2}$$

The relative weights shown in Table 4-4 were assigned to the parent nodes Q, R, S respectively in order to quantify the relative strengths of their influences on the child node T.

The weights are positive and in a normalised form, e.g. $0 \leq w_i \leq 1, for\ i = 1, \ldots, n$, and $w_i + \cdots + w_n = 1$.

The industry expert provides the relative weights, $w_1 + \cdots + w_n$ and the $k_1 + \cdots + k_n$ probability distributions over the child node, of the linear type, for the parental configurations.

The algorithm shown in Equation 5-3 was used to produce the distribution for the child node T, based on Das (2008).

$$\begin{aligned}P\left(x^l \middle| y_1^{S_1}, y_2^{S_2}, \ldots., y_n^{S_n}\right) = \textstyle\sum_{j=1}^{n} w_j . P(x^l| \left\{comp\left(Y_j = y_j^{S_j}\right)\right\}) \\ where\ l = 0,1, \ldots., m\ and\ S_j = 1,2, \ldots. k_j\end{aligned} \tag{5-3}$$

This was applied to the distribution over child node T for the compatible parental configurations, shown in Table 5-3.

Table 5-3: Distribution over child node T for compatible parent configurations.

Probability Distribution over T	**s=Yes**	**s=No**
$P(T = Yes|\{Comp(W = s)\})$	0.936	0.064
$P(T = No|\{Comp(W = s)\})$	0.064	0.936

The relative weights for the parent nodes are shown in Table 5-4. These were obtained from pair-wise comparison and AHP.

Table 5-4: Relative weights of parent nodes.

Parent Nodes	Weighting Notation	Relative Weights
Understanding of Onshore Legislation (Q)	W_1	0.10
Knowledge & Best Practice Sharing (R)	W_2	0.07
Understanding of Offshore Legislation (S)	W_3	0.60

The parental distributions for the child node, Understanding of Liability Across Waste Stream, were calculated using the data from Table 4-3 and 4-4. An example of the application of the algorithm where the probability of the child event = Yes is required and the possible parental configuration, as shown in Table 5-5, is as follows.

Table 5-5: Possible parental configurations for the parent nodes.

Parent Node	State: Yes or No
Understanding of Onshore Legislation (Q)	Yes
Knowledge & Best Practice Sharing (R)	No
Understanding of Offshore Legislation (S)	Yes

The states of the parent node shown in Table 5-5, resulted in the distribution over the child node:

$$P(T = Yes|Q = Yes, R = No, S = Yes) \tag{5-4}$$

This was then applied to Equation 5-4 resulting in the following:

$$\begin{aligned} P(T = Yes|Q = Yes, R = No, S = Yes) \\ &= w_1.P(T = Yes|\{comp(Q = Yes\}) + w_2.P(T = Yes|\{comp(R = No\}) \\ &+ w_3.P(T = Yes|\{comp(S = Yes\}) \end{aligned} \tag{5-5}$$

Equation 5-5 enabled the probability of the child node, when in the state Yes is:

$$P(T = Yes|Q = Yes, R = No, S = Yes) = 0.903 \tag{5-6}$$

When the child node is in state No, according to Axiom 2, the probability is:

$$P(T = Yes|Q = Yes, R = No, S = Yes) = 0.097 \quad (5\text{-}7)$$

This process was then applied to all conditional probability tables where there are several parent nodes. Calculations were completed using Microsoft Excel to reduce time and errors. The final conditional probability tables for the initial Bayesian network model are shown in Appendix G.

5.10 Test Cases

Four different test cases were conducted to determine the influence of different parent nodes on the chosen child node.

Case One

Test Case 1 examines the scenario where node N2 (Identification of Waste Materials) is set to state “No” (100 %), representing the complete failure to correctly identify waste materials at the start of the decommissioning process. Under this condition, the probability of sustainable and safe handling of hazardous waste decreases from 10.91 % to 9.15 %, as shown in Figure 5-4. This demonstrates that if waste materials are not correctly identified, the probability of achieving sustainable and safe handling of hazardous waste materials is reduced.

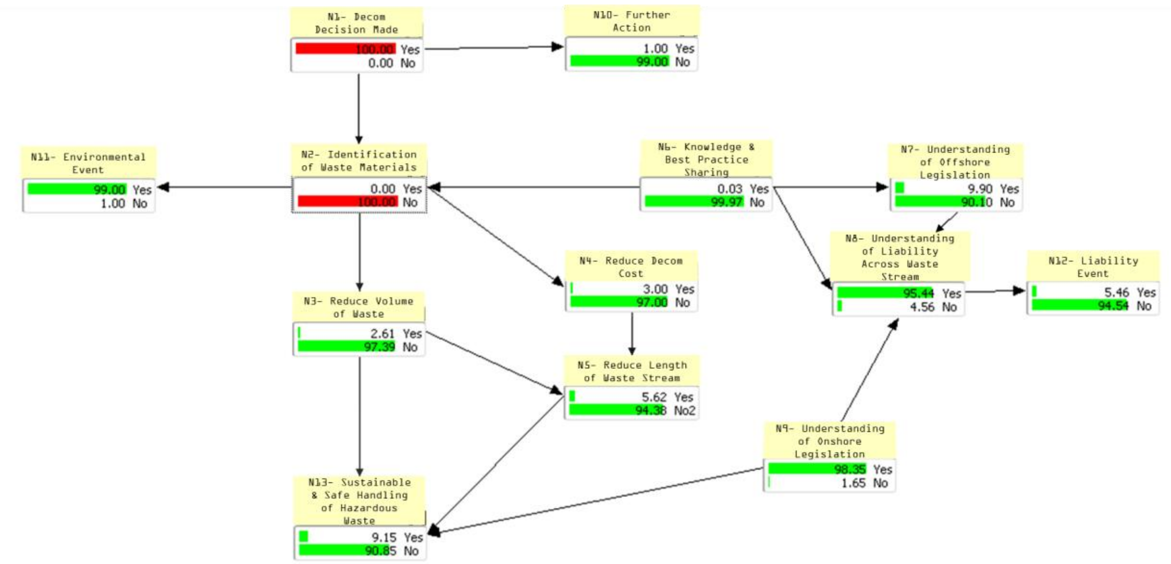


Figure 5-4: Test Case 1: Node N2 set to state “No”.

Case Two

Test Case 2 examines the scenario where node N6 is set to state "No" (100 %), representing an absence of knowledge exchange between stakeholders. The probability of sustainable and safe handling of hazardous waste decreases from 10.91 % to 9.94 %, as shown in Figure 5-5. This suggests that a lack of communication and best practice sharing among decommissioning stakeholders negatively affects the ability to manage hazardous waste safely and sustainably.

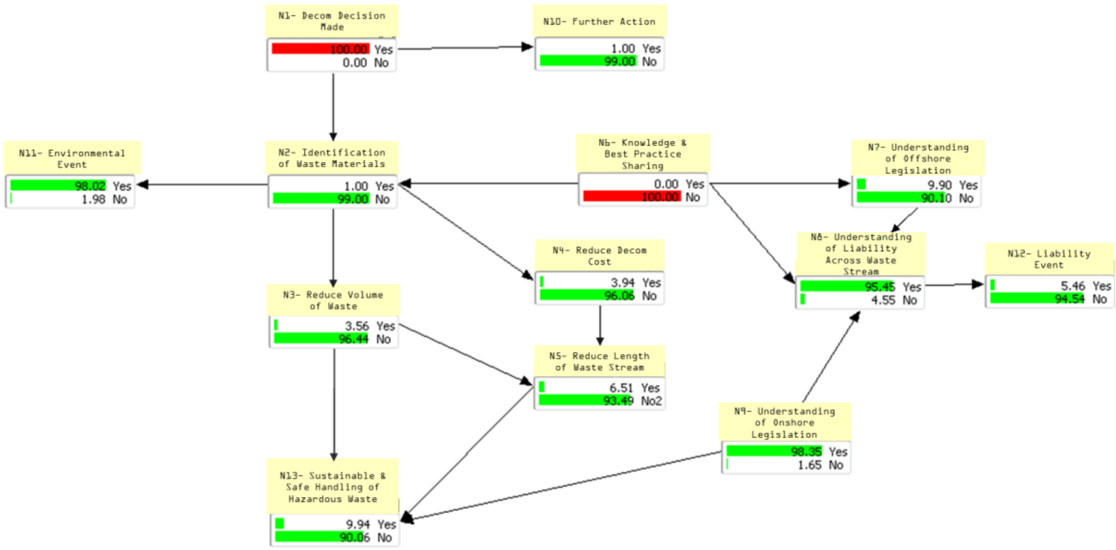


Figure 5-5: Test Case 2: Node N6 set to state "No".

Case Three

Test Case 3 examines the scenario where node N9 is set to state = "No" (0 %), representing a poor understanding of the onshore legislation that applies to decommissioning waste by the stakeholders involved. Under this condition, the probability of sustainable and safe handling of hazardous waste decreases from 6.37 % to 5.78 %, as shown in Figure 5-6. This illustrates that the understanding of onshore legislation has a direct influence on the overall sustainability and safety of waste-handling operations. If stakeholders have limited awareness of the legal requirements once waste transitions from offshore to onshore control, there is an increased risk of misclassification or mishandling. This can lead to contaminated materials being incorrectly processed, reused, or sent to landfill, raising the likelihood of non-compliance and potential accidents involving onshore personnel.

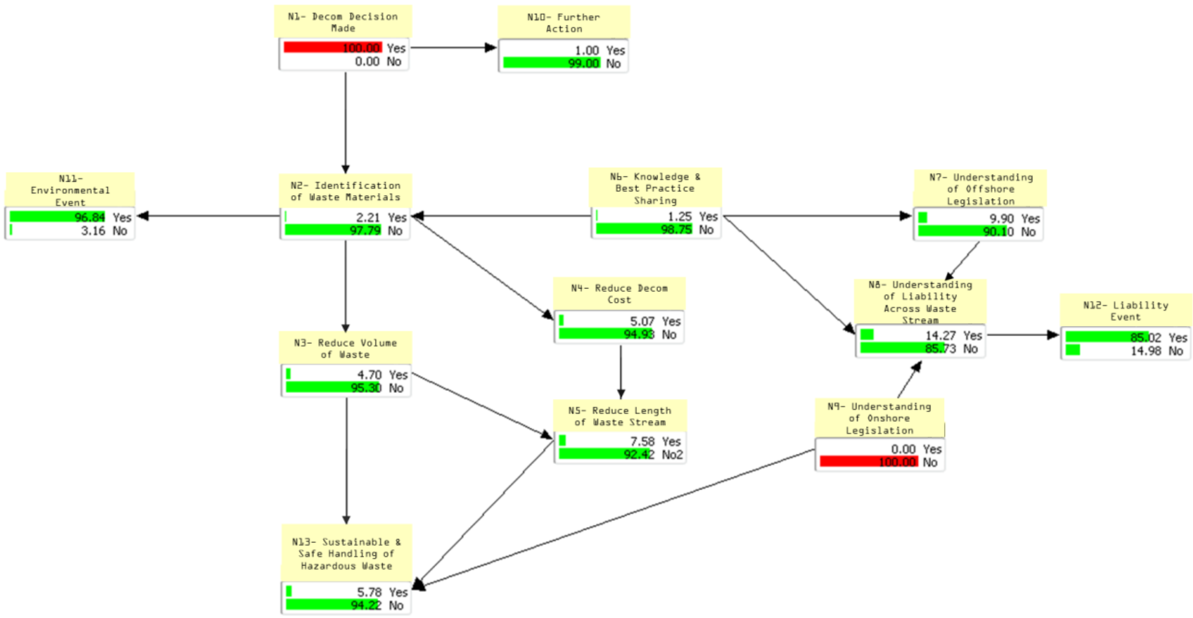


Figure 5-6: Test Case Three: Node N9 in state 100% No.

Case Four

Test Case 4 examines the combined scenario where nodes N2, N6, N8 and N9 are all set to state "No" (100 %), as shown in Figure 5-7. This represents a cumulative breakdown in identification, communication, liability understanding, and legislative awareness across the decommissioning process. Under these conditions, the probability of sustainable and safe handling of hazardous waste decreases from 6.37 % to 4.57 %. This outcome is logical, as it assumes materials are not correctly identified and there is an overall lack of understanding of the legislation and regulations that govern their handling. The result demonstrates that the model behaves as expected and highlights how failures in multiple knowledge and compliance areas can compound one another to significantly reduce sustainability performance.

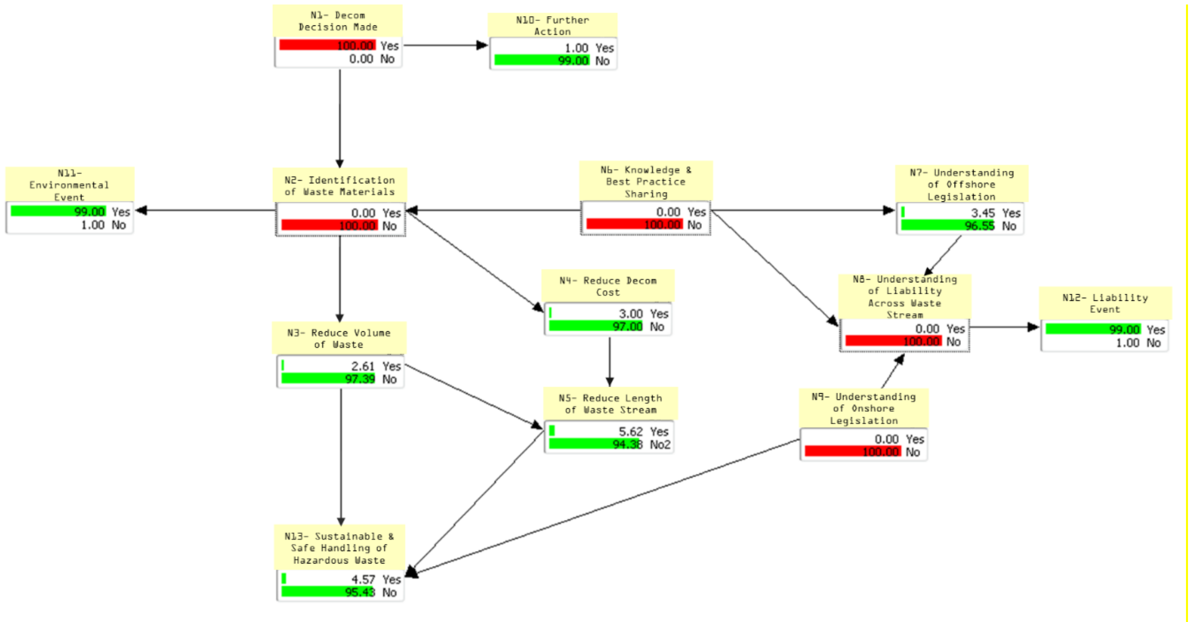


Figure 5-7: Test Case Four: Nodes N2, N6, N8 and N9 all set to state “No”.

5.11 Model Validation

The validation of the Bayesian Network model followed recognised approaches established in the literature on engineering and environmental decision systems. According to Fenton and Neil (2013) and Pitchforth and Mengersen (2013), effective BN validation requires both structural verification and behavioural testing to confirm that the model behaves logically and consistently with the real system it represents. These principles were applied here through a series of internal consistency tests based on the three axioms of Bayesian inference monotonicity, proportional influence, and relative impact (Neapolitan, 2004; Das, 2008). The framework of Weber and Simon (2016) was used to ensure that the structure and causal links of the network accurately reflected the relationships identified in earlier stages of the study. Quantitative validation was further supported by sensitivity analysis using the HUGIN software, following the procedures described by Chen and Pollino (2012), which assess the relative influence of each input node on the model’s output. Together, these steps demonstrate that the model structure, logic, and numerical behaviour are consistent with accepted Bayesian Network validation practices in engineering and environmental applications.

In order to ensure the model satisfies the axioms outlined in Chapter 2, it must undergo a series of validations. This involves examining several different combinations and scenarios to highlight any problematic areas within the model. This involved a three-axiom base verification and sensitivity analysis to be carried out.

Axiom 1: A slight increase/decrease in prior probabilities of each parent node should elicit an increase/decrease in the child node. For this axiom, the input of nodes N3, N6, N7, N9, and N10 were changed by 5%, and the effect on the output node, N9, was noted. It can be seen that this change in the input results in a change in the output node, N11, as shown in Table 5-6. This shows that the model satisfies axiom one as by altering the values of the parent nodes, the value of the child node has changed.

Table 5-6: Effect of the change of prior probabilities of the parent node on the output node.

	5% Change in Probability				
Probability of N11	**N3**	**N5**	**N6**	**N8**	**N9**
Yes	73.8%	6.45%	6.45%	6.62%	6.39%
No	26.2%	93.5%	93.5%	93.4%	93.6%

Axiom 2: The total influence magnitudes of the combination of the probability variation from (evidence) on the values should always be greater than one from the set of sub-evidence attributes. This is shown by the effect of changing the values of nodes N3, N6, N7, N9, and N10 on the output node N11.

Axiom 3: The total influence magnitudes of the combination of probability variation from the evidence should be greater than that from the set of x-y attributes. Axiom 3 requires that sub-evidence should have less influence on the values of a child node than evidence received from parent nodes. Parent nodes N11 is composed of nodes N6, N9 and N10. When evidence is entered 100% into the nodes and the states of each node are 100%, the results are shown in Figure 5-8. It can be seen that the variation satisfies axiom 3.

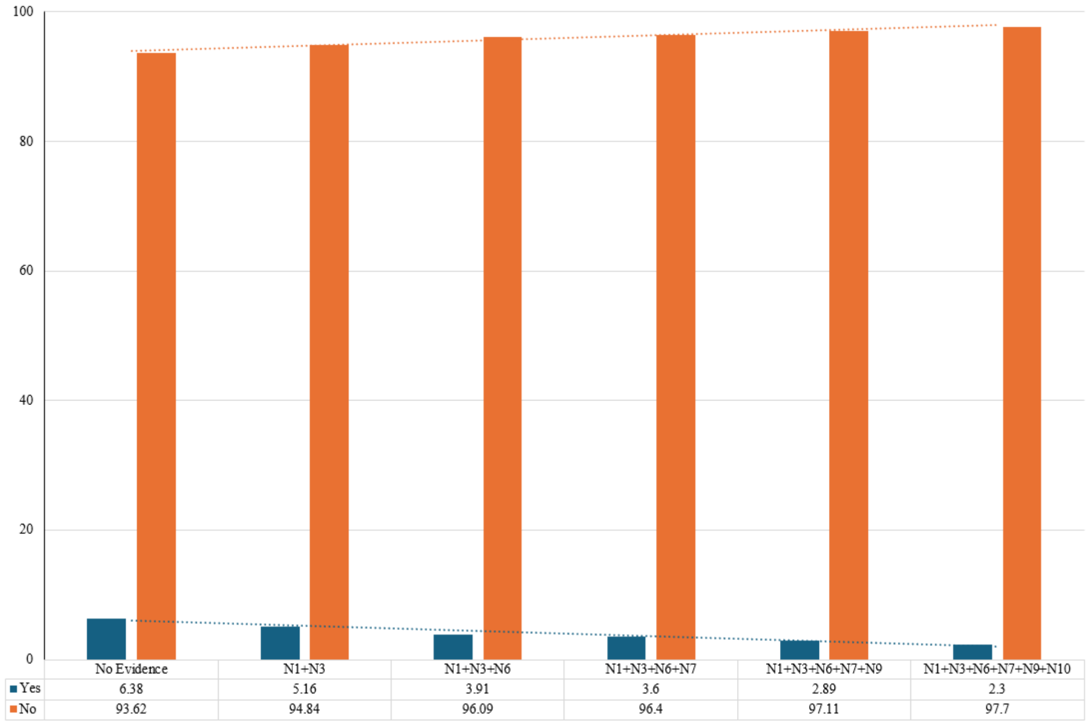


Figure 5-8: Effect of variation of child and parent nodes.

5.12 Sensitivity Analysis

The objective was to test the sensitivity of node N11 to its input nodes. The sensitivity analysis was conducted using the HUGIN sensitivity wizard. Without the use of this tool, the sensitivity analysis would involve increasing and decreasing the states of the chosen input variables by equal percentages to allow for a clear comparison with the chosen output node. The sensitivity wizard in HUGIN requires the user to select the desired focus node and the desired input node. The state for each node is selected so that it would have an impact on the focus node. HUGIN calculates a sensitivity value for the node. This value was, in turn, inputted into an Excel spreadsheet to allow the value to be increased and decreased. The results are presented in Figure 5-9. It can be seen that the graph produced is a straight line with a positive gradient. It also indicates that reduction in the length of the waste stream is most influential on the focus node N11 – sustainable and safe handling of hazardous waste. When this root node is increased by 10%, the focus node increases by 5%.

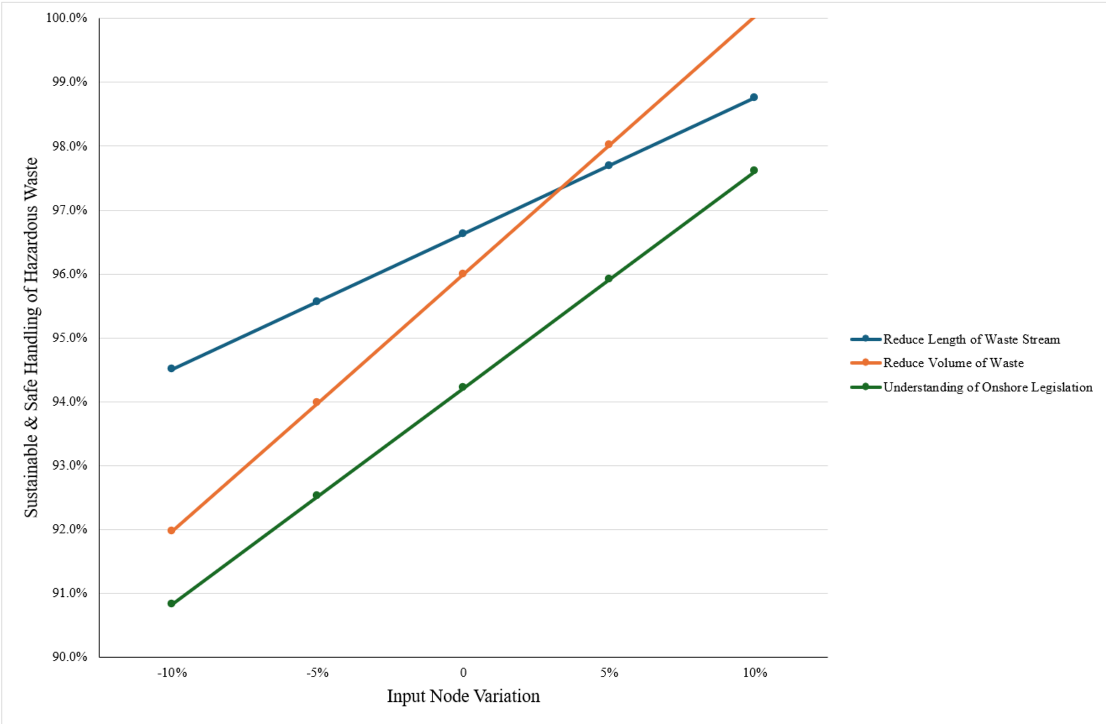


Figure 5-9: Sensitivity functions for the input nodes acting on the output node, N11 – Sustainability and Safe Handling of Hazardous Waste.

5.13 Discussion and Conclusion

The aim of this model was to determine how the key factors identified by industry experts, influence the sustainable and safe handling of hazardous waste materials. The numerical data for the model was obtained through discussions with industry experts and the distribution of pairwise comparison questionnaires. The marginalised probabilities are shown in Figure 5-10.

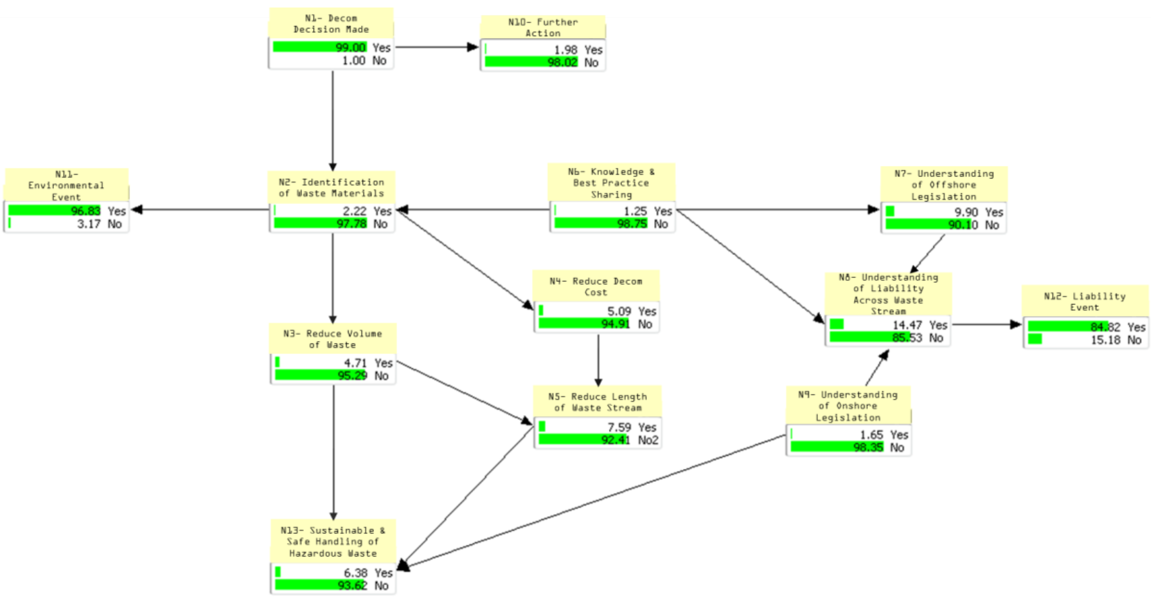


Figure 5-10: Marginalised probabilities for each node of the initial BN model.

This model was developed using feedback from industry experts and the findings of the literature review. A simple sequence of events was developed using identified key factors, which, in turn, allowed for the development of the BN model. The model was subjected to a series of test in order to validate it and determine its sensitivity. Following this, a series of test cases were modelled to determine how the nodes interacted.

The results from the test cases demonstrated that factors such as the accurate identification of waste materials, knowledge and best practice sharing, and a strong understanding of offshore and onshore legislation play a significant role in determining the sustainability of waste management practices. Sensitivity analysis further validated the model's responsiveness to changes in key input variables, confirming its reliability in assessing the influence of different factors.

Despite limitations in data availability, particularly due to the reliance on subjective expert opinions, the model provides valuable insights into how regulatory compliance, cost considerations, and knowledge-sharing dynamics impact the decommissioning process. It was found that the identification of waste materials and the knowledge and best practice sharing had a significant effect on the sustainability and safe handling of hazardous waste. This echoes the findings of the expert discussions and literature review. The findings align with previous studies and industry feedback, reinforcing the importance of a structured approach to waste management during decommissioning.

5.14 Future Work

Further refinement of the model could be achieved by integrating objective data from failure databases and historical decommissioning reports. Expanding the model to include a broader range of offshore installation types and waste management strategies would enhance its applicability. The use of real-time data collection and machine learning techniques could further improve predictive accuracy, aiding in more effective decision-making for sustainable decommissioning practices.

5.15 Concluding Remarks

The development of the initial Bayesian Network has shown the potential of combining expert knowledge with structured decision-making methods. The following points summarise the key takeaways from this chapter:

- The initial Bayesian Network demonstrated how expert judgement and literature-derived inputs can be structured into a working model.
- The model confirmed that waste identification, stakeholder understanding, and knowledge sharing are significant influencing factors.
- Sensitivity testing showed that changes in key nodes had measurable effects on downstream variables, supporting the model's structure.
- This model provided the groundwork for later refinements using updated data, expanded variable sets, and more robust validation.

CHAPTER 6: BAYESIAN NETWORK MODELLING OF KEY DECOMMISSIONING FACTORS USING OBJECTIVE DATA

6.1 Introduction

This chapter presents the development and validation of the Bayesian Network (BN) framework using objective data from publicly available sources. The structure of the network builds upon the expert-informed model described in the previous chapter and integrates data from close-out reports, PON1 notifications and Health and Safety Executive (HSE) records. The purpose of this stage is to verify the relationships identified previously and assess how empirical evidence supports or challenges subjective assumptions.

Once a decommissioning plan has been approved, production ceases and wells are sealed, allowing the removal of topsides, subsea equipment and associated infrastructure. These activities are governed by a series of legislative and regulatory requirements, and the handling of hazardous materials must comply with strict environmental standards. Equipment may require decontamination or isolation prior to removal for potential recycling or reuse. The sustainability of the overall process can be reduced if waste materials are diverted to landfill rather than reused or recycled.

The validated BN framework developed in this chapter provides a quantitative method to evaluate these sustainability outcomes and supports the integration of empirical data into the overall decision-support structure described in the following chapters.

6.2 Assumptions and Limitations

In order to ensure the model's validity and comprehension, the underlying assumptions and limitations must be defined:

- The model has been built for the situation where an offshore installation is undergoing decommissioning within the UKCS. The installation considered is of a fixed steel jacket type. There are several different types of installations within UKCS, each one presenting its own unique decommissioning requirements. Fixed steel installations account for the majority of aging installations in UK waters hence why they have been chosen as the basis for this model.

- Offshore installations contain a variety of equipment and potential waste materials that are dependent on their mode of operation, age, and location. This model outlines the basic scenario associated with hazardous waste materials as it would result in a network that would be extremely large if individual material types were considered. The data required to generate such a network would also be beyond the scope of this research project.

- Simplification of Waste Materials – Offshore installations contain a diverse range of equipment and materials, with waste characteristics varying depending on age, location, and operational history. To maintain feasibility, the model assumes a generalised waste classification system rather than analysing individual material types, as doing so would result in an overly complex network requiring extensive data that is beyond the scope of this study.
- Reliance on Publicly Available Data – The numerical data used in this model is sourced from HSE reports, OPRED close-out reports, and publicly accessible decommissioning documentation. While these provide valuable insights, not all decommissioning projects publish detailed reports, potentially limiting the dataset and introducing gaps in representation.
- Environmental and Safety Uncertainty – The model simplifies failure scenarios such as tote tank failure or containment breaches, using probabilistic estimates based on past reported incidents. However, real-world conditions may introduce unforeseen environmental and operational risks, which are not explicitly modelled in this study.
- Model Constraints – The Bayesian network is based on existing regulatory and industry practices. However, decommissioning policies, technological advancements, and market conditions are subject to change, which may alter waste management strategies, regulatory compliance mechanisms, and industry best practices in the future.

The nodes in this model were defined using binary states of “Yes” and “No”. This approach was selected because the available objective data from HSE incident reports, OPRED close-out documents, and PON1 notifications does not provide detailed quantitative or continuous information. These datasets generally record whether an event or condition has occurred rather than the extent or severity of that event. Defining the nodes in binary form therefore reflects the resolution of the available data and allows the conditional probability tables to be completed using reliable and traceable evidence.

Although multi-state or continuous nodes are conceptually capable of providing greater detail, this would require large volumes of high-quality data that are not currently available for UKCS decommissioning projects. Adopting a binary structure also maintains consistency with the expert-based model developed in the previous chapter, enabling direct comparison between subjective and objective outcomes. This simplification ensures that the model remains transparent, replicable, and suitable for progressive refinement as more detailed data becomes available in the future.

6.3 Nodes and Structure

The structure of the model, shown in Figure 6-1, was developed using the key factors identified during the AHP and built upon the structure used in Chapter 5. However, in contrast to the previous model, this network uses objective data sources instead of subjective expert opinion. The data was collected from publicly available sources, including OPRED close-out reports, historical PON1 records, and containment failure data published by the HSE.

The inclusion of this data allowed for a broader view of decommissioning activities and provided insight into operational challenges that could not be obtained through interviews alone. This approach ensured the model reflects actual events and documented observations, offering a more empirical basis for the conditional probability tables assigned to the nodes

The structure of this model follows the typical sequence of offshore decommissioning activities and the relationships between each stage. The initiating event represents the decision to begin decommissioning, which then influences the following stages such as the completion of equipment inventories, detailed surveys and the identification of materials. These stages are essential because the quality of the information gathered early in the process determines how waste is classified and managed later. Each node represents an activity or condition that can be supported by information from official records and published close-out reports.

The intermediate events represent points in the process that can be confirmed in practice. For example, if a complete inventory exists and detailed surveys have taken place, it increases the chance that all materials have been correctly identified and that the correct permits for transport and handling have been applied for. This reduces the likelihood of mishandling and liability incidents. The identification of waste materials is closely linked to the volume of waste produced and the final destination, since early and accurate identification allows more materials to be recycled or reused instead of being sent to landfill.

The nodes for materials transported in tote tanks and original containment failure represent physical or mechanical failures that could occur during transport or decontamination. These have been described as failure nodes to make it clear that they represent abnormal conditions rather than routine operations. Failures at these points can lead to environmental events or increase the chance of liability. The final event nodes, such as liability and environmental outcomes, reflect the consequences of the earlier stages. They show how the quality of planning, documentation and containment influences whether waste is handled safely and sustainably at the end of the process.

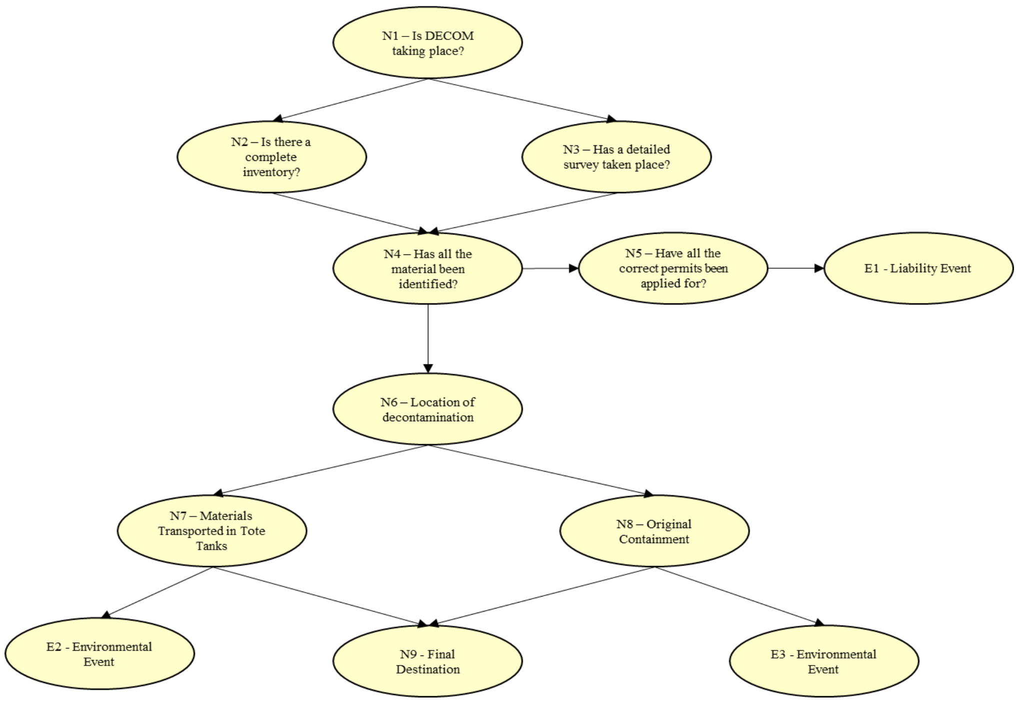


Figure 6-1: Initial Bayesian Network from objective data.

The marginalised probabilities for each node are shown in Figure 6.2.

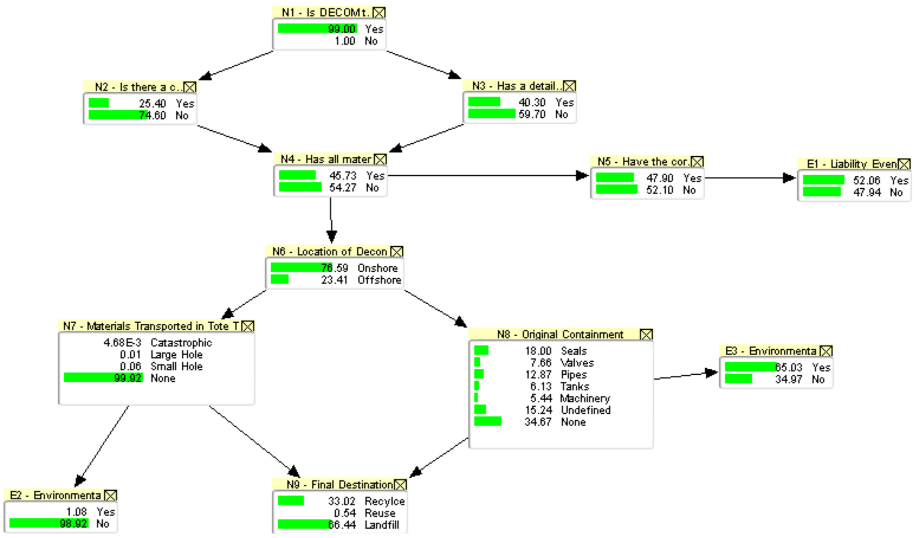


Figure 6-2: Marginalised probabilities for each node of the BN model.

The model contains twelve nodes representing key decommissioning activities and outcomes. Their descriptions and state definitions are as follows:

Initiating Event

1. Is decommissioning taking place [States: Yes, No] – This is the root node representing the initiating event, is decommissioning taking place? The data within this node represents the initiation of the decommissioning process.

Intermediate Events

2. Is there a complete inventory [States: Yes, No] – This chance node represents the probability that there is a complete inventory of equipment present.

3. Has a detailed survey taken place [States: Yes, No] – This chance node represents the probability that there is a detailed survey of hazardous materials has taken place and contains full details of materials that are present.

4. Has all the material been identified [States: Yes, No] – This chance node represents the probability that all waste materials have been correctly identified.

5 Have all the correct permits been applied for [States: Yes, No] – This chance node represents the probability that all the correct permits for transportation and handling have been applied for and obtained.

6. Location of decontamination [States: Onshore, Offshore] – This chance node represents the probability that the decontamination of equipment would take place onshore or offshore.

7. Materials transported in tote tanks [States: Catastrophic, Large Hole, Small Hole, None] – This chance node represents the probability that there is a failure in the tote tanks during the transportation of waste materials.

8. Original containment [States: Seals, Valves, Pipes, Tanks, Machinery, Undefined, None] – This chance node represents the probability that a failure in the equipment that has been isolated for transport to onshore for decontamination.

Final Events

9. Liability Event [States: Yes, No] – This chance node represents the probability is a liability event occurring.

10. Environment Event [States: Yes, No] – This chance node represents the probability that there is an environmental event occurring following a failure during transportation using tote tanks.

11. Environmental Event [States: Yes, No] – This chance node represents the probability that there is a failure in isolated equipment for decontamination onshore.

12. Final Destination [States: Recycle, Reuse, Landfill] – This chance node represents the probability that the waste material is recycled, reused, or sent to landfill.

6.4 Data Acquisition & Analysis

Table 6.1 summarises the twelve nodes used in the Bayesian Network and the data sources for each. The structure of the model, described in Section 6.3, follows the operational sequence of a typical offshore decommissioning project from initiation and material surveys through permitting, decontamination and final waste destination. Data for each node were obtained from OPRED close-out reports, HSE records and verified decommissioning documentation. This ensured that the conditional probabilities reflect real stages of the decommissioning process that can be observed and verified in practice.

Each node within the Bayesian Network represents a measurable factor or event influencing the handling and classification of hazardous waste during offshore decommissioning. The "number of states" indicates the distinct conditions that each node can occupy, such as "Yes/No" for binary decisions or multiple levels for events with variable outcomes, for example containment failure or waste destination. The "parent" column identifies the nodes that directly influence the selected node within the model. This structure allows dependencies between operational activities, failures and outcomes to be represented in a transparent way.

Table 6-1: Node details for bayesian network.

Node Name	Data Source	Number of states	Parents
N1 – Is DECOM taking place?	Yes/No Question	2 (Yes, No)	0 (None)
N2 – Is there a complete inventory?	OPRED close-out reports and technical appendices	2 (Yes, No)	1 (N1)
N3 – Has a detailed survey taken place?	HSE and OPRED reports	2 (Yes, No)	1 (N1)
N4 – Has all the material been identified?	Derived from N2 and N3 using weighted-sum algorithm	2 (Yes, No)	2 (N2, N3)
N5 – Have all the correct permits been applied for?	OPRED environmental permit data and BEIS guidance	2 (Yes, No)	1 (N4)
N6 – Location of decontamination	OPRED close-out reports	2 (Onshore, Offshore)	1 (N4)
N7 – Materials Transported in Tote Tanks	HSE report on tote tank and IBC failure rates in transport	4 (Catastrophic, Large hole, Small hole, None)	1 (N6)
N8 – Original Containment	PON1 incident data	7 (Seals, Valves, Pipes, Tanks, Machinery, Undefined, None)	1 (N6)
N9 - Final Destination	OPRED close-out reports	3 (Recycle, Reuse, Landfill)	2 (N4, N6)
E1 - Liability Event	OPRED enforcement notices and case reviews	2 (Yes, No)	1 (N5)
E2 - Environmental Event (due to tote tank failure)	HSE environmental release records	2 (Yes, No)	1 (N7)
E3 - Environmental Event (due to containment failure)	HSE and PON1 combined data	2 (Yes, No)	1 (N8)

The details of each node and their connections are shown in Table 6.1. The table identifies the data source, number of states and the parent nodes that influence each event. The data for each node was obtained from a combination of HSE incident records, OPRED close-out reports, published decommissioning documentation and verified research findings. These sources provide information on reported events, operational activities and waste management outcomes from completed decommissioning projects.

The number of states shown in the table reflects the distinct conditions that each node can take. Binary states such as “Yes” and “No” were used where only the presence or absence of an activity could be confirmed from the available data. Nodes with more than two states were used where graded conditions exist, such as the degree of containment failure or the waste destination. The use of both binary and multi-state nodes reflects the level of detail and variability in the information extracted from public datasets.

Direct data from HSE, OPRED and publicly available close-out reports was used wherever possible, while derived nodes such as N4 and N9 were informed by aggregated or combined data. The event nodes were based on documented evidence of real incidents reported through HSE environmental release records, OPRED enforcement notices, PON1 submissions and close-out reports. Incident frequencies were extracted and normalised to produce probability distributions for each node. This approach ensures that all conditional probabilities within the model are based on objective and verifiable data sources and that each node represents a measurable condition influencing the overall performance of decommissioning waste management.

The environmental event nodes were differentiated according to their underlying cause. The first represents releases associated with tote tank transport (E2), while the second captures events linked to containment failures during decontamination (E3). This distinction ensures that the Bayesian network correctly models the separate mechanisms that can lead to environmental consequences during the decommissioning process.

Case One

This test case involves the scenario where nodes N2, N3 and N4 are in a state of 100% No, as shown in Figure 2-2. In this event, the probability of waste reaching landfills increases from 66% to 71%, and the possibility of waste materials being recycled decreases from 33% to 29%. This shows that in the event there is no comprehensive inventory present, and no detailed survey has taken place, the probability of the waste materials being correctly identified decreases, and more waste would be destined for landfill. This would reduce the sustainability of the overall decommissioning project, increase the risk of mishandling, and lead to further consequences.

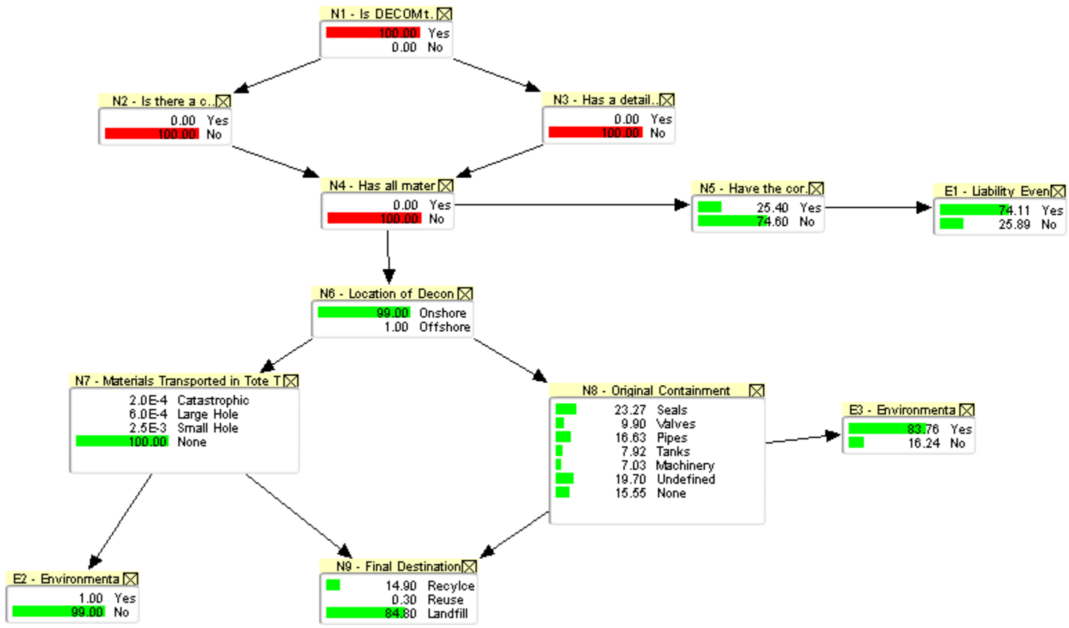


Figure 6-3: Test case 1: Nodes 2 to 4 in state 100% No.

Case Two

This test case involves the scenario where nodes N2, N3, and N4 are in a state where 100% Yes, as shown in Figure 6-4. In this scenario, all the historical information concerning equipment and materials is present, the surveys have been completed to a high standard, and the waste materials present have been correctly identified. This results in an increase in the probability of the waste materials being recycled or reused, ultimately increasing the sustainability of the overall project.

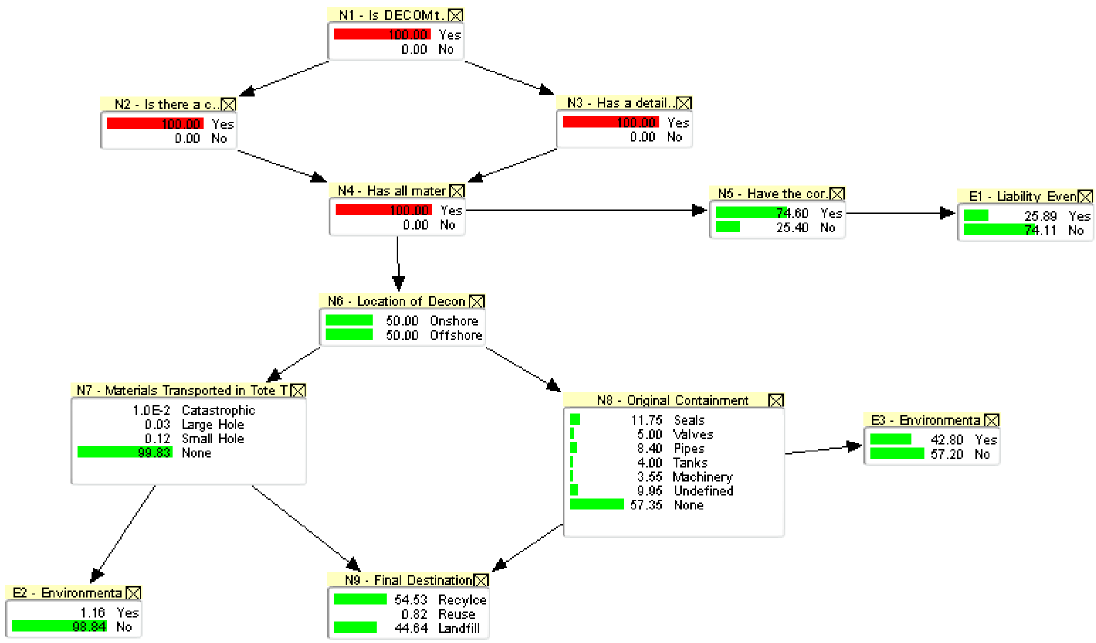


Figure 6-4: Test case 2: Nodes 1-4 in state 100% yes.

Case Three

This test case focuses on the failure of containment during transport. Node 7 is set to 100% catastrophic failure of tote tanks, as shown in Figure 6-5. The effect on the final destination node is an increase in probability of the waste materials reaching landfill of 66.4% to 99.8%.

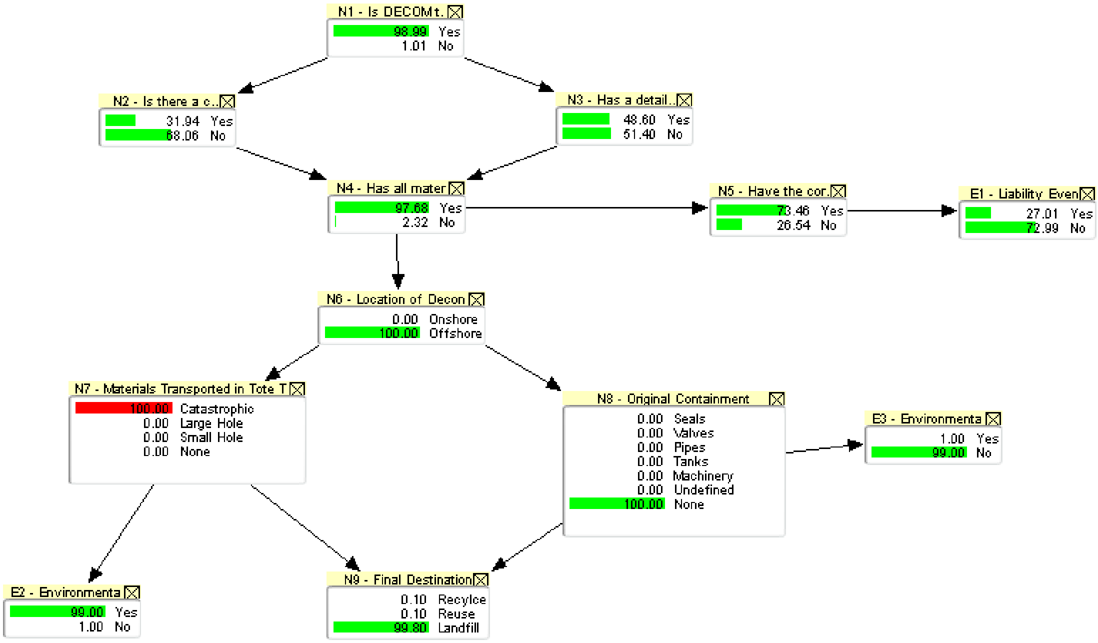


Figure 6-5: Test Case 3: Node N7, is set to 100% catastrophic failure.

6.5 Model Validation & Sensitivity Analysis

A Bayesian network must undergo validation to ensure that it satisfies the axioms (Loughney, 2018). The validation of the model provides confidence in its results. The validation process involves examining several different combinations and scenarios in order to highlight potential problematic areas. A three axiom–based verification procedure was followed, which is used for partial verification of the proposed BN model (Matellini et al, 2013). On completion, a sensitivity analysis is carried out in order to demonstrate how sensitive the network output is to the variations of its inputs.

Axiom 1: A slight increase/decrease in prior probabilities of each parent node should elicit an increase/decrease in the child node. For this axiom, the input of nodes N2-8 were changed by 5%, and the effect on the output node, N9, was noted. It can be seen that this change in the input results in a change in the output node, N9, as shown in Table 2-1. This shows that the model satisfies axiom one as by altering the values of the parent nodes, the value of the child node has changed.

Table 6-2: Effect of the change of prior probabilities of parent node on output node.

	5% change in probability					
Probability of N9	N2	N3	N4	N6	N7	N8
Recycle	32.10%	32.58%	32.34%	20.39%	33.05%	55.47%
Reuse	0.52%	0.53%	0.53%	0.37%	0.54%	0.82%
Landfill	67.37%	66.69%	67.13%	79.24%	66.42%	44.61%

Axiom 2: The total influence magnitudes of the combination of the probability variation from (evidence) on the values should always be greater than one from the set of sub-evidence attributes. This is shown by the effect of changing the values of nodes N2-8 on the output node N9.

Axiom 3: The total influence magnitudes of the combination of probability variation from the evidence should be greater than that from the set of x-y attributes. Axiom 3 requires that sub-evidence should have less influence on the values of a child node than evidence received from parent nodes. Parent nodes N7 and N8 are composed of nodes N6, N4, N3 and N2. When evidence is entered 100% into the nodes and the states of each node are 100%, the results are shown in Figure 6-6. It can be seen that the variation satisfies axiom 3.

Figure 6-6: Effect of variation of child and parent nodes.

A sensitivity analysis was carried out in order to assess the robustness of the model. It demonstrates the response of a given node to the changes in values of other input nodes

(Matellini et al, 2013) (Loughney, 2018). This demonstrates whether the model works as intended. For the sensitivity analysis, the node N9 – final destination was examined as this was an output of the model. Knowing which nodes are most influential can assist in experimentation, analysis and further development of the model. Nodes which are not important could subsequently be discarded or replaced. The objective was to test the sensitivity of node N9 to its input nodes. The sensitivity analysis was conducted using the HUGIN sensitivity wizard. Without the use of this tool, the sensitivity analysis would involve increasing and decreasing the states of the chosen input variables by equal percentages to allow for a clear comparison with the chosen output node. The sensitivity wizard in HUGIN requires the user to select the desired focus node and the desired input node. The state for each node is selected so that it would have an impact on the focus node. HUGIN calculates a sensitivity value for the node. This value was, in turn, inputted into an Excel spreadsheet to allow the value to be increased and decreased. The results are presented in

Figure 6-7. It can be seen that the graph produced is a straight line with a positive gradient. It also indicates that tote tank failure is most influential on the focus node N9 – final destination. When this root node is increased by 5%, the focus node increases by 2%.

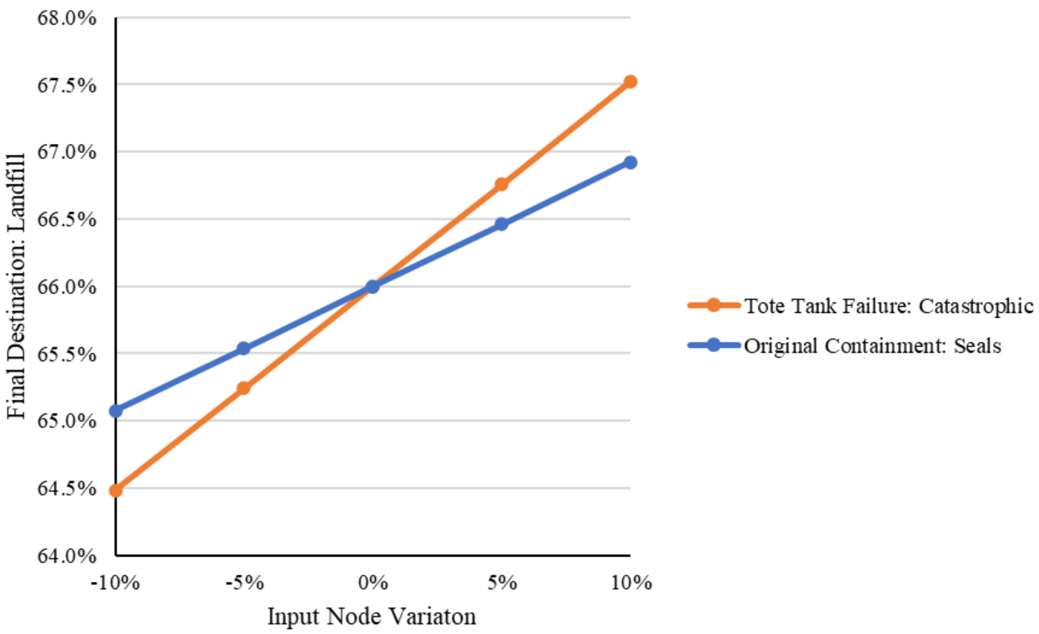


Figure 6-7: Sensitivity functions for the input nodes acting on the output node, N9 – final destination.

6.6 Results & Discussion

The focus of the model is to determine the interaction between the critical factors identified through expert discussions and AHP analysis completed as previous research by the author (Ford et al, 2023). The numerical data has been obtained from a combination of these analyses and publicly available data from the HSE and OPRED close-out reports. Three different test cases were analysed to determine the influence of different parent nodes on a chosen child node.

The Bayesian network model provided a structured approach to evaluating the interaction of key decommissioning factors, particularly in relation to hazardous waste identification, transport, and final disposal outcomes. By incorporating objective data from public sources alongside expert-driven inputs, the model offers insights into how various factors influence the sustainability of decommissioning practices within the UKCS.

The results highlight the importance of early-stage decommissioning planning, particularly in terms of survey completeness, inventory management, and permitting processes. The test cases conducted provide a clear understanding of how different factors interact and affect waste management outcomes. This discussion examines each test case in detail, analysing the causal relationships, implications, and potential mitigation strategies for improving decommissioning sustainability.

The first two test cases focus on the impact of inventory completeness and material identification on the final destination of hazardous waste materials.

Test Case 1 showed that when no complete inventory is present, and no detailed material survey has been conducted, the probability of waste reaching landfill increases from 66% to 71%, while the likelihood of recycling decreases from 33% to 29%. This demonstrates that a lack of historical records and inadequate surveys lead to misclassification of hazardous materials, which in turn affects waste handling decisions. The increased landfill rate suggests that materials with potential for recycling or reuse are instead classified as general waste, leading to a loss of valuable resources and a reduction in the sustainability of the decommissioning project.

Test Case 2 demonstrated that where all historical information is available, surveys are completed to a high standard, and waste materials are properly identified, the probability of materials being recycled or reused increases significantly. This underscores the importance of early-stage planning and comprehensive documentation in ensuring that hazardous waste is correctly classified and processed according to best environmental practices.

These findings align with existing literature, which suggests that incomplete waste inventories and knowledge gaps in hazardous material classification are common challenges in offshore decommissioning. Addressing these issues requires greater knowledge sharing, improved record-keeping practices, and investment in surveys.

Test Case 3 scenario showed that the failure of tote tanks during transport results in a sharp increase in the probability of waste being sent to landfill, rising from 66.4% to 99.8%. This is due to contaminated or damaged materials being deemed unsuitable for recycling or reuse, leading to their classification as hazardous waste requiring disposal. The environmental risk associated with tote tank failure is significant, as spills can result in soil and water contamination, potential regulatory penalties, and increased liability for operators.

Containment integrity during transport is a critical factor in waste management decisions. Failure of storage or transport systems can render potentially reusable materials non-compliant for recycling, leading to increased landfill rates and higher decommissioning costs. Environmental and liability risks are heightened when hazardous materials are not securely contained, necessitating stricter monitoring and enforcement of transport regulations. Ensuring safe and compliant transport of hazardous materials is critical to minimising environmental impact and improving waste management efficiency in offshore decommissioning. Test Case 3 focused on the consequences of containment failures during the transport of hazardous materials from offshore installations to onshore decontamination facilities.

6.7 Summary

This chapter has demonstrated how a Bayesian network model can be applied to offshore decommissioning, using publicly available data, to evaluate the interaction of key decommissioning factors. The findings indicate that the identification and classification of hazardous waste materials play a critical role in determining whether materials are recycled, reused, or sent to landfill. The model also highlights the influence of historical documentation, survey quality, and permitting processes on the final waste destination.

The results of the test cases reinforce the importance of maintaining accurate equipment inventories and conducting detailed surveys. When historical records and material assessments are incomplete, the probability of waste materials reaching landfill increases, reducing the sustainability of the decommissioning process. Additionally, failures in containment during transport were found to have a significant impact on environmental and liability risks, further underscoring the importance of safe handling and compliance with transportation regulations

The Bayesian network shows that the final destination of hazardous waste materials is ultimately influenced by their identification. This is dependent on the historical information available and the quality of the survey and testing during the initial decommissioning process. It follows that if hazardous waste materials are incorrectly identified or their presence unknown, they may eventually end up in landfill instead of recycling or reuse. It also increases the risk of environmental or personnel accidents when the material reaches the onshore processing site.

In conjunction with the findings of the previous research, which highlighted the issues surrounding the understanding of legislation, lack of knowledge sharing and the emphasis on reducing costs, this highlights the current issues with decommissioning occurring in the UKCS. Despite stringent legislation and regulations, there is still uncertainty in their understanding.

This discussion has provided a detailed examination of the Bayesian network model results, demonstrating how key decommissioning factors influence waste classification, transport safety, and sustainability outcomes. The findings reinforce the need for comprehensive survey procedures, stringent transport safety measures, and enhanced regulatory compliance frameworks to ensure that offshore decommissioning aligns with best environmental practices.

The findings of this chapter reinforce several key considerations for improving offshore decommissioning sustainability and regulatory compliance:

i. The completeness of material inventories and survey data directly impacts waste classification and disposal outcomes.
ii. Failures in transport containment systems increase the risk of landfill disposal, environmental incidents, and regulatory non-compliance.
iii. A structured approach to decommissioning planning, including early-stage assessments and robust transport safety measures, can significantly improve sustainability outcomes.
iv. Improved data collection, digital record-keeping, and knowledge sharing among stakeholders are critical for ensuring compliance with regulatory requirements and best practices.

The study underscores the need for enhanced industry collaboration to develop standardized waste tracking systems, optimise transport safety protocols, and ensure that sustainability objectives are met in offshore decommissioning projects.

6.8 Concluding Remarks

The objective-data-based Bayesian Network has strengthened the findings of the initial model and allowed for improved validation. The following points summarise the key outcomes of this chapter:

- The inclusion of objective data provided improved granularity to the risk relationships, particularly regarding containment failure and reporting inconsistencies.
- The model reinforced the importance of accurate waste identification and thorough site surveys prior to dismantling.
- Data limitations still exist across several sources, but their integration proved valuable in supporting expert-driven assumptions.

CHAPTER 7: DEVELOPMENT OF A BAYESIAN NETWORK USING COMBINED DATA FOR THE HANDLING OF HAZARDOUS WASTE MATERIALS.

7.1 Introduction

This chapter presents the development of an integrated Bayesian Network (BN) model created by combining the two previous networks described in Chapters 4 and 5. The purpose of this model is to explore how the integration of subjective and objective data can strengthen the overall robustness of the analysis and improve understanding of the interactions between the key factors influencing hazardous-waste management during offshore decommissioning.

The combined network incorporates relationships derived from expert input, literature findings, and empirical data from decommissioning programmes and close-out reports. This merged structure allows both qualitative and quantitative evidence to be represented within a single probabilistic framework. The model was verified through sensitivity analysis and a series of test cases to ensure consistency and reliability.

The results of this chapter form the basis for the final decision-support framework presented in Chapter 8, providing a more comprehensive representation of the uncertainties and dependencies that affect sustainable offshore decommissioning outcomes.

7.2 Network Development

In order to determine the interaction of key factors, a sequence of events would need to be established. The sequence of events would be the same as that developed in Chapter 4. The handling of hazardous waste materials would be initiated during the decommissioning process; hence the sequence of events would start with the commencement of decommissioning. The identification of the waste materials would influence the volume of waste produced, the length of the waste stream and, ultimately the handling of the waste materials. The process is also influenced by the knowledge and understanding of the offshore and onshore legislation.

The networks developed in Chapters 4 and 5 were combined to produce a new network. Figure 7-1 shows the new, combined network indicating the nodes that are common to all networks and those that are from individual networks.

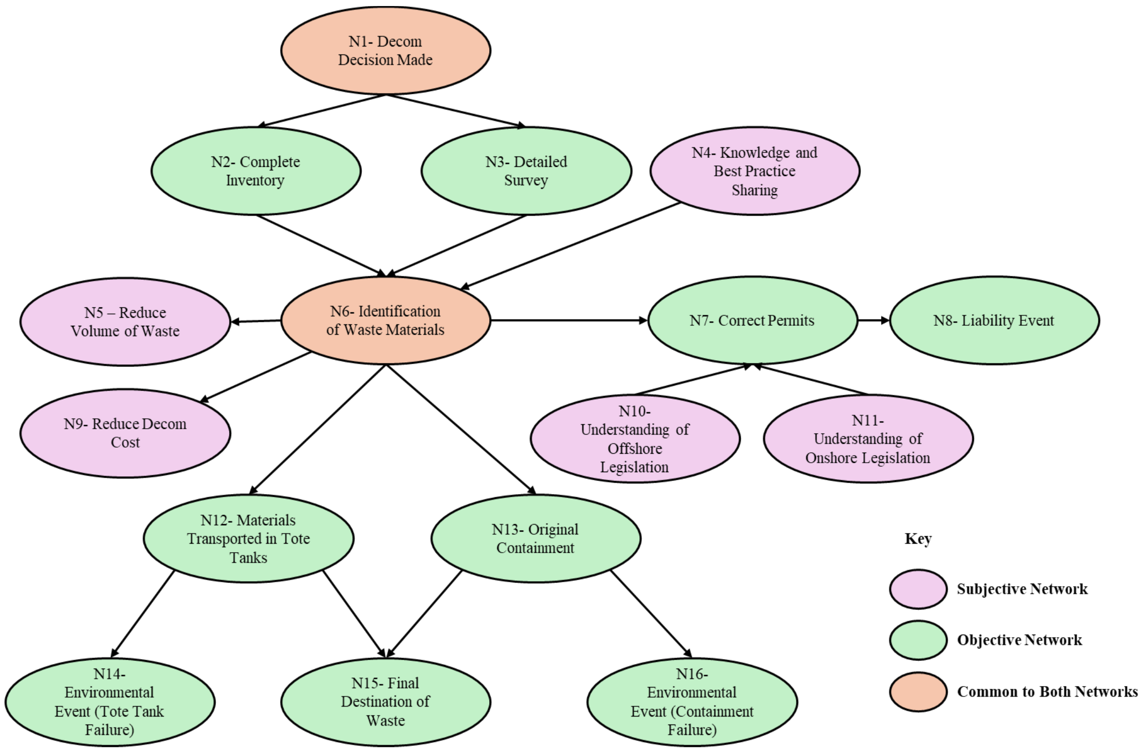


Figure 7-1: Bayesian network developed from previous networks.

The initiating event node, is decommissioning taking place, is common to the previous networks as this is an established starting point for the overall process and defines whether any further activity occurs. If no decommissioning is taking place, then no additional waste management actions are required. The node representing the identification of waste materials is also common to the previous network models as it is a key stage in the handling of hazardous waste. The identification of materials present directly influences the overall cost, volume and final destination of the waste. If the materials have been correctly identified, they can be processed accordingly, reducing the risk of inappropriate disposal and increasing the potential for reuse or recycling.

The intermediate event nodes were selected from the previous models based on their influence on the probability of the materials being correctly identified. Materials are identified through surveys, testing and historical inventories, supported by the knowledge of the decommissioning process and of individual installations held by experienced stakeholders. The understanding of both offshore and onshore legislation was identified as a key factor from the literature review and expert discussions and therefore included in the combined model. These nodes are linked to the node concerned with the correct permits for the transfer and handling of waste materials, as gaps in legislative understanding often result in compliance or liability issues. The nodes related to reducing cost and waste volume were also included, reflecting both the findings from expert discussions and the current UK Government objective to reduce decommissioning costs by 35%. These nodes influence decisions relating to recycling, reuse and waste minimisation and therefore have a direct impact on sustainability outcomes.

The final group of nodes relates to the physical transport and containment of the waste materials. The method of transport depends on where decontamination takes place, either offshore or onshore, and this in turn affects the likelihood of containment or tote tank failure. These nodes have been retained because they represent real points of failure that can lead to environmental incidents. Separate environmental event nodes were included to distinguish between incidents caused by tote tank failures and those resulting from containment failures, as these are reported and managed differently in practice. The liability event node was retained to represent the risk of non-compliance or regulatory breach, while the final destination node acts as the sustainability outcome for the model, identifying whether waste is recycled, reused or sent to landfill. Nodes that duplicated information or had minimal influence, such as further action or reduction in waste stream length, were removed. The remaining nodes therefore represent the most significant causal factors identified through previous analysis, literature and expert evidence, ensuring that the combined model is both focused and aligned with the aim of improving the sustainable management of hazardous waste during offshore decommissioning.

7.3 Model Assumptions & Limitations

In order to ensure the validity and comprehension of the model, the underlying assumptions and limitations are defined:

- The model has been developed for the instance an offshore oil and gas installation is undergoing decommissioning within the UKCS. While the general structure of the model may be applicable to other regions, the legislative, logistical, and operational conditions outside the UKCS may introduce additional variables that have not been considered in this model.
- The model has been developed based on the key factors identified in Chapter 1 and 3 as well as the models previously developed in Chapters 4 and 4.
- The model is concerned with the handling of generic hazardous waste materials. Specific hazardous materials such as NORM and LSA are not spotlighted as this

would increase the number of nodes, the size of the conditional probability tables and the requirement for specific data that is not readily available. It is the purpose of the network to influence the development of a framework that would aid the decommissioning process.

- The model is based on a combination of expert opinions, literature review findings, and publicly available close-out reports. Some conditional probability tables had missing data, requiring completion using established probabilistic methods such as the weighted sum algorithm. While these methods provide reasonable estimations, the lack of comprehensive real-world data limits the model's precision.
- While the model includes transport-related failure nodes (such as tote tank failures), it does not account for all potential failure mechanisms, including human error, weather-related incidents, or mechanical malfunctions. A more detailed analysis could refine these risk assessments.

7.4 Network Details

The final combined network model is shown in Figure 7.1. The network consists of sixteen nodes that integrate the subjective expert-based relationships established in Chapter 5 with the objective data-driven structure developed in Chapter 6. The model represents the combined framework for assessing how operational, regulatory, and environmental factors influence the sustainable management of hazardous waste during offshore decommissioning. The individual nodes are described in the following section. The network includes initiating, intermediate, and final event nodes, integrating both objective data and inferred relationships identified from previous models and public datasets.

Initiating Circumstance

1. Decommissioning Decision Made [States: Yes, No] – This is the root node representing the initiating event, confirming whether decommissioning activities are taking place. The data within this node represents the initiation of the overall decommissioning process.

Intermediate Events

2. Complete Inventory [States: Yes, No] – This chance node represents the probability that a full and accurate materials inventory has been produced as part of the decommissioning plan.

3. Detailed Survey Completed [States: Yes, No] – This chance node represents the probability that a detailed survey of hazardous materials has been conducted and that the findings are complete.
4. Knowledge and Best Practice Sharing [States: Yes, No] – This chance node represents the probability that knowledge and best practices are effectively shared among the stakeholders involved.
5. Reduce Volume of Waste [States: Yes, No] – This chance node represents the probability that the total waste volume generated during decommissioning can be reduced through recycling, reuse, or waste minimisation strategies.
6. Identification of Waste Materials [States: Yes, No] – This chance node represents the probability that all waste materials are correctly identified before handling or removal, based on survey and inventory completeness.
7. Correct Permits [States: Yes, No] – This chance node represents the probability that all required permits for waste handling, transport, and disposal are correctly obtained.
8. Reduce Decommissioning Cost [States: Yes, No] – This chance node represents the probability that cost-saving measures are achieved without compromising safety or environmental performance.
9. Understanding of Offshore Legislation [States: Yes, No] – This chance node represents the probability that stakeholders have an accurate understanding of the legislation and regulations applying offshore.
10. Understanding of Onshore Legislation [States: Yes, No] – This chance node represents the probability that stakeholders understand the regulations governing onshore waste handling and processing.
11. Materials Transported in Tote Tanks [States: Catastrophic, Large Hole, Small Hole, None] – This chance node represents the probability of a containment failure in tote tanks during transport of hazardous materials.
12. Original Containment [States: Seals, Valves, Pipes, Tanks, Machinery, Undefined, None] – This chance node represents the probability of failure in the original containment of equipment before or during transport.

Final Events

13. Liability Event [States: Yes, No] – This chance node represents a liability event occurring if permits are incomplete, incorrectly issued, or if responsibility for compliance is unclear.

14. Environmental Event (Tote Tank Failure) [States: Yes, No] – This chance node represents an environmental event occurring due to the failure of tote tanks during hazardous waste transport.
15. Environmental Event (Containment Failure) [States: Yes, No] – This chance node represents an environmental event occurring due to the failure of original containment during transport or decontamination.
16. Final Destination [States: Recycle, Reuse, Landfill] – This chance node represents the probability that the waste material is recycled, reused, or sent to landfill based on the preceding conditions.

7.5 Data for Combined Bayesian Network

The data for the model have been obtained from a variety of sources, as shown in Table 7-1. For some nodes, the conditional probability tables were incomplete so were populated using the method outlined in Chapter 2.

Table 7-1: Node details for bayesian network.

Node Name	Data Source	Number of States	Parent Nodes
N1 – Decom Decision Made	Yes/No Question	2 (Yes, No)	0 (None)
N2 – Complete Inventory	OPRED close-out reports and technical appendices	2 (Yes, No)	1 (N1)
N3 – Detailed Survey	HSE and OPRED reports	2 (Yes, No)	1 (N1)
N4 – Knowledge and Best Practice Sharing	Expert opinion and literature findings	2 (Yes, No)	1 (N3)
N5 – Reduce Volume of Waste	Expert opinion supported by close-out data	2 (Yes, No)	1 (N6)
N6 – Identification of Waste Materials	Derived from AHP and expert feedback (Ch. 5 & 6 integration)	2 (Yes, No)	2 (N2, N3)
N7 – Correct Permits	OPRED permit records and BEIS guidance	2 (Yes, No)	1 (N6)
N8 – Liability Event	Inferred from incident trends and compliance reports (OPRED, BEIS)	2 (Yes, No)	1 (N7)
N9 – Reduce Decom Cost	Expert opinion and historical project data	2 (Yes, No)	1 (N6)
N10 – Understanding of Offshore Legislation	Expert opinion and literature review	2 (Yes, No)	1 (N7)
N11 – Understanding of Onshore Legislation	Expert opinion and OPRED compliance data	2 (Yes, No)	1 (N10)

Node Name	Data Source	Number of States	Parent Nodes
N12 – Materials Transported in Tote Tanks	HSE tote tank failure data and incident records	4 (Catastrophic, Large Hole, Small Hole, None)	1 (N6)
N13 – Original Containment	PON1 incident data and close-out reports	7 (Seals, Valves, Pipes, Tanks, Machinery, Undefined, None)	1 (N6)
N14 – Environmental Event (Tote Tank Failure)	Inferred from reported tote tank failure patterns (HSE data)	2 (Yes, No)	1 (N12)
N15 – Final Destination of Waste	OPRED close-out reports	3 (Recycle, Reuse, Landfill)	2 (N6, N13)
N16 – Environmental Event (Containment Failure)	Inferred from historical containment incident trends (PON1, HSE)	2 (Yes, No)	1 (N13)

The data shown in Table 7.1 combine both objective and inferred sources to form a representative model of decommissioning waste management. The environmental and liability event nodes were informed by patterns observed in incident and compliance records rather than by direct numerical datasets. Where published numerical data were available, such as tote tank failures and containment breaches, these were used directly to inform the conditional probabilities. In cases where detailed data were not available, such as for liability and environmental events, the probabilities were determined using logical inference based on engineering judgement and the causal relationships observed in incident reporting and operational practice. For example, a greater level of containment or transport failure was considered to increase the likelihood of an environmental event, while missing permits or poor legislative understanding increased the likelihood of a liability event. This ensured that all relationships within the network were realistic and consistent with established decommissioning behaviour. This approach follows the same principles adopted in previous engineering Bayesian network studies (Loughney, 2017; Matellini et al., 2013), where conditional probabilities are derived through logical inference when full empirical datasets are unavailable. The purpose of this approach was to enable the network to demonstrate correct cause-and-effect behaviour when evidence was entered and propagated through the model.

7.6 Test Cases

Validation follows established Bayesian-network practice used in engineering and environmental risk studies. The process focuses on two aspects: that the network structure reflects the actual sequence of decommissioning activities, and that the numerical behaviour remains logical when evidence is entered and propagated. This approach follows published guidance on BN verification and validation (Fenton & Neil 2013; Pitchforth & Mengersen 2013; Neapolitan 2004; Weber & Simon 2016; Chen & Pollino 2012; Matellini et al. 2013). In line with these sources, the model was tested along its main causal pathway and through targeted adjustments of key parent nodes. Sensitivity analysis was used to confirm that the most influential inputs behave in a manner consistent with engineering reasoning and observed decommissioning practice. Test cases were conducted to determine the influence of the parent nodes on chosen child nodes. The initial prior probabilities are shown in Figure 7-2.

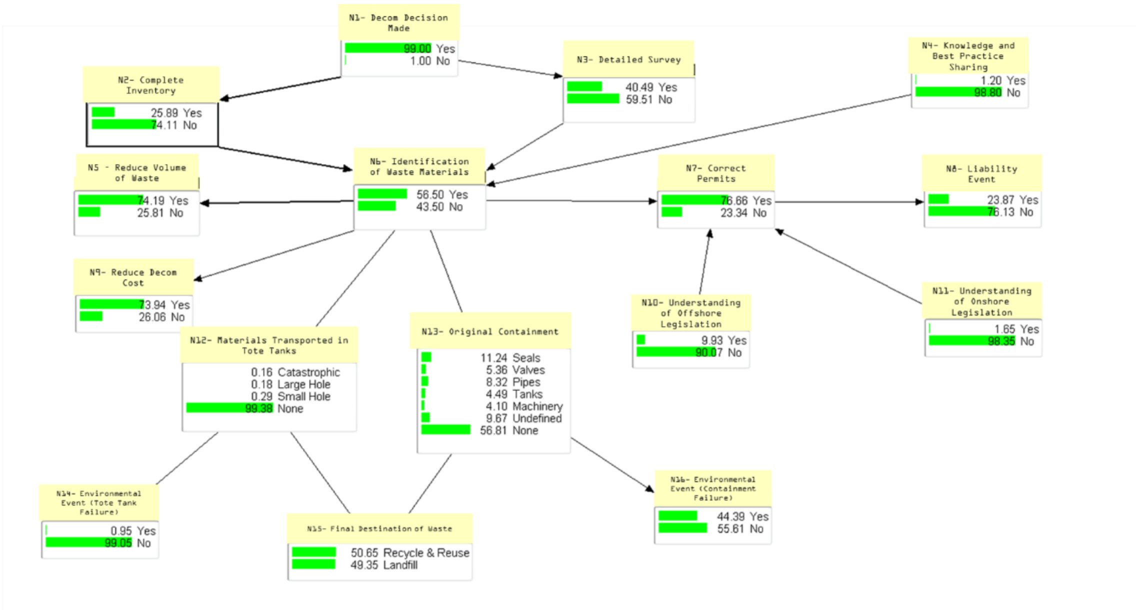


Figure 7-2: Initial prior probabilities of combined network.

The test cases were chosen to evaluate the main causal chain that influences the handling and final destination of hazardous waste in the combined network. This chain links early-stage planning and information accuracy (N1–N4) to waste-reduction performance (N6 and N7), containment reliability (N8 and N9), and the ultimate environmental or operational consequences (N10–N15). These are the stages that have been identified in both literature and industry guidance as the points of highest uncertainty and impact in decommissioning projects.

Nodes N2, N3 and N4 were selected because they represent the quality of information entering the system through inventories and surveys, which determine whether hazardous materials are correctly identified. Node N6 links this knowledge to the ability to reduce waste and cost (N7), while N8 and N9 represent physical containment systems whose performance directly affects environmental and safety outcomes. The outcome nodes represent compliance, environmental performance and waste-destination results. Testing along this chain allows the model to be assessed where the strongest causal influence occurs and where real-world failures have historically been observed.

Case One

Test case one involves the scenario where decommissioning is taking place, but the materials present have not been identified due to lack of complete surveys and inventories. Nodes 2, 3 and 4 are set to 100% no whilst node 1 is set to 100% yes, as shown in Figure 7-3. In this case, the probability of a reduction in the overall cost of the decommissioning process, node N7, decreases from 74% to 42%. The probability of a reduction in the volume of waste produced, node N6, decreases from 74% to 42%. This demonstrates that if the waste materials are incorrectly identified, the volume of waste produced increases along with the overall cost of the handling and processing of the waste materials. This occurs because misidentified or undocumented materials must undergo additional processing or be classified as general hazardous waste, increasing the likelihood of disposal in landfill rather than recycling or reuse.

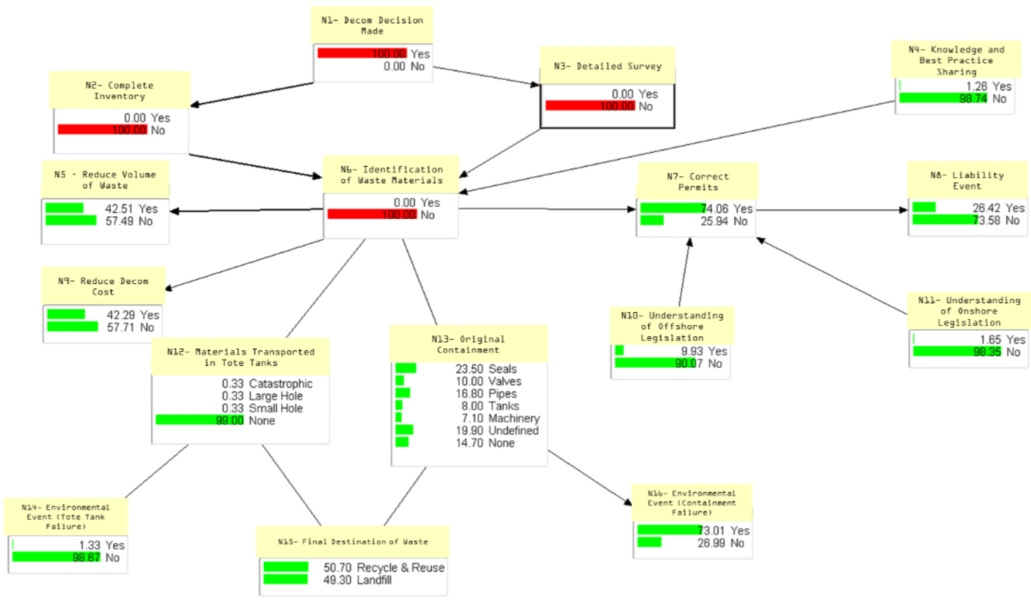


Figure 7-3: Test case one for the combined network.

Case Two

Test case two involves the scenario where node N4 is set to 100% no indicating that all the materials had not been identified, as shown in Figure 7-4. Node N6 is also set to 100% catastrophic indicating that there has been a catastrophic failure in the tote tanks transporting the hazardous materials. This results in an increase in the probability of an environmental event due to tote tank failure occurring from 99.05% to 99.9%. The probability that the materials would be disposed of via landfill increases from 49.5% to 99.5%.

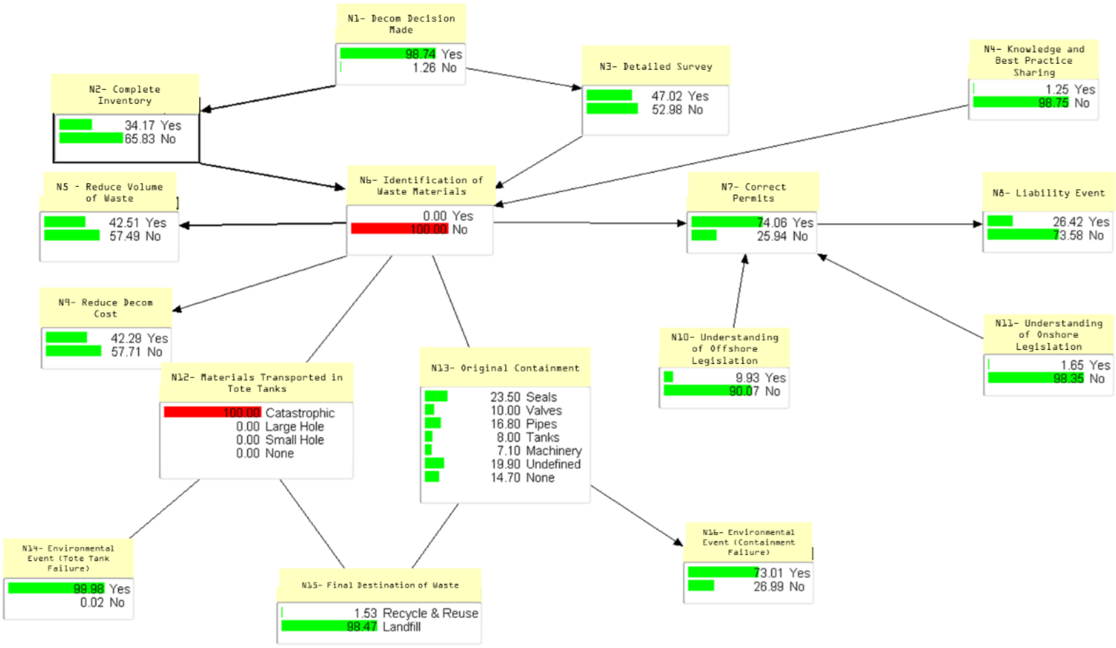


Figure 7-4: Test case two for combined network.

Test Case 2 examined the consequences of waste material transport failures, particularly focusing on tote tank integrity, reinforcing the relationship between transport failures and unsustainable waste handling outcomes. Catastrophic failures in transport systems lead to waste contamination, material loss, and regulatory non-compliance, necessitating immediate disposal in controlled landfill sites rather than sustainable recycling or reuse. Transport containment failures significantly increase environmental risks and regulatory liabilities. These failures lead to contamination, reducing opportunities for recycling and reuse. Enhanced transport monitoring and secondary containment strategies should be implemented to mitigate these risks.

7.7 Model Validation

In order to ensure that the model satisfies the axioms as discussed in Chapter 3, the model is subjected to a series of validations. This involved a three-axiom base verification and sensitivity analysis.

The validation used the same three axioms of Bayesian inference, monotonic response, combined influence and dominance of direct parents, that are standard in applied BN verification (Neapolitan 2004; Das 2008; Matellini et al. 2013).

For the first axiom, small changes were applied to the prior probabilities of N2, N3 and N4 while observing the child node N8. These nodes represent information quality and material identification, which are expected to have a clear, proportional effect on containment performance. Confirming that variations in these inputs produced consistent changes in N8 demonstrates that the model behaves predictably when the quality of survey and inventory information changes.

The second axiom was examined by entering evidence into pairs and combinations of N2, N3 and N4 to test whether the combined effect on N8 was greater than that of any single input alone. This reflects the converging nature of these nodes, where both survey and inventory completeness jointly determine identification accuracy. The same principle was tested for N8 and N9 in relation to environmental-event nodes. This confirmed that the network aggregates evidence sensibly across converging inputs.

The third axiom was tested by comparing the effect of changing direct parents of N10 (such as N8 and N9) with that of non-parent nodes that are not directly connected, such as N6 and N7. The result showed that parent nodes have greater influence on the child node than any non-parent, verifying that the model structure and conditional-probability tables are correctly aligned. This provides assurance that the combined network behaves logically and in line with the structural dependencies identified earlier in the study.

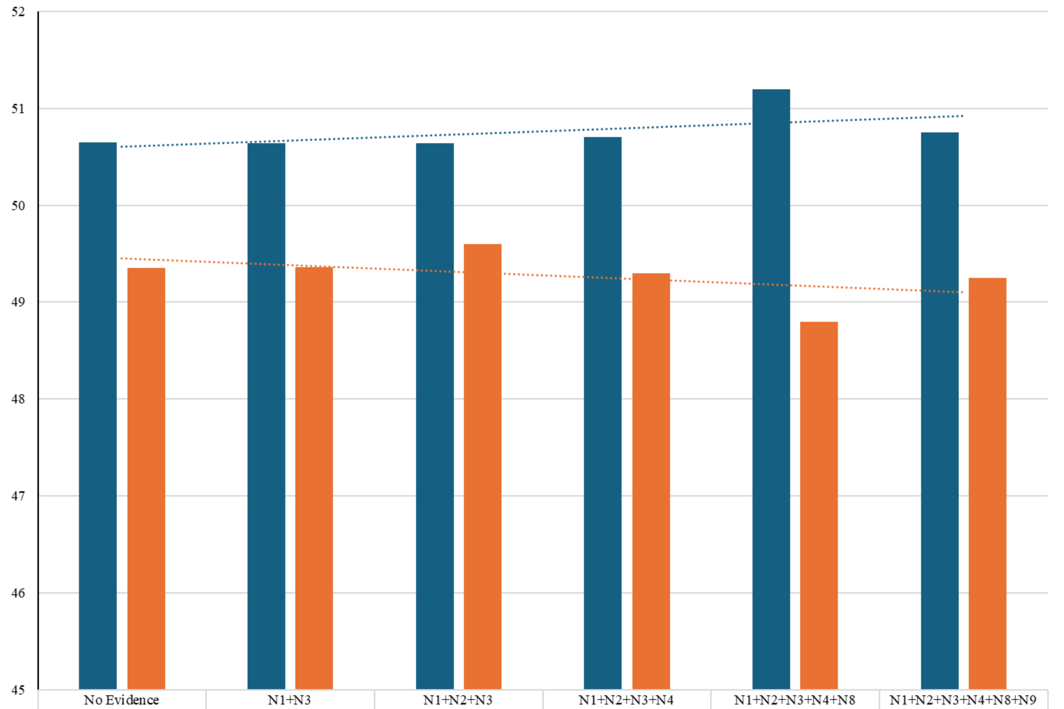
Axiom 1: A slight increase/decrease in prior probabilities of each parent node should elicit an increase/decrease in the child node. For this axiom, the inputs of nodes N2, N3 and N4 were changed by 5% and the effect on the child node, N8 was noted. The changes to the child node can be seen in Table 7-2. This shows that the model satisfies axiom one as by altering the value of the parent nodes, the value of child node has changed.

Table 7-2: Effect of the change of prior probabilities of the parent nodes on the child node.

		5% Change in Probability		
Probability of N8	original	N2	N3	N4
Catastrophic	0.16	0.15	0.15	0.13
Large Hole	0.18	0.17	0.18	0.16
Small Hole	0.29	0.28	0.29	0.28
None	99.38	99.40	99.38	99.44

Axiom 2: The total influence magnitudes of the combination of the probability variation from (evidence) on the values should always be greater than one from the set of sub-evidence attributes. This is shown by the effect of changing the values of nodes N2, N3 and N4 on the child node N8.

Axiom 3: The total influence magnitudes of the combination of probability variation from the evidence should be greater than that from the set of x-y attributes. Axiom 3 requires that sub-evidence should have less influence on the values of a child node than evidence received from parent nodes. Node N10 is composed of nodes N1, N2, N3, N4, N8 and N9. When evidence is entered 100% into the nodes and the states of each node are 100%, the results are shown in Figure 7-5. It can be seen that this variation satisfies axiom three.



	No Evidence	N1+N3	N1+N2+N3	N1+N2+N3+N4	N1+N2+N3+N4+N8	N1+N2+N3+N4+N8+N9
Recycle & Reuse	50.65	50.64	50.64	50.7	51.2	50.75
Landfil	49.35	49.36	49.6	49.3	48.8	49.25

Figure 7-5: Effect of variation of child nodes and parent nodes.

The pattern observed in Figure 7-6 is consistent with expectations from validated Bayesian network studies in engineering systems (Fenton and Neil 2013; Matellini et al. 2013). The results shown in Figure 7-6 reflect the combined influence of the parent nodes and the conditional dependencies within the network. Each parent node (N1–N4, N8 and N9) contributes discrete probability states rather than continuous values, and these interact through converging relationships. When evidence is entered simultaneously across multiple nodes, the combined effect can produce small non-linear shifts in the output probabilities without indicating any numerical error. The overall direction of change remains logical and shows that as more evidence supporting correct planning, identification and containment is introduced, the probability of landfill disposal decreases while the probability of recycling or reuse increases. The minor variation between groups reflects realistic interdependencies within the Bayesian model rather than inconsistency in its operation.

The sensitivity analysis was conducted using the HUGIN sensitivity wizard. Without the use of this tool, the sensitivity analysis would involve increasing and decreasing the states of the chosen input variables by equal percentages to allow for a clear comparison with the chosen output node. The sensitivity wizard in HUGIN requires the user to select the desired focus node and the desired input node. The state for each node is selected so that it would have an impact on the focus node. HUGIN calculates a sensitivity value for the node. This value was, in turn, inputted into an Excel spreadsheet to allow the value to be increased and decreased. The objective was to test the sensitivity of the output node N10 to its input nodes. The results are shown in

Figure 7-6 and Figure 7-7. It can be seen that node N9 is more influential on the output node.

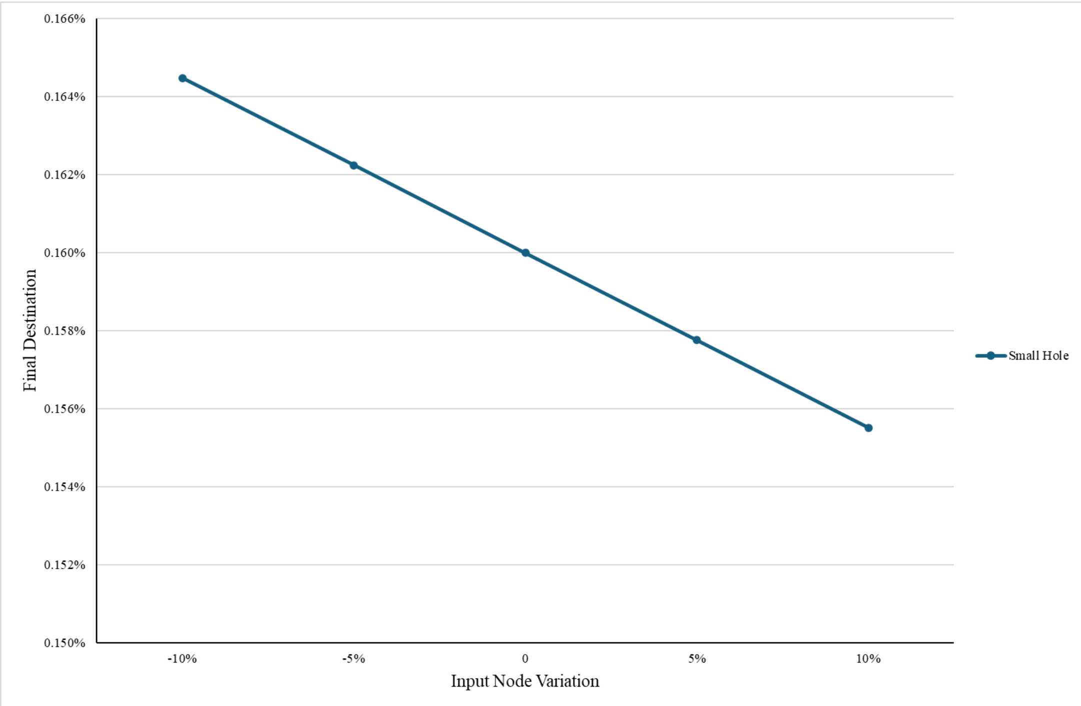


Figure 7-6: Sensitivity functions for the input node, N8 acting on the output node, N15 – final destination.

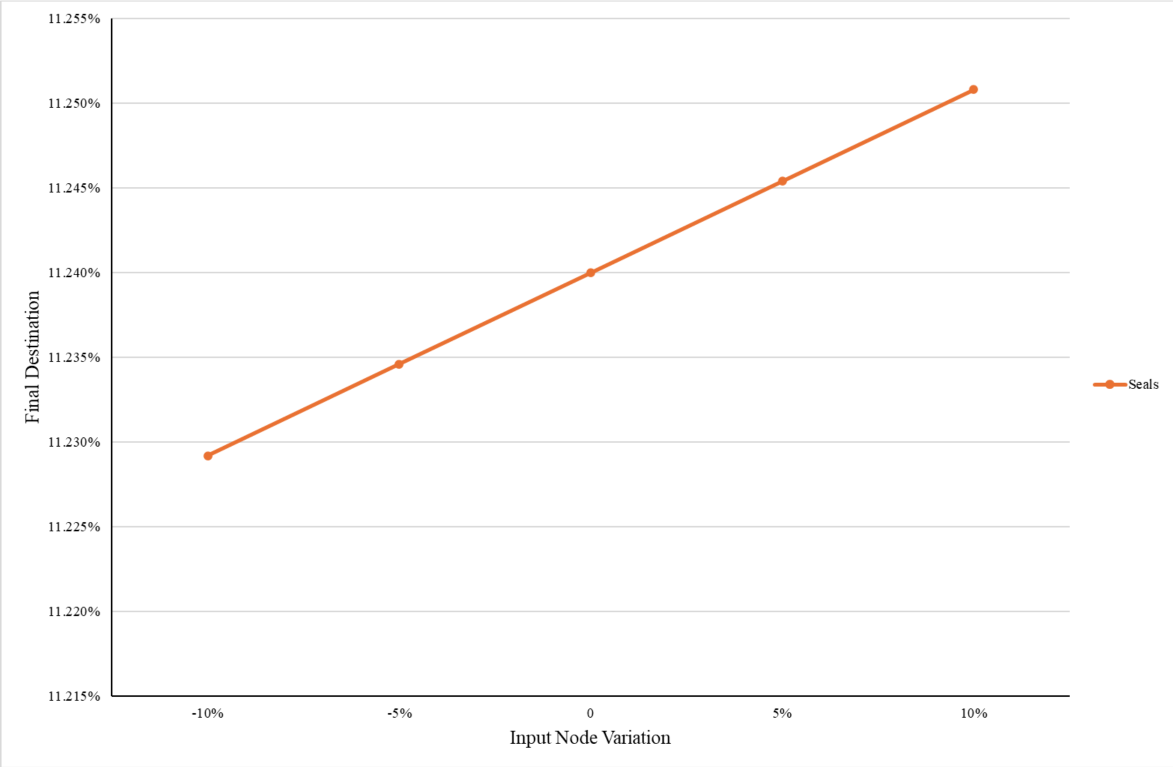


Figure 7-7: Sensitivity functions for the input node, N9 acting on the output node, N15 – final destination.

7.8 Discussion & Conclusion

The aim of this model was to further investigate the interactions between the identified key factors in the handling of hazardous waste materials during the decommissioning process by developing a network that combined the previous models. The model contained nodes that were both common to the previous models and also unique to each one. The model was subjected to a series of test cases to ensure its validity and to determine its sensitivity.

It was found that the identification of the materials had the greatest impact on the final destination of the waste materials. The development of this Bayesian network model aimed to investigate the interactions between key factors affecting the handling of hazardous waste materials during decommissioning. By combining elements from the previous two Bayesian network models, the new model provides a holistic representation of decommissioning processes, integrating aspects of waste identification, cost reduction, transport risks, and regulatory compliance.

The Bayesian network model developed in this chapter builds upon previous models by integrating key decommissioning factors into a single framework. The results of test cases and sensitivity analyses highlight the importance of waste identification, containment integrity, and regulatory compliance in determining hazardous waste disposal outcomes.

The model reinforces several key findings:

i. Material identification is the most significant determinant of waste classification and disposal.
ii. Poor survey data and incomplete inventories lead to higher landfill rates and increased decommissioning costs.
iii. Failures in containment and transport systems significantly impact environmental risk levels and sustainability outcomes.
iv. Regulatory compliance and knowledge-sharing mechanisms need to be strengthened to improve hazardous waste handling efficiency.

7.9 Concluding Remarks

The following key points summarise the development and findings from this chapter:

- A Bayesian Network was developed that combined the structures and data inputs of the two previous models.
- The network integrates both expert-based subjective data and empirical objective data from publicly available sources.
- The model structure was refined to remove redundancy and reflect shared factors influencing the handling of hazardous waste.
- Scenario-based reasoning was used to validate the model using test cases, and sensitivity analysis was performed to assess robustness.
- The combined model allows for a more holistic representation of offshore decommissioning waste management, showing how data type integration enhances decision-making insight.

CHAPTER 8: DECOMMISSIONING FRAMEWORK

8.1 Introduction

This chapter outlines a proposed framework to be used during the decommissioning process of offshore oil and gas installations. A comparison is made between the current nuclear decommissioning framework and oil and gas guidance. The findings from the previous chapters have also been used to inform the framework. The application of the proposed framework to an installation within the United Kingdom Continental Shelf that has undergone decommissioning is demonstrated using a series of case studies. The background to each decommissioning project is outlined, the key issues are highlighted, and the application of the framework is illustrated.

8.2 Background

Since the discovery of oil and gas within the United Kingdom Continental Shelf (UKCS), legislation and regulations governing the industry have continually evolved (Kemp, 2011). A fundamental change occurred following the Piper Alpha disaster, with the Cullen Report (1990) leading to the implementation of 106 safety recommendations. These resulted in a shift toward goal-setting health and safety regulations. The importance of strong regulatory systems has since been reaffirmed by incidents such as the Deepwater Horizon accident (Tikka et al., 2024).

A framework is a structured set of rules, ideas, or guidance used to bring consistency and clarity to the implementation of laws, policies, and processes. In the UK, such frameworks span the full lifecycle of offshore oil and gas projects, from exploration through to decommissioning. These frameworks have evolved over time, beginning in the early 1900s (Martin, 2024), and have increasingly focused on risk-based environmental management and regulatory compliance. The findings of the Bayesian Network, and AHP, will be used to influence the framework's design. The framework will be based on the following areas: planning, dismantling, waste management, site remediation, and environmental monitoring.

Frameworks have been successfully used in the nuclear industry focusing on safe handling and the use of materials since the Manhattan project in the 1940s. With the development of nuclear power in the commercial sector during the 1950s, these frameworks were developed further with an emphasis on safety and security. Current nuclear frameworks are comprehensive, covering radiation protection and waste management to emergency preparations.

1946 saw the creation of the Atomic Energy Research Establishment and by 1954 the United Kingdom Atomic Energy Authority had been established in response to the need to coordinate the development of nuclear weapons power and further research. In 1956, the first nuclear reactor to be used for generating electrical power was opened at colder Hall in Cumbria. Due to the complexity of the plants, hazardous nature of waste materials produced. Within the UK, there are also general advisory bodies and government departments stakeholders in the nuclear decommissioning process. There are several similarities between nuclear decommissioning and oil and gas decommissioning projects as well as several differences. Due to the scale and maturity of nuclear decommissioning as well as the amount of research that has been conducted, there is a vast amount of information available concerning decommissioning projects.

Despite the differences between nuclear and oil and gas industry the concepts within the nuclear industry framework can be applied and carried over to oil and gas. The IAEA guidance (IAEA, 2023) offers guidance on the selection of decommissioning strategy is much like the guidance offered to the oil and gas industry by OPRED. Both industries require stringent safety protocols to protect workers public and the environment. Both industries operate within strict regulatory frameworks and compliance is a must within the lifespan of either industries. Regulatory compliance is ensured through the life cycle by the relevant rectory bodies.

The Nuclear Decommissioning Authority (NDA) Framework (NDA, 2024) outlines the governance and operational framework for the decommissioning of nuclear sites in the UK. The main purpose of the NDA framework is to define the relationship and responsibilities between the NDA and its sponsoring department, the Department for Energy Security and Net Zero (DESNZ). The objective shared by both organisations is the safe, secure, and cost-effective cleanup of the UK's nuclear sites, with a focus on environmental protection and community well-being. The framework prioritises safety, accountability, and financial responsibility throughout the entire decommissioning process.

The decommissioning stages of a nuclear installation follows the same generic stages as that of oil and gas installations. These stages are shown in Figure 8-1.

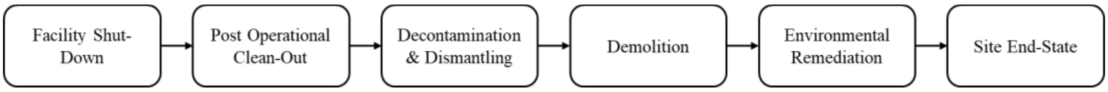


Figure 8-1: Stages in Nuclear Decommissioning.

The stages are similar in that they both involve decontamination and dismantling, site remediation and monitoring. Nuclear decommissioning often faces heightened public scrutiny and political sensitivities due to concerns about radiation and nuclear waste. Oil & gas decommissioning, while attracting increasing attention, generally has a lower public profile. Both industries prioritise the safety of workers, the public, and the environment. Hence, they both incorporate hazard analysis, risk assessment, and safety control measures throughout the decommissioning process.

Safety assessments form a cornerstone of the nuclear decommissioning planning, meticulously identifying potential hazards and implementing stringent control measures to protect workers, the public, and the environment.

This includes:

i. Thorough characterisation of the facility: Determining the types, quantities, and locations of radioactive materials.
ii. Analysis of operational history: Understanding past incidents, modifications, and the current state of structures and systems.
iii. Detailed planning of decommissioning activities: Defining the sequence of tasks, techniques, and required resources.
iv. Hazard identification and risk assessment: Proactively identifying potential hazards, both radiological and non-radiological, and evaluating their associated risks.
v. Implementation of robust control measures: Establishing limits, controls, and conditions to ensure the safe execution of decommissioning tasks.
vi. Environmental monitoring and compliance: Monitoring for radioactive releases and ensuring adherence to environmental regulations.

Decommissioning nuclear facilities also presents unique organisational and human factors challenges, similar to those experienced in oil ang gas decommissioning. This includes:

i. Staffing and competency: Ensuring an adequately skilled workforce capable of handling the specialized tasks involved in decommissioning, often requiring retraining or recruitment of personnel with specific expertise.

ii. Knowledge management: Preserving corporate memory and capturing lessons learned from past operations and decommissioning projects, especially as experienced personnel transition out of the workforce.
iii. Communication and stakeholder engagement: Effectively communicating with workers, local communities, and other stakeholders to address concerns and maintain transparency throughout the process.
iv. Psychological and social impacts: Recognising and addressing the potential stress and anxiety experienced by workers facing job uncertainty and the social impact on communities reliant on

Both nuclear decommissioning and oil and gas decommissioning prioritise the safety of workers, the public, and the environment. They both incorporate hazard analysis, risk assessment, and safety control measures throughout the decommissioning process. Both sectors operate under stringent regulatory frameworks that dictate decommissioning procedures, waste management, and site clearance criteria. International agreements like OSPAR and the Basel Convention apply to both, ensuring environmentally sound practices. Both industries recognise the need to engage with stakeholders, including regulatory bodies, local communities, and workers, throughout the decommissioning process. This includes transparent communication, addressing concerns, and building trust. Both frameworks encourage learning from experience and implementing continuous improvement initiatives. This involves analysing lessons learned from previous projects and incorporating best practices into future decommissioning plans.

The nuclear industry has a longer history of decommissioning, particularly in Europe and the US, where several nuclear power plants have been fully decommissioned. The oil & gas sector, while facing a growing wave of decommissioning projects, has comparatively less experience. Nuclear decommissioning projects, especially for power plants, often involve larger and more complex facilities compared to many oil & gas installations. This difference in scale can influence the complexity of planning, engineering, and execution.

The nuclear decommissioning framework heavily emphasises managing radiological hazards but also this significance of the non-radiological hazards including waste produced that is still classified as hazardous to the environment and individuals. While oil & gas decommissioning deals with hazardous materials like hydrocarbons and heavy metals, the nuclear industry has developed specific protocols and technologies for handling and disposing of radioactive waste. Both industries deal with non-radioactive hazardous waste that must be disposed of in accordance with the relevant environmental regulations.

8.3 Limitations and Assumptions

- The proposed decommissioning framework is designed to enhance the management of hazardous waste materials and improve sustainability outcomes in offshore oil and gas decommissioning. It draws on lessons learned from both oil and gas and nuclear decommissioning sectors (Gu, 2018). However, the following assumptions and limitations must be acknowledged to clarify its scope and constraints: Scope of Application – The framework has been developed for offshore oil and gas decommissioning within the UK Continental Shelf (UKCS). While some principles may be applicable to other regions, variations in regulatory frameworks, environmental policies, and industry best practices could influence the effectiveness of the proposed approach outside the UK.
- Comparison with Nuclear Decommissioning – The comparison between nuclear decommissioning and oil and gas decommissioning provides valuable insights into best practices. However, fundamental differences in waste classification, radiological hazards, and risk management requirements limit the extent to which nuclear decommissioning methodologies can be directly applied to oil and gas decommissioning projects.
- Regulatory Compliance Assumptions – The framework assumes that all operators and contractors fully comply with UK regulations and industry guidelines. However, variability in regulatory interpretations and enforcement could affect real-world implementation.
- Data Availability and Transparency – The framework relies on data from publicly available decommissioning reports, expert insights, and case studies. While these provide useful guidance, incomplete or inconsistent reporting of hazardous waste management practices may introduce gaps or uncertainties in the framework's recommendations.
- Generalisation of Waste Handling Practices – The framework categorises hazardous waste management strategies based on general industry practices. However, specific waste streams (e.g., radioactive waste, contaminated drill cuttings, or chemical residues) may require customised handling procedures beyond the framework's scope.
- Assumption of Stakeholder Collaboration – The framework emphasises knowledge sharing and stakeholder engagement as key components of successful decommissioning. However, variations in industry practices, confidentiality

agreements, and competitive interests may limit the extent to which operators and contractors share best practices and lessons learned.

Despite these limitations, the framework provides a structured methodology for improving hazardous waste management and regulatory compliance in offshore decommissioning. Future refinements could incorporate real-time data collection, adaptive regulatory updates, and expanded case study analyses to enhance its applicability across different decommissioning projects.

8.4 Developed Decommissioning Framework

8.4.1 Scope & Application

This framework is designed to be flexible enough to be used for different types of installation and by different stakeholders. It is not designed to be used in place of any legislation or regulatory requirements but, instead, to be used alongside as guidance.

8.4.2 Framework Structure

This framework, as shown in Figure 8-2, is structured to focus on the key principles that have been identified as most important to the sustainable handling of hazardous waste materials during decommissioning. Each component contains an overview, purpose statement and set of expectations that define the intended outcome.

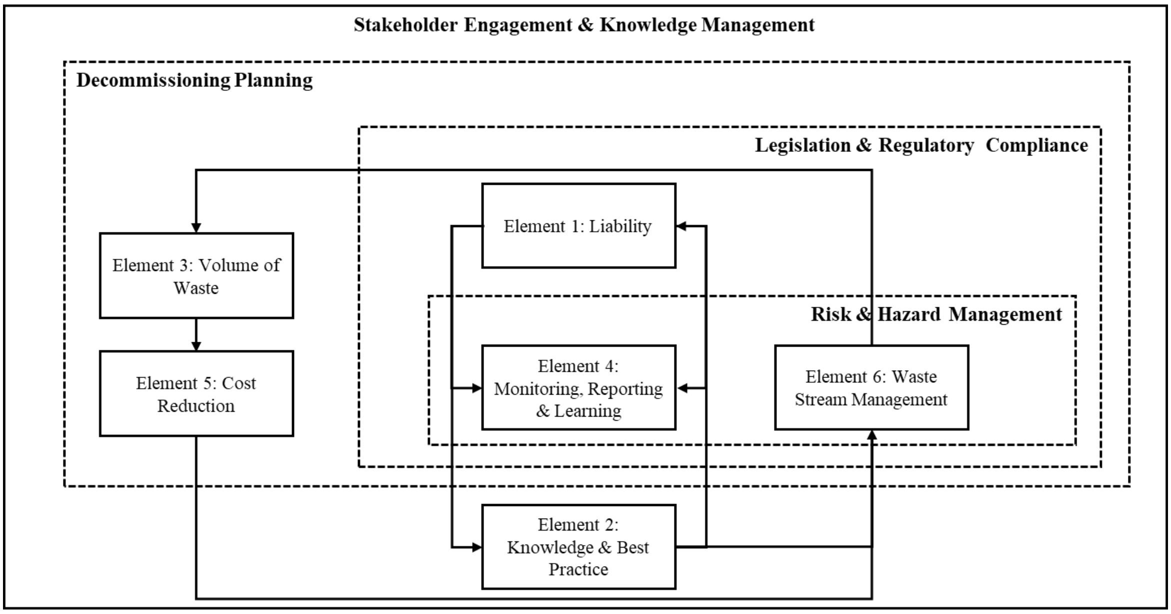


Figure 8-2: Proposed decommissioning framework.

The sequence of elements within Figure 8-2 follows a logical progression from governance to implementation and improvement. The framework begins with Liability (Element 1) because a clear understanding of legal and regulatory obligations forms the foundation for all other activities. Without a defined allocation of responsibility, no other element of the decommissioning process can be effectively managed.

Knowledge and Best Practice (Element 2) follows because the sharing of experience, lessons learned and technical expertise enables operators and contractors to meet their legal obligations safely and efficiently. Together, Elements 1 and 2 establish the organisational and cultural conditions required for the remaining components of the framework to function.

Volume of Waste (Element 3) is placed next as the primary sustainability outcome. Reducing waste generation depends upon compliance with regulation and the application of good practice. Considering waste volume early in the planning process influences downstream decisions on transport, treatment and disposal, ensuring that sustainability objectives are embedded from the outset.

Monitoring, Reporting and Learning (Element 4) provides the control and feedback mechanism for the earlier elements. It ensures that liabilities are traceable, lessons are captured and performance against sustainability objectives is measured. This element links back to Elements 1–3 by verifying compliance, validating knowledge-sharing outcomes and providing data on waste volumes and material movements.

Cost Reduction (Element 5) is introduced once governance, knowledge and monitoring are in place. It focuses on improving efficiency through recycling, reuse and process optimisation, while ensuring that cost savings do not compromise safety or environmental responsibility. Managing cost at this stage allows efficiencies to be achieved within the boundaries of compliance and sustainability.

Finally, Waste Stream (Element 6) represents the operational execution of the preceding elements. By this stage liabilities are defined, knowledge has been shared, waste has been minimised, performance is being monitored, and costs have been optimised. These factors enable the waste stream to be shortened, simplified and made more transparent. Element 5 directly influences Element 6 by promoting logistical efficiencies and responsible contractor selection that reduce unnecessary handovers while maintaining traceability and accountability.

The overall sequence therefore, reflects a logical and iterative flow from governance and capability (Elements 1–2), through sustainability and feedback (Elements 3–4), to efficiency and implementation (Elements 5–6). Arrows in Figure 8-2 indicate the direction of influence and feedback between elements. This structure is consistent with the cause-and-effect relationships identified in the Bayesian Network and AHP analyses presented in Chapters 6 and 7, where liability, knowledge transfer and waste volume were shown to be the highest-influence factors affecting sustainability in the decommissioning process.

8.4.3 Fundamental Considerations

Legislation: Successful decommissioning projects require a deep understanding of current legislation and regulatory requirements. This will reduce the risk of non-compliance and, in the worst-case scenario, a hazardous event occurring. An understanding of legislation across the entire waste stream would be beneficial, as well as provide clarity on areas of jurisdiction for each regulatory body. Understanding liability throughout the decommissioning process, including across the entire waste stream, is essential for success. Identifying liabilities involves a thorough understanding of legislation and regulations. All obligations and liabilities must be clearly communicated to all stakeholders, including waste handlers and transporters. As noted in IAEA guidance for nuclear decommissioning (IAEA, 2023), aligning strategy selection with legal and safety standards is essential. Similarly, in offshore oil and gas decommissioning, liability must be identified, communicated clearly, and managed through collaboration between operators, waste handlers, and transporters (Shell, 2024).

Knowledge Sharing and Best Practice: Sharing knowledge, best practices, and lessons learned is crucial to improving the efficiency and safety of decommissioning projects. This facilitates the identification, handling, and treatment of waste materials. Establishing a central knowledge-sharing database/forum enables information sharing between different projects. Lessons learned should continue to be published in decommissioning close-out reports.

Identification: Part of the decommissioning process includes the identification of hazardous waste materials. All installations should have an inventory detailing the materials that are present onboard. During their lifetime, ownership, staffing, mode of operation and legislation have changed. Knowledge and information may not have been passed on to ensure the identification of materials. A survey should take place during the early stages of the decommissioning process. This would identify and classify materials in order to determine how they will be handled and, ultimately, their final location. The survey must be completed to a high standard, verified and in accordance with up-to-date legislation, regulations and guidance. Comprehensive records of hazardous waste generation, treatment, transportation, and disposal must be maintained. These activities should be reported to regulatory bodies as required, ensuring transparency and accountability. Accurate and current records of waste materials and equipment, including quantities, locations and transport methods, are essential for traceability throughout the waste stream.

Decontamination: Following well isolation and closure, equipment must be decontaminated or sealed for transport to shore. The decontamination technique relies on the identification of materials present during the survey and inventory generation.

Final Destination: In order to maximise sustainability, ultimately, materials and equipment should be recycled or reused. This may not always be possible, depending on the nature of the materials and equipment. Information about the nature of the materials and equipment must be passed on from offshore to onshore stakeholders. This is important to prevent accidents from occurring, resulting in environmental events, injury or death.

8.4.4 Elements

8.4.4.1 Element 1: Liability.

The understanding of liability during the decommissioning process is essential to its success. In order to understand liabilities, there must be an understanding of legislation and regulations.

Purpose Statement: To ensure all parties are aware of their obligations and liabilities, thereby safeguarding the company and stakeholders throughout the decommissioning process.

Expectations

i. Initial liabilities across the waste stream from offshore to onshore are identified.
ii. Management updates this to include any waste handlers and transporters.
iii. Individual requirements and commitments are identified through the identification of liability.
iv. Effective communication is maintained.
v. Liability and obligations are communicated across all levels.
vi. Policies, standards, and procedures are kept up to date with legislation and regulations and are achievable.

8.4.4.2 Element 2: Knowledge & Best Practice.

Knowledge and best practice sharing, as well as lessons learnt, enable the improvement, efficiency and safety of decommissioning projects. It also assists with the identification, handling and treatment of waste materials.

Purpose Statement: To improve decommissioning processes by preventing accidents and ensuring proper handling and treatment of waste materials through shared knowledge and best practices.

Expectations

i. Lessons learned are published in decommissioning close-out reports.
ii. Dialogue and forums are established between stakeholders.
iii. A central knowledge-sharing database/forum is established for information sharing between projects.
iv. Commitment to learning from internal and external sources.
v. Effective communication mechanisms are established.
vi. Good relationships and an environment where feedback is encouraged and welcomed are established.
vii. Continuous improvement is supported.
viii. Performances are evaluated, and feedback is provided at each stage of decommissioning.
ix. Positive relationships are established to enable thorough communication.

8.4.4.3 Element 3: Volume of Waste

Reducing the volume of waste produced is critical to improving the sustainability of a project. By reducing waste, reuse and recycling will be increased. This helps to meet UN sustainability goals and government guidelines as well as improve public image and opinion.

Purpose Statement: To enhance sustainability by minimizing waste, promoting reuse and recycling, and aligning with government guidelines and public expectations.

Expectations:

i. Waste materials are correctly identified, and volumes are estimated.
ii. Possible reuse of equipment is explored, and industry experts are consulted.
iii. Waste materials are contained and transported to avoid contamination and accidents.
iv. Equipment is rigorously decontaminated.
v. Waste recyclers are consulted.
vi. Best practices are shared.

vii. Knowledge of up-to-date legislation is maintained.

8.4.4.4 Element 4: Monitoring of Materials, Reporting & Learning.

Close monitoring of materials during the decommissioning process is essential. This includes volumes, permits, destinations, and types of material.

Purpose Statement: To maintain accurate records and ensure compliance with regulations through diligent monitoring and reporting of materials.

i. Waste material and equipment inventories/registers are kept up-to-date, including volumes, location, and transport mode.
ii. Knowledge and best practice sharing across projects.
iii. Communication between stakeholders and personnel onshore and offshore.
iv. Plans and procedures are maintained in accordance with legislation/regulations/guidance.
v. Monitoring requirements and links to liability are communicated across all levels.
vi. Regular testing, inspections, and surveys are conducted to monitor volumes and locations of waste.
vii. A culture of responsibility is established among the workforces.

8.4.4.5 Element 5: Cost Reduction.

Cost reduction is an important consideration in meeting government and industry expectations for efficient decommissioning. By aligning cost management with waste reduction initiatives, projects can achieve financial savings while supporting sustainability objectives.

Purpose Statement: To achieve cost savings while ensuring waste handling processes favour recycling and reuse over disposal.

Expectations:

i. All costs are assessed, and competitive quotes are obtained.
ii. Options to reduce the cost of waste handling are explored without favouring disposal over recycling or reuse.
iii. Recycling or reuse of materials is prioritised wherever possible.
iv. Processes are in place to continually monitor costs throughout the project.
v. Key performance indicators are clearly defined and communicated.
vi. A culture of reuse/recycling alongside cost reduction is established.

8.4.4.6 *Element 6: Waste Stream.*

Minimizing the length of the waste stream is crucial for efficient waste management.

Purpose Statement: To streamline the waste stream, reducing handovers and ensuring accountability at all stages.

Expectations:

i. The waste stream is reduced in length to minimize changes/handover of materials.
ii. Liability across waste streams is identified.
iii. Waste definition across boundaries is updated and understood.
iv. Reputable parties are used.
v. Adequate supervision and accountability are maintained across all stages of the waste stream.

8.5 Discussion

Frameworks serve to provide a common understanding, guide actions, and facilitate collaboration among stakeholders involved in addressing a complex challenge (Velenturf & Purnell, 2021, Efthymiou, 2022). In the context of decommissioning projects, a framework aims to enhance consistency and clarity by providing a shared understanding of key factors, processes, and responsibilities. It would promote consistency in approach and reduce ambiguity in decision-making. Frameworks incorporate best practices and lessons learned from previous experiences, helping stakeholders to avoid common pitfalls and implement effective solutions. It would also provide a platform or mechanism for sharing knowledge, expertise, and best practices among stakeholders, fostering a collaborative and learning-oriented environment in the future.

The results of the previous chapters have indicated that the key factors affecting the sustainability of the handling of hazardous waste materials during the decommissioning process are:

i. Understanding of legislations and regulations
ii. Knowledge and best practice sharing
iii. Identification of waste materials

A recurring theme is the critical need for a comprehensive and shared understanding of the complex web of legislation and regulations governing hazardous waste management in the decommissioning process (Robinson & Cowie, 2003, NSTA, 2022, OGUK, 2019) . This complexity is compounded by the involvement of multiple stakeholders with potentially differing interpretations of legal requirements and their respective responsibilities.

Inadequate knowledge sharing among stakeholders has a detrimental effect on the decommissioning process and hinder the effective management of hazardous waste, potentially leading to poor decisions and increased risks (Shell, 2024, Akinyemi, Sun & Gray, 2020). A collaborative approach, where knowledge and best practices are openly shared and disseminated, fostering a culture of collective responsibility and continuous improvement would aid in the sustainability of the decommissioning process.

Accurate identification and characterisation of hazardous waste has also been identified as a crucial factor in ensuring its proper handling, treatment, and disposal. Incomplete inventories, inadequate surveys, and insufficient testing increase the likelihood of misclassification, potentially resulting in hazardous materials being inappropriately managed, leading to environmental contamination and safety hazards (Efthymiou, 2022; Akinyemi et al., 2020). This emphasises the need for robust procedures and comprehensive data collection to ensure the reliable identification of hazardous waste throughout the decommissioning process.

The proposed framework should aim to enhance regulatory clarity through the promotion of a clear and consistent understanding of applicable legislation and regulations among all stakeholders (NDA, 2020; IAEA, 2023; BSEE, 2020). This could involve developing guidance documents, training programs, and collaborative platforms for sharing interpretations and best practices. It should facilitate open communication and knowledge exchange among stakeholders. This could include establishing industry forums, knowledge repositories, and mentoring programs to capture and disseminate valuable experience and expertise.

The framework should develop and implement standardised procedures for identifying, characterising, and documenting hazardous waste. This would ensure consistency and accuracy, reducing the risk of misclassification and inappropriate handling.

The framework should encourage the adoption of best practices for minimising waste volume, reducing waste stream length, and prioritising reuse and recycling over disposal. This could involve incentivising sustainable approaches and providing guidance on implementing such practices.

8.6 Application of Proposed Framework to a Decommissioned Installation

The following case studies demonstrate the practical application of the proposed decommissioning framework. Beyond verifying the framework's relevance, each case has been re-examined to identify how its application could optimise project design and scenario planning. The purpose of this analysis is not to retrospectively critique the projects, but to illustrate how the framework can improve decision-making and sustainability outcomes when applied proactively. In each case, the elements of the framework highlight opportunities to minimise waste, reduce cost, shorten the waste stream and enhance regulatory compliance. These optimisations also illustrate how the framework supports a systems-based approach that integrates technical, economic and environmental considerations throughout the decommissioning process.

8.6.1 Introduction – Goldeneye

Within the Moray Firth Basin, approximately 100 km off the Northeast coast of Scotland, lies the Goldeneye gas-producing field 14/29, 14/28b, 20/30b and 20/40b, as depicted in Figure 8-3. The field was discovered in 1996 (Stewart & Marshall, 2020). Gas production started in 2004, cessation of production was granted in 2011(Shell, 2024) and well abandonment was completed in 2018. The Goldeneye platform was operated by Shell (52.5%) on behalf of Esso (39%), Lasmo (4.5%), Paladin (3%) and Veba (1%) (Offshore Technology, 2002). The platform was a normally unattended (NUI) wellhead platform, with 1,400 tonnes topside, five platform wells in 120 m water, and a direct tie-back to the St. Fergus onshore facility (Shell, 2024). The platform consisted of a four-leg piled steel jacket anchored by eight piles. The platform included wellhead equipment, detection, measurement and control facilities, 12-man overnight accommodation, a crane and a helideck (Offshore Technology, 2002).

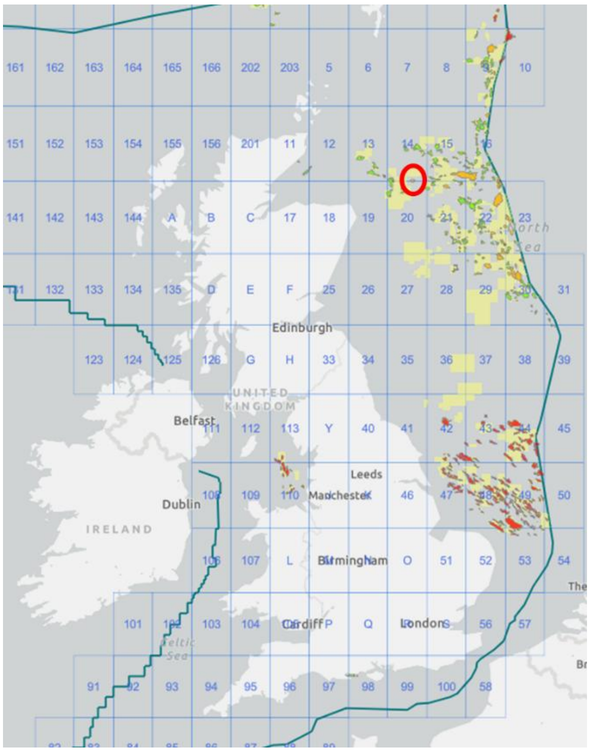


Figure 8-3: Location of Goldeneye Field, depicted by red circle, 100km off the coast of Scotland (NSTA, 2024).

The draft decommissioning programme was submitted to BEIS in 2018 and approved in 2019. The removal and dismantlement of the topside were carried out by Heerema Marine Contractors, the onshore dismantlement was conducted by AF Offshore Decom (Norway) and the subsea removals were completed by DeepOcean (Shell, 2024). The initial decommissioning programme encompassed the proposed decommissioning activities for the topsides, jacket, wells and subsea infrastructure up to but excluding the main pipeline tie-in flanges.

8.6.2 Summary of Decommissioning Programme

The initial decommissioning programme consisted of 4 phases (Shell, 2019):

- Phase 1 – Removal of bulk hydrocarbons and pipeline cleanout.
- Phase 2 - Platform wells plug & abandonment (P&A), convert NUI to Permanently Unattended Installation (PUI) platform.
- Phase 3 – Disconnection and removal of the platform.
- Phase 4 – Subsea infrastructure removal and remediation within Goldeneye areas.

The topside structure was to be removed and recovered to shore. The 1280-tonne topside and 3019-tonne jacket structure were removed and transported to AF Environmental Base in

Norway by Heerma's Thialf (Kilow, 2021). The topside structure was dismantled, recycled and disposed of. Prior to dismantlement, the process equipment was drained, flushed, purged and vented offshore (Shell, 2024). Further cleaning and decontamination took place onshore.

The closeout report submitted to BEIS, detailed the materials removed, permits for waste transfer applied for, environmental monitoring and lessons learned.

8.6.3 Waste Materials

The initial volumes of waste and the actual volumes of waste generated are shown in Table 8-1. It can be seen that there were discrepancies between the values. The volume of hazardous water and materials increased from the original estimate as it was found that approximately 250 tonnes of carbon steel was contaminated with heavy metals from paints and coatings (Shell, 2024). For the installation, 94.9% of the waste materials were reused, recycled or used for energy recovery. The remaining 5.1% was sent to land fill. The as-weighed values from the heavy lift vessel and the yard showed a 0.16% difference in values.

Table 8-1: Materials and waste returned to shore (Shell, 2024).

Material/Waste	Original Estimate (Te)	Tonnage to Shore (Te)	Disposal Method
Carbon Steel	8745	3980	3269Te re-used 3304Te recycled 407Te recycled following PUI campaign
Stainless Steel	141	120	Recycled
Non-Ferrous Metals	113	64	Recycled
Concrete	123	134	Re-Use
Plastics	30	0	The plastics were included within the non-hazardous material for energy recovery
Haz Mat/Norm	2	267	3.3Te recycled 1.6Te Energy recovery 262Te landfill
Other Non-Hazardous	608	148	5.4Te Re-use 133.6Te Recycling 9.1Te Energy Recovery

8.6.4 Lessons Learned

The closeout report submitted to BEIS by Shell outlined the lessons learned from the decommissioning project. The areas identified for improvement were:

i. Identification of hazards for mobilisation and demobilisation.
ii. Applications for transfrontier shipment of waste.
iii. Identification of hazardous waste – particularly in the fire protection materials.
iv. Handling of radioactive sources in ionising smoke detectors.

v. Awareness of the roles and responsibilities of the Duty Holder, contractors, and sub-contractors.

8.6.5 Application of Network

The Goldeneye decommissioning project was applied to the Bayesian network, as detailed in Chapter 6, to determine how the issues identified in the close-out report would affect the handling of hazardous waste. The nodes that are directly influenced by these issues are listed in Table 8-2 with their corresponding states.

Table 8-2: Altered nodes and their inputs for the Goldeneye decommissioning project.

Node	State
N1-Decommissioning Decision Made	100% Yes
N2-Complete Inventory	100% No
N3-Detailed Survey Completed	100% No
N4-Knowledge and Best Practice Sharing	100% No
N5-Correct Permits	100% Yes
N11-Understanding of Onshore Legislation	100% No
N12-Materials Transported in Tote Tanks	100% No
N13-Original Containment	100% No

Node 1: 100% Yes as decommissioning was taking place.

Node 2: 100 % No as the closeout report highlighted that not all the waste had been correctly identified and suggested that hazardous waste inventories needed to be explicit. This alludes to the inventories not being complete and accurate.

Node 3: 100% No as although surveys had taken place prior to the dismantlement to determine types and volumes of waste present, it could be argued that as not all the hazardous waste had been identified, the surveys were not detailed enough.

Node 4: 100% No as the closeout report indicated that not all hazardous material had initially been identified. For example, ceramic fibres were found within passive fire protection that had not been initially identified (Shell, 2024).

Node 5: 100% Yes as the close out report detailed the permits and consents that were obtained for the works authorisations, discharges and transportation.

Node 11, 12 & 13: 100% No as the closeout report described that meetings had been held between stakeholders but the role and responsibilities of the Duty Holder were not clear.

The resulting Bayesian network is shown in Figure 8-4.

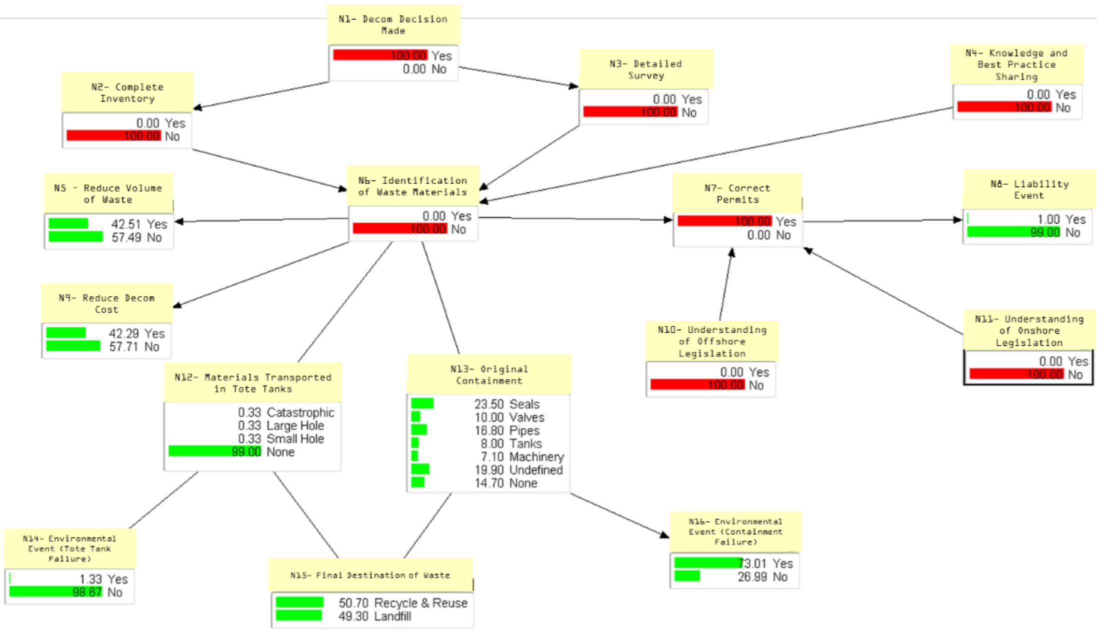


Figure 8-4: Bayesian network for Goldeneye decommissioning project.

It can be seen that the output of nodes N6 – reduce volume of waste and N7 – reduce decommissioning cost both have been impacted negatively. This corresponds to the findings of the closeout report. The volume of hazardous waste increased which would have had a negative effect on the overall cost of the project.

Table 8-3: Changes in probabilities of target nodes for the Goldeneye decommissioning project.

Node							
N6-Reduce Volume of Waste				N7-Reduce Decommissioning Cost			
State	Original	Goldeneye	Change	State	Original	Goldeneye	Change
Yes	74.19	42.51	-31.68	Yes	73.94	42.29	-31.65
No	25.81	57.49	+31.68	No	26.06	57.71	+31.65

8.6.6 Application of Framework

The framework proposed was applied to the Goldeneye installation decommissioning project.

Element 1 – Liability

Purpose Statement: To ensure all parties are aware of their obligations and liabilities, thereby safeguarding the company and stakeholders throughout the decommissioning process.

Application to Goldeneye:

Initial liabilities: Identified across the waste stream from offshore to onshore, including the repatriation of ionising smoke detectors.

Management updates: Included waste handlers and transporters, ensuring compliance with transfrontier shipment regulations.

Individual requirements: Identified through the Permits and Consents Familiarisation session.

Effective communication: Maintained through sessions with contractors and subcontractors.

Policies and procedures: Updated to reflect the latest regulations, such as the Transfrontier Shipment of Radioactive Waste and Spent Fuel (EU Exit) Regulations 2019.

Element 2 – Knowledge & Best Practice

Purpose Statement: To improve decommissioning processes by preventing accidents and ensuring proper handling and treatment of waste materials through shared knowledge and best practices.

Application to Goldeneye:

Lessons learned: Captured in close-out reports and shared during Lessons Learned sessions.

Dialogue and forums: Established between Shell, Heerema Marine Contractors, and AF Decommissioning.

Knowledge-sharing database: Could be implemented to store and share information from the Permits and Consents Familiarisation session and HIRA exercises.

Commitment to learning: Demonstrated through continuous improvement and feedback mechanisms.

Element 3 – Volume of Waste

Purpose Statement: To enhance sustainability by minimizing waste, promoting reuse and recycling, and aligning with government guidelines and public expectations.

Application to Goldeneye:

Waste identification: Included ceramic fibres and ionising smoke detectors.

Reuse of equipment: Explored during the dismantling process.

Containment and transport: Ensured to avoid contamination, particularly for hazardous materials like ceramic fibres.

Decontamination: Rigorous decontamination of equipment before disposal or recycling.

Element 4 – Monitoring of Materials, Reporting & Learning

Purpose Statement: To maintain accurate records and ensure compliance with regulations through diligent monitoring and reporting of materials.

Application to Goldeneye:

Waste inventories: Kept up-to-date, including volumes and locations of waste like ionising smoke detectors.

Communication: Maintained between stakeholders onshore and offshore.

Plans and procedures: Aligned with regulations, such as those for the transfrontier shipment of waste.

Regular inspections: Conducted to monitor waste volumes and locations.

Element 5 – Cost Reduction

Purpose Statement: To achieve cost savings while ensuring waste handling processes favour recycling and reuse over disposal.

Application to Goldeneye:

Cost assessment: Competitive quotes obtained for waste handling.

Cost reduction options: Explored without compromising on recycling or reuse.

Recycling prioritisation: Ensured for materials like ionising smoke detectors.

Monitoring costs: Throughout the project to identify savings opportunities.

Element 6 – Waste Stream

Purpose Statement: To streamline the waste stream, reducing handovers and ensuring accountability at all stages.

Application to Goldeneye:

Waste stream reduction: Minimized changes and handovers of materials.

Liability identification: Across the waste stream, particularly for hazardous materials.

Waste definition: Updated and understood across boundaries.

Reputable parties: Used for waste handling and disposal.

Supervision and accountability: Maintained throughout the waste stream.

8.6.7 Application of Framework to Goldeneye Conclusion

The decommissioning of the Goldeneye installation illustrates how a decommissioning project within the UK can be conducted. The project involved several different stakeholders and Transfrontier shipments. The close-out report highlighted issues that occurred during the project. These involved hazardous waste not being identified and the understanding of roles and responsibilities. Despite the project being conducted by an experienced operator, issues still arose. Through the application of the framework proposed, these factors affected the volume of hazardous waste produced and the amount of recycling and reuse of materials. By addressing these issues, the handling of hazardous waste materials can be improved.

Applying the framework to the Goldeneye project also highlights how the process could be optimised through scenario-based planning. Element 1 (Liability) would ensure clearer allocation of responsibilities between the operator, waste contractors and transporters, reducing duplication and uncertainty. Element 2 (Knowledge and Best Practice) would improve communication between offshore and onshore teams, allowing lessons learned from earlier projects to inform operational decisions in real time. Enhanced Monitoring and Reporting (Element 4) would provide accurate data on waste movements and recycling outcomes, supporting transparency and accountability. Integrating Cost Reduction (Element 5) with Waste Stream (Element 6) would enable logistical efficiencies by consolidating shipments and minimising unnecessary transfers while maintaining full regulatory compliance. Collectively, these optimisations demonstrate how the framework can be used proactively to improve efficiency, sustainability and stakeholder coordination in future decommissioning projects.

8.7 Introduction – Brent Delta

The Brent Field lies in block 211/29 and extends down to Brent South in block 3/4A 186km north-east of the Shetland Isles (Taylor et al, 2003) in 140m of water (Shell, 2009), as shown in Figure 8-5. The field was discovered in 1971 (Whaley, 2017) and was one of the first UK fields to begin production. Initially the field was expected to have a life span of 25 years but with investment and several upgrades, it was extended beyond 40 years.

Four platforms were installed between 1975 and 1978 – Alpha, Bravo, Charlie and Delta. Production commenced in 1976 and at its peak in the 1980s, was producing over 0.5 MMbopd supplying 13% of the UK's oil and 10% of the UK's gas (Whaley, 2017, Shell, 2016). The field underwent a program of development during the 1990s to transform the field from predominantly oil production to predominantly gas production at a cost of £1.2 billion (Shell, 2009).

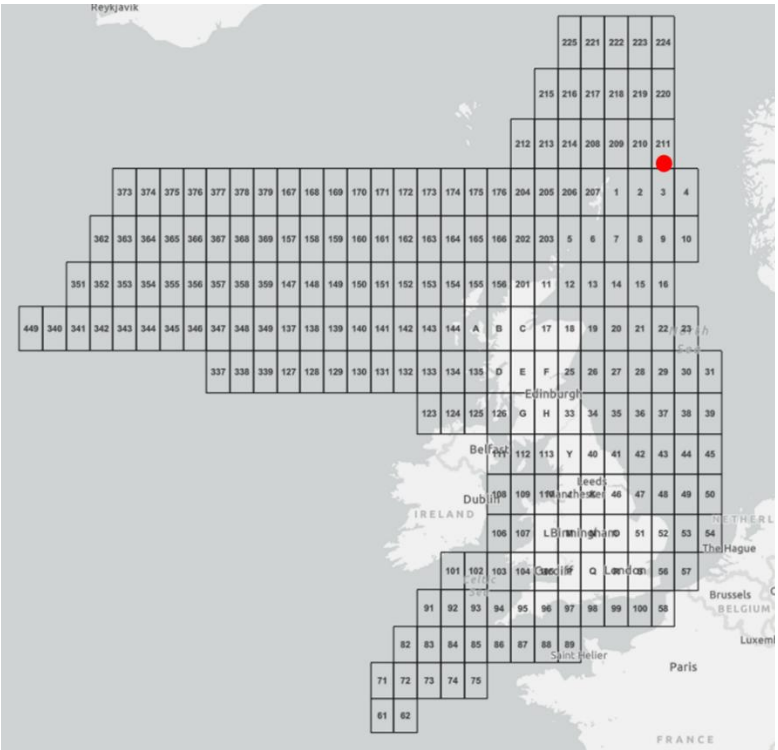


Figure 8-5: Location of Brent Delta Installation (NSTA, 2024)

Brent Delta was a three-leg concrete gravity base structure that consisted of 19 reinforced concrete cells secured to the seabed by steel skirts. Three of the cells extended above sea level, acting as the legs for the topside structure and as crude oil storage (Beckman, 2012). The topside platform structure consisted of three levels – plate girder deck structure, module deck and drilling deck. As well as normal modules and systems such as accommodation, utilities and processing, the topside also was equipped with a helideck and drilling derrick (Shell, 2015, Beckman, 2012).

Planning for decommissioning of the entire field commenced in 2006 and the decommissioning programme for the Delta platform was submitted in early 2015 and approved by BEIS in July 2015 (Shell, 2019). The removal of the topside structure was completed as a single piece lift and carried out using a single lift vessel, Pioneering Spirit and transported to Able Seaton Port, Teeside for dismantling, recycling and disposal (Shell, 2024).

The decommissioning of the Delta platform was carried out separately to the rest of the installations. The topside was removed in April 2017 and dismantling onshore was completed in February 2019 (Shell, 2024). The initial decommissioning programme outlined the method of removal and disposal of the topside structure only. The gravity base structure was to remain in situ and undergo continuous monitoring. The detail for decommissioning of the GBS was included in the Brent Field Decommissioning Programme (Shell, 2015).

8.7.1 Summary of Decommissioning Programme

The decommissioning programme consisted of the following main activities (Shell, 2019):

- Well plugging & abandonment
- Conductor removal
- Topside Preparation including leg cutting.
- Topside lift & transfer
- Topside dismantling onshore.

Prior to the topside being lifted, the process systems onboard were drained, purged and vented to ensure no hydrocarbons remained (Shell, 2019). All drains were flushed, plugged and left open to sea. Residual chemicals were collected in drip trays, bunds and tote tanks to be shipped to shore. The dismantling and disposal were carried out over a 20-month period onshore. The closeout report submitted to BEIS, detailed the materials removed, permits for waste transfer applied for, environmental monitoring and lesson learned.

8.7.2 Waste Materials

The volumes of waste materials generated are shown in Table 8-4. These are the values that were reported in the closeout report submitted to BEIS. The total mass of materials recovered was 23560 tonnes which is approximately 600 tonnes less than estimated in the initial decommissioning programme (Shell, 2019).

Table 8-4: Actual values of waste materials recovered from Brent Delta topside (Shell, 2019)

Material/Waste	Actual Value (Te)	Disposal Method
Ferrous	20,538.13	Recycled
Non-Ferrous	1,650.11	Recycled
Ni-Cd Batteries	6.54	Recycled
Smoke Detectors	0.55	Recycled
Waste Recovery		
Recycled	287.48	Recycled
Waste Recovery (WtE)	196.84	Waste to Energy (WtE)
Gases	0.01	Recycled
Reuse Items	320.72	Reused
NORM Waste	21.12	Landfilled
Asbestos Waste	64.62	Landfilled
MMMF	147.26	Landfilled
General Waste	304.96	Landfilled
Other Waste	21.66	Landfilled

Due to the method of reporting the estimated materials is difficult to make a direct comparison with the actual volumes of materials recovered. It is specified within the close-out report that the over-estimate in waste volume was due to overestimating the volumes of copper-nickel alloys and stainless steel. For the Brent Delta topside, 95.4% of total material was recycled, 1.4% reused, 0.8% used for energy and 2.4% disposed of to landfill. There was an underestimate of the volume of asbestos containing materials which will have impacted on the volume of waste disposed of (Shell, 2019).

8.7.3 Lesson Learned

The submitted closeout report outlined the lessons learned and issues encountered during the decommissioning process. The identified areas were:

i. Improve stakeholder and market engagement and collaboration.
ii. Focus on cost saving in early stages of decommissioning.
iii. Ensure accurate data with regards to types and volumes of hazardous materials present.
iv. Ensure accurate and detailed surveys of materials.
v. Ensure full purging of pipes and tanks.

8.7.4 Application of Network

The Brent Delta decommissioning project was applied to the Bayesian network, as detailed in Chapter 6 to determine how the identified issues in the close-out report would affect the handling of the hazardous waste materials. The nodes directly influenced by these issues are listed in Table 8-5with their corresponding states.

Table 8-5: Altered nodes and their inputs for the Goldeneye decommissioning project.

Node	State
N1-Decommissioning Decision Made	100% Yes
N2-Complete Inventory	100% No
N3-Detailed Survey Completed	100% No
N4-Knowledge and Best Practice Sharing	100% No

Node 1: 100% Yes as decommissioning was taking place.

Node 2: 100% No as the close-out report highlighted that despite an overestimate in the volume of waste materials, there was still a volume of hazardous waste materials that had not been initially identified (Shell, 2019).

Node 3: 100% No as the close-out report indicated that the surveys which had taken place offshore prior to the removal of the installation had not been detailed and additional surveys were carried out onshore.

Node 4: 100% No as the closeout report indicated that not all hazardous materials had been identified.

The resulting Bayesian network is shown in Figure 8-6.

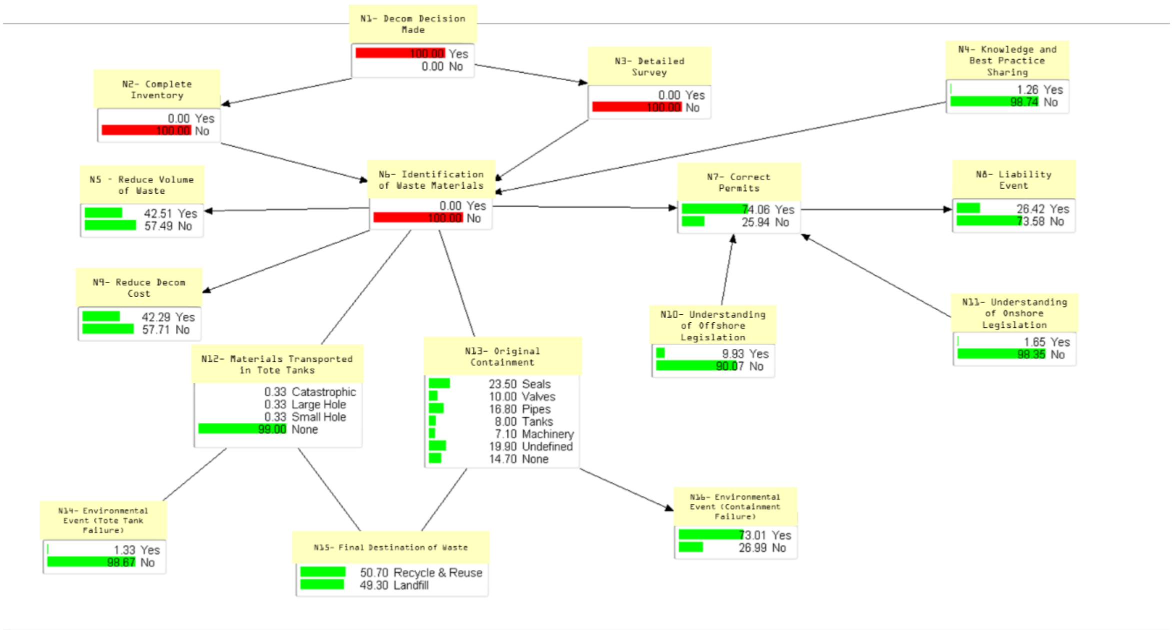


Figure 8-6: Bayesian network for the Brent Delta decommissioning project.

It can be seen that the outputs of nodes N6 – reduce volume of waste and N7 – reduce decommissioning cost have both been impacted negatively. This is in agreement with the published close-out report.

Table 8-6: Changes in probabilities of target nodes for the Brent Delta decommissioning project.

Node							
N6-Reduce Volume of Waste				N7-Reduce Decommissioning Cost			
State	Original	Brent Delta	Change	State	Original	Brent Delta	Change
Yes	74.19	42.51	-31.68	Yes	73.94	42.29	-31.65
No	25.81	57.49	+31.68	No	26.06	57.71	+31.65

8.7.5 Application of Framework

The proposed framework was applied to the Brent Delta decommissioning project.

Element 1 – Liability

Purpose Statement: To ensure all parties are aware of their obligations and liabilities, thereby safeguarding the company and stakeholders throughout the decommissioning process.

Application to Brent Delta:

Initial liabilities: Identified across the waste stream as both the decommissioning programme and close-out report identify the relevant regulations and legislation.

Management of liabilities: Individual responsibilities were identified within the published reports.

Individual requirements: Details of significant contracts awarded to individual stakeholders such as Able UK Limited suggesting individual requirements and commitments were clear.

Effective communication: Maintained through regular stakeholder engagement by means of newsletters and meetings.

Policies and procedures: The decommissioning activities were conducted in compliance with BEIS Guidance Notes and other relevant regulations. A dismantlement safety case was approved during the project by HSE.

Element 2 – Knowledge & Best Practice

Purpose Statement: To improve decommissioning processes by preventing accidents and ensuring proper handling and treatment of waste materials through shared knowledge and best practices.

Application to Brent Delta:

Lessons Learned: captured in close-out report, specifically the individual lessons learned sections for each stage of the decommissioning project.

Dialogue and forums: established between the operator and the various stakeholders.

Knowledge sharing: established between the operator and the various stakeholders which included the sharing of material volumes and inventories. Previous operational personnel collaborated with the dismantling team to share insights on the topside structure.

Commitment to learning: the project utilised the expertise and experience of stakeholders to aid in the design of the single lift vessel and its successful deployment.

Element 3 – Volume of Waste

Purpose Statement: To enhance sustainability by minimizing waste, promoting reuse and recycling, and aligning with government guidelines and public expectations.

Application to Brent Delta:

Waste Identification: an inventory of materials was prepared and distributed but did not successfully identify all hazardous materials.

Reuse of equipment: explored successfully during the onshore dismantling.

Containment and transport: residual liquid chemicals were transported with tote tanks. Radioactive materials were sealed and transported according to Radioactive Substance Act (1993).

Decontamination: carried out offshore prior to lifting of the topside but equipment was found to still contain residual materials during the dismantling phase.

Element 4 – Monitoring of Materials, Reporting & Learning

Purpose Statement: To maintain accurate records and ensure compliance with regulations through diligent monitoring and reporting of materials.

Application to Brent Delta:

Waste inventories: inventories were prepared and present, but volumes were not always correct. In some instances, they volumes were over-estimated and in others, they were lower than the actual volume present.

Communication: maintained between stakeholders both offshore and onshore.

Plans and Procedures: aligned with regulations such as those for the transfer of radioactive substances.

Regular inspections: inspections and surveys took place both offshore and onshore throughout the project.

Element 5 – Cost Reduction

Purpose Statement: To achieve cost savings while ensuring waste handling processes favour recycling and reuse over disposal.

Application to Brent Delta:

Cost reduction options: recycling and reuse were promoted, but the close-out report indicated that cost reduction should have been considered earlier in the project.

Recycling priorities: recycling and reuse promoted.

Monitoring costs

Element 6 – Waste Stream

Purpose Statement: To streamline the waste stream, reducing handovers and ensuring accountability at all stages.

Application to Brent Delta:

Waste stream reduction: the use of a single dismantling site onshore assisting in reducing the length of the waste stream.

Liability identification: liabilities identified through consideration of relevant regulations and legislations.

Wate definition: understood as waste was transferred from offshore to onshore and whilst in transit.

Reputable parties: established contractors were used for each stage of the decommissioning project.

Supervision and accountability: maintained throughout the waste stream.

8.7.6 Discussion and Conclusion

Through the analysis of the publicly available documentation for the Brent Delta decommissioning project, the network and framework were applied. It was identified that issues encountered included insufficient detail in the offshore material surveys, inaccurate estimates of hazardous materials and insufficient purging of pipes and tanks. It was also identified that the project would have benefitted from earlier consideration of cost saving measures. When the Bayesian network was applied to the Brent Delta project, it was shown that the identified issues did have a negative effect on cost reduction and volume of waste reduction.

The proposed framework emphasised the need for thorough monitoring and reporting of materials, which would have enhanced the accuracy and comprehensiveness of the material inventories. This would have reduced the volume of waste that was not recycled. Consideration of cost reduction, whilst maximising recycling and reuse of materials, must occur from the planning stages through to implementation of the decommissioning programme. This would be supported by detailed surveys prior to the removal of the topside structure to allow for the identification of the final destination of waste materials.

Applying the framework to the Brent Delta project demonstrates how scenario-based optimisation could have improved both efficiency and sustainability outcomes. Element 1 (Liability) would have ensured clearer definition of ownership and accountability between the operator, contractors and waste receivers, reducing administrative delays. Strengthening Knowledge and Best Practice (Element 2) through early dissemination of lessons from comparable North Sea projects could have improved the accuracy of offshore material surveys and purging procedures. Enhanced Monitoring and Reporting (Element 4) would have provided traceable data on hazardous materials, supporting compliance and timely corrective action. Early integration of Cost Reduction (Element 5) with Waste Stream (Element 6) would have allowed logistical optimisation of waste transfers, minimising redundant handling and transportation. Collectively, these measures illustrate how the framework could be used proactively to optimise planning, reduce waste volumes and improve the overall performance of future large-scale decommissioning projects.

8.8 Legislative Alignment

Findings from the framework's application indicate that improved alignment across existing legislation would strengthen coordination, reduce duplication and support sustainable decommissioning outcomes. One of the major challenges identified in offshore decommissioning is the complexity of the current legislative environment. Numerous overlapping laws, regulations and conventions govern hazardous waste management, including national legislation, international maritime requirements and environmental agreements such as OSPAR and the Basel Convention. Although these collectively ensure high standards of safety and environmental protection, they also create duplication and uncertainty for operators, particularly where multiple agencies share oversight of the same activity. Case studies such as Brent Delta and Goldeneye have shown that unclear boundaries of responsibility can delay decisions and contribute to inconsistent interpretation of waste classification or shipment requirements. There is therefore an argument for greater legislative alignment to improve clarity, efficiency and accountability. Streamlining approval processes and harmonising definitions could reduce administrative burden and promote earlier engagement between regulators and industry, supporting more effective planning and waste reduction.

Any changes toward alignment, however, must avoid weakening the regulatory safeguards that have been developed through incidents such as Piper Alpha. The aim should not be deregulation but improved coordination, communication and consistency between governing bodies. Clearer guidance documents, shared data systems and unified reporting templates would achieve many of the benefits of alignment without compromising environmental or safety standards. The proposed framework could act as a bridging tool by mapping legal and operational responsibilities across the waste stream, providing a structured interface between regulatory requirements and on-site practice. In this way, the framework contributes to legislative alignment in a practical sense, promoting transparency, cooperation and efficiency rather than reduction of control.

8.9 Summary

The development of a structured decommissioning framework is essential for ensuring sustainable hazardous waste management in offshore oil and gas decommissioning. This chapter has outlined the key principles of the proposed framework, integrating insights from nuclear decommissioning practices, Bayesian network models, and real-world case studies.

The comparison between nuclear and oil and gas decommissioning highlights several shared challenges, including regulatory oversight, environmental risk management, and stakeholder engagement. While nuclear decommissioning frameworks are highly structured and compliance-driven, offshore decommissioning lacks standardised waste-tracking mechanisms and relies more heavily on operator-led compliance. The proposed framework aims to bridge these gaps by providing a structured approach to waste identification, knowledge sharing, and regulatory clarity.

The application of the framework to the Goldeneye and Brent Delta decommissioning projects demonstrated its effectiveness in addressing critical issues such as incomplete waste inventories, cost inefficiencies, and insufficient hazardous waste tracking. By aligning with best practices from nuclear decommissioning, the framework offers practical strategies for improving sustainability, cost efficiency, and regulatory compliance in offshore decommissioning.

8.10 Concluding Remarks

The following summarises the key outcomes presented in this chapter:

- A decommissioning framework was developed, based on the findings from the Bayesian Networks, expert opinion, and regulatory analysis.
- The framework addresses six main principles: liability, knowledge sharing, waste volume reduction, material monitoring, cost reduction, and waste stream management.
- It has been structured to be used alongside existing legislation, not to replace it, and to provide a clearer route through complex decommissioning challenges.

- The application of the framework to two case studies demonstrated that it can highlight key areas for improvement in planning, inventory control, and stakeholder understanding.
- The framework offers a practical tool to improve consistency, traceability, and environmental outcomes during offshore decommissioning.

CHAPTER 9: DISCUSSION

9.1 Introduction

This chapter discusses the findings of this study in relation to its original aims and objectives. It evaluates how the research contributes to the sustainable management of hazardous waste in offshore oil and gas decommissioning, outlines the limitations of the work, and identifies areas for future research. The following sections examine how the research was developed and applied and reflect on how the study's objectives have been achieved.

9.2 Development and Applicability of the Research

This thesis utilised the input of industry experts alongside a detailed literature review to develop a series of Bayesian Networks that were used to identify the key factors in the handling of hazardous waste materials during the decommissioning of offshore oil and gas installations. The findings were used to influence the development of a framework that could be used to support the decommissioning process. This approach builds on previous studies that highlighted the importance of combining expert input with probabilistic modelling when empirical data is limited (França et al., 2020; Babaleye, Kurt and Khan, 2019).

The rationale for this research originates from the growing need for a framework that aids the decommissioning process. The initial analysis of available literature and previous research indicated that there is a gap between the sustainability of the decommissioning of offshore installations and the management of hazardous waste materials. The correct identification of hazardous waste enables its safe handling and treatment. Uncertainty in liability and waste classification is a recurring theme in offshore decommissioning research, with calls for clearer procedural standards and improved traceability (Fowler et al., 2019; Franz and Larson, 2002). The ever-changing regulation result in a loss of clarity of liability for stakeholders which, in turn, impacts the handling of the waste materials.

The discussions with industry experts confirmed further that there were issues surrounding the understanding of the legislation and regulations by all stakeholders involved in the decommissioning process (Wilkinson et al., 2016; Engelseth, 2017). In order to ensure the sustainable and safe handling of any hazardous waste materials, authority understanding the current environmental legal requirements must be held. Another issue identified is the persistent lack of knowledge sharing amongst stakeholders, a concern also raised by Engelseth (2017) and Fowler et al. (2019), who highlighted the risks associated with information loss across project transitions. This can pose issues when there have been a number of changes in operators, staffing and mode of operation.

Decommissioning is not only an issue faced by the UK. Worldwide there are over 12,000 operational offshore installations. Each one is subject to the legislation and regulation of the country governing the waters where they are situated. There are similarities and differences between these countries and the UK. The UK is highly respected as having a mature decommissioning market.

Initially a Bayesian network developed around the findings of the literature review, expert discussions and the AHP. This followed methodological insights from Loughney and Wang (2018) and Matellini et al. (2013), who demonstrated the suitability of Bayesian networks for modelling causal relationships in offshore risk environments. The aim of this model was to determine how the key factors identified influence the sustainable and safe handling of hazardous waste materials. This initial model highlighted that the identification of the materials and knowledge best practice sharing had a significant effect on the sustainable and handling of the handle hazardous waste.

A further Bayesian network was developed using the initial model in chapter 6 and data from the HSE, decommissioning programs and closeout reports. This model also indicated the identification of the hazardous materials present influenced final destination-reuse, recycle or landfill. This demonstrated the importance of understanding of the decommissioning process, the importance of knowledge sharing and the duty of care of each stakeholder.

A third Bayesian network was developed by combining the previous models. This network consists of nodes common to both models as well as selecting individual nodes unique to each model. This model also showed that the identification of the materials present greatly impacted their final destination, thus affecting the overall sustainability of the projects.

A framework was developed using the findings from the literature review, expert discussion and the Bayesian networks. The proposed framework was demonstrated using case studies from already completed decommissioning projects. This framework aimed to improve the clarity of the decommissioning process and to be used alongside current legislation, regulations and guidance document. The framework highlights the importance of clarity throughout the decommissioning process.

9.3 Limitations

The project has several specific limitations that are identified in Chapter 1. The Bayesian networks contained conditional probability tables that had incomplete data, a common constraint in offshore risk modelling where empirical datasets are limited (Babaleye, Kurt and Khan, 2019; Shafiee and Adedipe, 2022). When the networks were developed, the nodes were selected based on the findings of the literature review, expert discussions and AHP. This approach ensured that expert judgement was structurally embedded within the model, as recommended in similar decision-support research (França et al., 2020; Sum and Ismail, 2023). The nodes do not include specific types of hazardous waste materials due to the availability of data. The same is applicable to the considerations of overall cost and the length of the waste streams which were beyond the resolution of publicly available datasets (Tan et al., 2021; OGUK, 2019).

9.4 Further Research

In order to expand and develop the research project it is suggested the following areas could be explored:

Expansion of number of experts used for discussion - further research would benefit from a larger sample size of experts, potentially through broader engagement with industry stakeholders both within the UK and worldwide. This would provide a larger view on the current decommissioning climate.

Long term case study: This research project provides a snapshot of the decommissioning process. A larger scale, long term project that follows the decommissioning of an installation over time, potentially from the initial planning stage to completion could offer valuable insights into the effectiveness of different strategies and the long-term impacts of decommissioning activities. This would be particularly useful in tracking the implementation and effectiveness of the proposed framework and identifying any unanticipated issues.

Focus on specific waste stream: the literature review highlighted that there is existing research on waste materials such as NORM and drill cuttings but not other hazardous waste materials. Further research could investigate specific waste stream such as residual hydrocarbons

Economic analysis: With the focus on cost reduction across the decommissioning industry, the research could be expanded to include an in-depth look at the costs of a decommissioning project. This could be an overall look at total costs or a focus on the costs associated with a specific type of waste materials.

Stakeholder Engagement: Further studies could investigate methods for improving stakeholder engagement throughout the decommissioning process. This would ensure a more collaborative and inclusive approach and increase the potential for knowledge sharing and best practices.

In addition to these general areas, future research should seek to operationalise the proposed framework within live or upcoming decommissioning projects on the UK Continental Shelf. This would enable practical validation of its ability to improve hazardous-waste traceability, cost control and inter-stakeholder coordination. The Bayesian Network could be further developed by integrating real-time monitoring data or digital twin technologies to allow predictive risk assessment during active dismantling operations. Extending the model to include economic and social impact indicators would also provide a more holistic measure of sustainability performance. Comparative application of the framework across different regulatory regimes, such as Norway or the Gulf of Mexico, could help identify transferable best practices and inform international policy harmonisation.

Beyond its academic contribution, this research has clear implications for both industry and policy. For operators and contractors, the framework provides a structured route to demonstrate compliance, reduce waste-handling costs, and enhance sustainability performance within decommissioning programmes. For regulators and policymakers, it highlights opportunities to improve alignment between environmental, safety and waste-management legislation, reducing duplication while maintaining high standards of protection. The integration of probabilistic decision-support tools, such as Bayesian Networks, offers a foundation for evidence-based policy design and supports the UK's transition towards a more sustainable offshore sector.

9.5 Concluding Remarks

This section summarises the key findings discussed in the chapter.

- The AHP supported the prioritisation of key factors, showing that regulatory understanding, waste stream management, and cost reduction are consistently high priorities across industry respondents.

- The results reinforced the finding that gaps in regulatory understanding and legacy knowledge have tangible effects on safe waste handling and environmental compliance.
- The Bayesian network models provided a means to simulate the complex interactions across the offshore decommissioning waste stream. They highlighted the importance of correct identification, traceability, and stakeholder understanding of liabilities.
- The combination of AHP and Bayesian analysis enabled both structured expert judgement and scenario-based modelling, filling the gap in previous offshore decommissioning research.
- The insights gained from the modelling stages were critical in informing the structure of the proposed framework, linking empirical and qualitative evidence to a practical tool that can be applied in industry.

CHAPTER 10: CONCLUSION

10.1 Introduction

This chapter provides the overall conclusion to the research project. It reviews how the research objectives were achieved and outlines the key contributions to knowledge.

10.2 Review of Research Aims and Objectives

The decommissioning of offshore oil and gas installations is a complex process involving numerous stakeholders, regulations, and potential hazards. This research project aimed to investigate the sustainability of UK offshore decommissioning activities and the management of hazardous waste, with the objective of identifying key issues and developing a framework for improvement, as outlined in Chapter 1. The conclusions for each of the objectives are as follows:

i. *Identify & evaluate gaps in the current regulatory regime & offshore waste stream.* It was identified that there are gaps in existing research surrounding the handling of hazardous waste materials. There is a lack of understanding of the legislative requirements along the waste stream, specifically when the waste crosses the boundary from offshore to onshore and the tracking of the waste materials as they are transferred between different parties. There is a strong requirement for a clearer understanding of liabilities amongst stakeholders in the decommissioning process.

   This adds to the existing body of knowledge by clearly identifying the disjointed nature of offshore and onshore waste tracking systems and highlighting specific areas where regulatory responsibilities lack clarity. Unlike previous studies, this research identifies the transitional phase of the waste movement as a critical but underexplored aspect of the decommissioning process.

ii. *Conduct a risk-based verification of operator roles & responsibilities and subsequent non-compliance.* A series of discussions with industry experts took place as well as the distribution of pairwise comparison questionnaires. This sought to identify the various key factors that would be as a basis for a series of Bayesian Networks. The discussions with industry experts identified that there was a lack of understanding of legislative compliance along the waste stream by operators. This includes the extent of conformity and discrepancies along the waste stream. It was also identified that there is a lack of knowledge sharing amongst stakeholders. This lack of knowledge sharing contributes to issues with the identification of legacy chemicals and older assets. The experts' concerns align with findings from a previous study, highlighting the importance of legislative requirements along the waste stream. Factors that contribute to these concerns include the length of the waste stream and the large number of stakeholders involved. It was also identified that high volumes of waste are still being produced, and there is a need to reduce the overall length of the waste stream.

The thesis used AHP to identify the most important factors affecting decommissioning. The results from AHP indicated that an understanding of offshore regulations was of high importance. While there was no consensus on which factor was most important, the experts highlighted the importance of the understanding of offshore regulations, reduction in costs, knowledge and best practice sharing, and the understanding of liabilities throughout the waste stream.

This thesis contributes by providing a structured account of how knowledge gaps and misalignment of responsibilities impact compliance across the waste stream. The use of expert interviews combined with AHP prioritisation offers a replicable method for evaluating risk perception and awareness among stakeholders, which has not been applied to this context in such depth.

iii. *Conduct multi attribute decision analysis to rank requirements to determine the most influential factors across the offshore waste stream.* The Bayesian network models developed in this research project provided insights into the key factors influencing the sustainable and safe handling of hazardous waste during offshore decommissioning. The models were developed using data from expert opinions, literature reviews, and publicly available information, and aimed to simulate the complex interactions of decommissioning processes.

The models highlighted the importance of the identification of hazardous waste materials. If waste materials are not correctly identified, the probability of them being disposed of in landfills increases. The lack of identification is influenced by the presence of historical inventories of materials on the installations and from the thoroughness of surveys that have taken place prior to the commencement of the decommissioning activities.

This represents a novel application of Bayesian Networks by combining subjective insights with public datasets to simulate risk pathways across decommissioning operations. It advances current thinking by showing how incomplete inventories and historical uncertainty can be linked directly to sustainability outcomes using probabilistic reasoning.

iv. *Develop a holistic benchmarking framework for decommissioning waste streams.* A framework was proposed to be used during the decommissioning process, based on the identified key principles for sustainable handling of hazardous waste materials. This framework was structured around liability, knowledge sharing, waste volume reduction, materials monitoring, cost reduction, and waste stream management. The framework is intended to be used as guidance and not replace any legislation.

    This framework offers a practical tool that can inform future decommissioning guidance documents and regulatory reforms. It brings together technical, regulatory, and operational aspects in one decision-support system, filling a gap in how decommissioning practices are currently benchmarked.

v. *Use a case study to demonstrate the application of the framework.* The proposed framework was applied to two case studies of decommissioned installations: Goldeneye and Brent Delta. For both projects, issues relating to incomplete inventories, insufficient surveys, and misidentification of hazardous waste were identified. The framework was then used to highlight areas for improvement on these projects, including clarification of liabilities, better knowledge sharing, improved waste identification, thorough monitoring, consideration of cost reduction and streamlined waste streams.

    This demonstrated the real-world use of the proposed framework on UKCS decommissioning projects. It provides evidence that the tool can help identify missed hazards, improve waste handling strategies, and flag gaps in stakeholder responsibility, showcasing its value beyond theoretical development.

10.3 Concluding Remarks

The thesis highlighted significant gaps in the current regulatory regime and offshore waste stream, particularly concerning the understanding of legislative requirements, knowledge sharing among stakeholders, and the understanding of individual responsibilities and liabilities. It was emphasised the necessity for detailed inventories of hazardous chemicals and materials, highlighting the challenges in identifying older assets.

The thesis revealed confusion and a lack of clarity in the roles and responsibilities of various stakeholders, including the duty holder, contractors, and subcontractors, and an overall lack of awareness of liabilities, especially along the waste stream. Industry experts highlighted concerns about a lack of understanding of legislative compliance, waste management, knowledge sharing, duty of care, and high volumes of waste. These concerns align with the literature review and other findings.

The analytical hierarchy process identified that the understanding of offshore regulations, reduction in costs, knowledge and best practice sharing, and the understanding of liabilities throughout the waste stream are key factors influencing decommissioning. Bayesian network models showed that correct identification of waste materials, knowledge sharing, and the understanding of liabilities were critical factors for sustainable and safe handling of hazardous waste. The models also highlighted the importance of detailed surveys and inventories.

A holistic framework was developed to guide decommissioning processes, focusing on liability, knowledge sharing, waste volume reduction, materials monitoring, cost reduction, and waste stream management. The application of the framework to the Goldeneye and Brent Delta case studies demonstrated how issues related to incomplete inventories, insufficient surveys, and misidentification of hazardous waste could negatively affect project outcomes.

The application of the framework to the Goldeneye and Brent Delta case studies demonstrated how issues related to incomplete inventories, insufficient surveys, and misidentification of hazardous waste could negatively affect project outcomes.

In summary, the project has identified key areas for improvement in offshore decommissioning, emphasising the interconnectedness of regulatory compliance, knowledge sharing, waste management, and stakeholder collaboration. The proposed framework and the BN models provide practical tools for addressing these issues and improving the sustainability and safety of future decommissioning projects.

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APPENDIX .A: AHP Questionnaire.

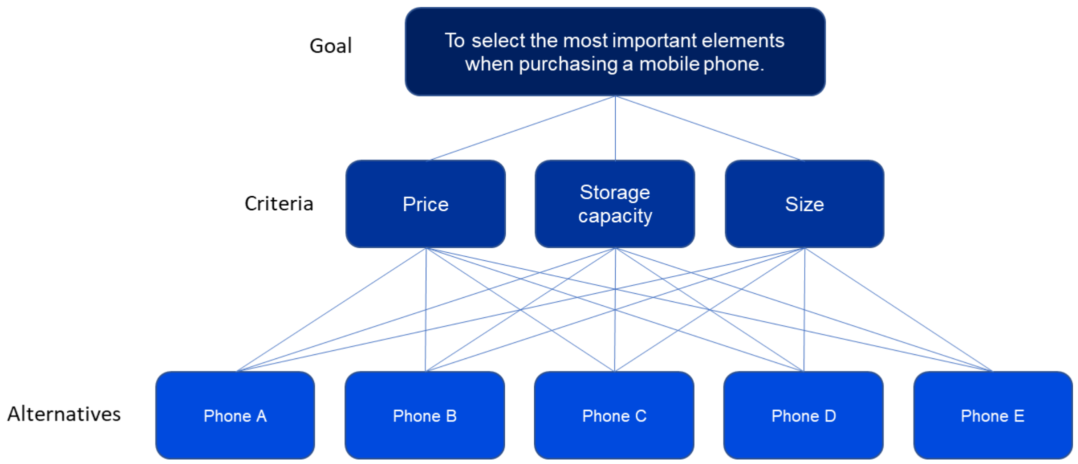
Example Explanation

The goal of this study is to investigate the sustainability of UK offshore decommissioning activities and the management of hazardous waste during the decommissioning stage of an offshore installation. comparison technique. Table 1 shows the weightings for the importance and unimportance. The key factors are to be evaluated using a pair-wise comparison technique.

Table 1 - Importance Weightings

Important		***Unimportant***	
Intensity of importance	Definition	Intensity of unimportance	Definition
1	Equal Importance	1	Equal Importance
3	Moderate importance	1/3	Moderate unimportance
5	Strong importance	1/5	Strong unimportance
7	Very strong importance	1/7	Very strong unimportance
9	Extreme importance	1/9	Extreme unimportance
2,4,6,8	Intermediate importance values	1/2, 1/3, 1/4, 1/6	Intermediate unimportance values

The questions are to be judged based on the definitions in Table 1 and your expertise and experience in the offshore industry. The following is an example of how to apply Table 1.



Objective: To select the most important elements when purchasing a mobile phone.

Criteria	Extremely unimportant								Equal	Extremely important							
To achieve the stated objective, how important is price compared to storage capacity?	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is price compared to mobile phone size?	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
To achieve the stated objective, how important is mobile phone size compared to storage capacity?	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Explanation:
The price of the mobile phone is 7 times more important than the storage capacity.
The price of the mobile phone is 2 times more important than the mobile phone size.
The mobile phone size is 1/6 times more unimportant than the storage capacity.

Respondent Demographics

Q1 Are your core activities:

- onshore
- offshore
- both
- other

If you selected other, please specify:

Q2

- Less than 1 year
- 1 - 5 years
- 5 - 10 years
- More than 10 years

Q3 What is your area of expertise?

- Waste management
- Well plugging and abandonment
- Project Management
- Permitting and regulatory compliance
- Safety engineering
- Materials disposal and site clearance
- Surveying
- Civil Engineering
- Maritime Engineering
- Other

If you selected other, please specify:

Q4 What is your highest level of qualification?

- GCSES
- Apprenticeship
- A-Levels
- HNC
- HND
- Bachelor's Degree
- Master's Degree
- Postgraduate Diploma or Certificate
- Doctorate
- Other

If you selected other, please specify:

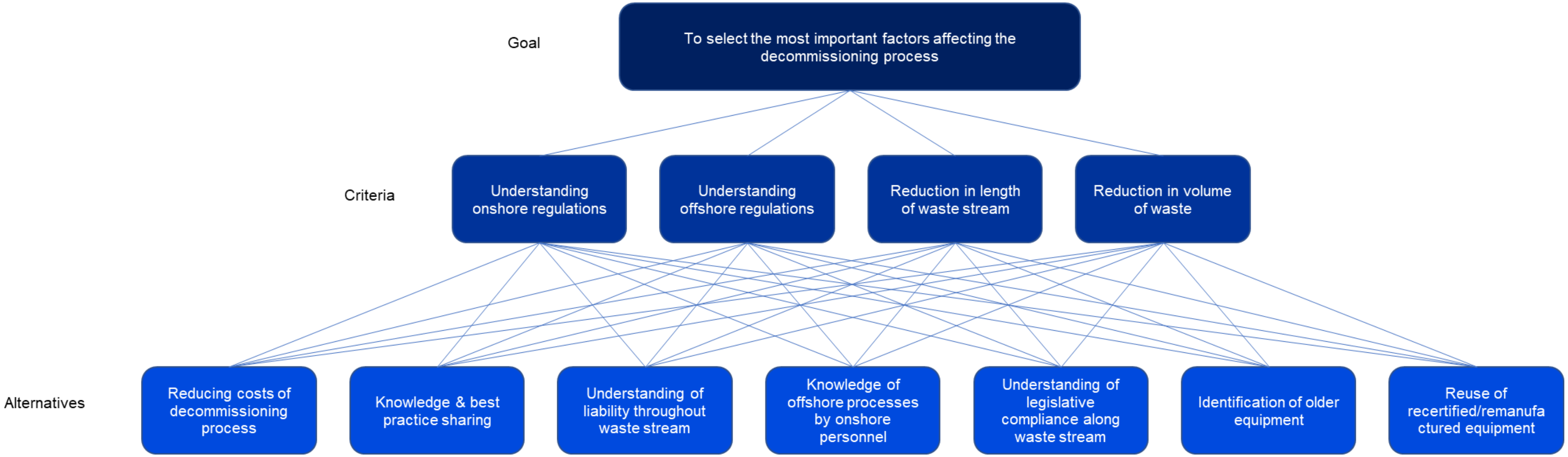
Q5 Do you hold chartered engineer status?

- Yes
- No

Q6 Do you hold incorporated engineer status?

- Yes
- No

The questionnaire will be based on the following hierarchy.



Part 1: With regards to the goal "to select the most important factors affecting the decommissioning process" rank the relative importance of the following:

Goal	**To select the most important factors affecting the decommissioning process**															
Criteria	Extremely unimportant ←								Equal	→						Extremely important
Understanding of **onshore** regulations compared to understanding of **offshore** regulations.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of **onshore** regulations compared to reduction in length of waste streams.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of **onshore** regulations compared to reduction in volume of waste.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of **offshore** regulations compared to reduction in length of waste streams.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of **offshore** regulations compared to reduction in volume of waste.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reduction in length of waste stream compared to reduction in volume of waste.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Part 2: With regards to the criteria "Understanding of onshore regulations" rank the relative importance of the following:

Criteria	**Understanding of onshore regulations**																
Alternative	Extremely unimportant ←								Equal	→ Extremely important							
Reducing costs of decommissioning process compared to knowledge & best practice sharing.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of liability throughout waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the knowledge of offshore processes by onshore personnel	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the understanding of liability throughout the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Criteria	**Understanding of onshore regulations**																
Alternative	Extremely unimportant ←								Equal	→ Extremely important							
Understanding of liability throughout waste stream compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the understanding of legislative compliance along waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge of offshore processes by onshore personnel compared to the understanding of legislative compliance along the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge of offshore processes by onshore personnel compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge of offshore processes by onshore personnel compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of legislative compliance along waste stream compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of legislative compliance along waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Identification of older equipment compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Part 3: With regards to the criteria "Understanding **offshore** regulations" rank the relative importance of the following:

Criteria	**Understanding of offshore regulations**																
Alternative	Extremely unimportant ←								Equal	→ Extremely important							
Reducing costs of decommissioning process compared to knowledge & best practice sharing.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of liability throughout waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the knowledge of offshore processes by onshore personnel	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the understanding of liability throughout the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Criteria	Understanding of offshore regulations																
Alternative	Extremely unimportant								Equal								Extremely important
Knowledge & best practice sharing compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the understanding of legislative compliance along waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge of offshore processes by onshore personnel compared to the understanding of legislative compliance along the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Knowledge of offshore processes by onshore personnel compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Criteria	**Understanding of offshore regulations**																
Alternative	Extremely unimportant ←								Equal	→							Extremely important
Knowledge of offshore processes by onshore personnel compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Understanding of legislative compliance along waste stream compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of legislative compliance along waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Identification of older equipment compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Part 4: With regards to the criteria "Reduction in length of waste stream" rank the relative importance of the following:

Criteria	**Reduction in length of waste stream**																
Alternative	Extremely unimportant ←								Equal	→							Extremely important
Reducing costs of decommissioning process compared to knowledge & best practice sharing.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of liability throughout waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the knowledge of offshore processes by onshore personnel	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the understanding of liability throughout the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Criteria	Reduction in length of waste stream																
Alternative	Extremely unimportant ←								Equal	→							Extremely important
Knowledge & best practice sharing compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the understanding of legislative compliance along waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Understanding of liability throughout waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Criteria	**Reduction in length of waste stream**																
Alternative	Extremely unimportant								Equal								Extremely important
Knowledge of offshore processes by onshore personnel compared to the understanding of legislative compliance along the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge of offshore processes by onshore personnel compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge of offshore processes by onshore personnel compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of legislative compliance along waste stream compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of legislative compliance along waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Identification of older equipment compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Part 5: With regards to the criteria “Reduction in volume of waste" rank the relative importance of the following

Criteria	Reduction in volume of waste																
Alternative	Extremely unimportant ←								Equal	→							Extremely important
Reducing costs of decommissioning process compared to knowledge & best practice sharing.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of liability throughout waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the knowledge of offshore processes by onshore personnel	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Reducing costs of decommissioning process compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the understanding of liability throughout the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Knowledge & best practice sharing compared to the understanding of legislative compliance along waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Criteria	**Reduction in volume of waste**																
Alternative	Extremely unimportant ←								Equal	→ Extremely important							
Knowledge & best practice sharing compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge & best practice sharing compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Understanding of liability throughout waste stream compared to the knowledge of offshore processes by onshore personnel.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the understanding of legislative compliance along waste stream	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the identification of older equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of liability throughout waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Knowledge of offshore processes by onshore personnel compared to the understanding of legislative compliance along the waste stream.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Knowledge of offshore processes by onshore personnel compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Knowledge of offshore processes by onshore personnel compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Criteria	**Reduction in volume of waste**																
Alternative	Extremely unimportant ←								Equal	→							Extremely important
Understanding of legislative compliance along waste stream compared to the identification of older equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Understanding of legislative compliance along waste stream compared to the reuse of recertified/remanufactured equipment	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Identification of older equipment compared to the reuse of recertified/remanufactured equipment.	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

APPENDIX .B: AHP Data

Response 1

Goal

To select the most important factors affecting the decommissioning process

Demographics

Core Activities	Both
Years Experience	More than 10
Role	Supply chain
Expertise	Safety Engineering
Highest Qualification	Masters
Chartered?	Yes
Incorporated?	No

Criteria

C1	Understanding onshore regulations
C2	Understanding offshore regulations
C3	Reduction in length of waste stream
C4	Reduction in volume of waste

Alternatives

A1	Reducing costs of decommissioning process
A2	Knowledge & best practice sharing
A3	Understanding of liability throughout waste stream
A4	Knowledge of offshore processes by onshore personnel
A5	Understanding of legislative compliance along waste stream
A6	Identification of older equipment
A7	Reuse of recertified/ remanufactured equipment

Objectives

Objective 1	To ensure sustainable and successful decommissioning of offshore installations
Objective 2	To ensure onshore legislation and regulations are understood.
Objective 3	To ensure offshore legislation and regulations are understood.
Objective 4	To reduce the length of the waste stream.
Objective 5	To reduce the volume of waste.

Objective 1

Pairwise Matrix

	C1	C2	C3	C4
C1	1	1/9	6	8
C2	9	1	9	9
C3	1/6	1/9	1	1/3
C4	1/8	1/9	3	1
SUM	10 2/7	1 1/3	19	18 1/3

Normalised Matrix

	C1	C2	C3	C4	Criteria Weights
C1	0.10	0.08	0.32	0.44	0.23
C2	0.87	0.75	0.47	0.49	0.65
C3	0.02	0.08	0.05	0.02	0.04
C4	0.01	0.08	0.16	0.05	0.08
SUM	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	5.4831

Consistency Index

n (size of comparision matrix)	4
CI	0.494

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.549

Objective 2

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1/8	5	5	7	9	1
A2	8	1	9	9	9	1	9
A3	1/5	1/9	1	9	9	9	7

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.716

Objective 4

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1/9	1/9	9	9	9	9
A2	9	1	1/9	9	9	9	1/2
A3	9	9	1	9	9	9	1/2
A4	1/9	1/9	1/9	1	1/9	9	1/9
A5	1/9	1/9	1/9	9	1	9	9
A6	1/9	1/9	1/9	1/9	1/9	1	1/9
A7	1/9	2	2	9	1/9	9	1
SUM	19 4/9	12 4/9	3 5/9	46 1/9	28 1/3	55	20 2/9

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.05	0.01	0.03	0.20	0.32	0.16	0.45	**0.17**
A2	0.46	0.08	0.03	0.20	0.32	0.16	0.02	**0.18**
A3	0.46	0.72	0.28	0.20	0.32	0.16	0.02	**0.31**
A4	0.01	0.01	0.03	0.02	0.00	0.16	0.01	**0.03**
A5	0.01	0.01	0.03	0.20	0.04	0.16	0.45	**0.13**
A6	0.01	0.01	0.03	0.00	0.00	0.02	0.01	**0.01**
A7	0.01	0.16	0.56	0.20	0.00	0.16	0.05	**0.16**
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	**1.00**

Consistency

λ_{max}	15.79951

Consistency Index

n (size of comparision matrix)	7
CI	1.467

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	1.111

Objective 5

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1/9	9	9	1/9	1/2	1/9
A2	9	1	1/9	9	1/2	9	1/2
A3	1/9	9	1	9	1/2	9	1/2
A4	1/9	1/9	1/9	1	1/9	1/9	1/9
A5	9	2	2	9	1	9	1/9
A6	2	1/9	1/9	9	1/9	1	1/9
A7	9	2	2	9	9	9	1
SUM	30 2/9	14 1/3	14 1/3	55	11 1/3	37 3/5	2 4/9

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights

A4	1/5	1/9	1/9	1	1/7	9	8
A5	1/7	1/9	1/9	7	1	8	5
A6	1/9	1	1/9	1/9	1/8	1	1/9
A7	1	1/9	1/7	1/8	1/5	9	1
SUM	10 2/3	2 4/7	15 1/2	31 1/4	26 1/2	46	31 1/9

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.09	0.05	0.32	0.16	0.26	0.20	0.03	0.16
A2	0.75	0.39	0.58	0.29	0.34	0.02	0.29	0.38
A3	0.02	0.04	0.06	0.29	0.34	0.20	0.23	0.17
A4	0.02	0.04	0.01	0.03	0.01	0.20	0.26	0.08
A5	0.01	0.04	0.01	0.22	0.04	0.17	0.16	0.09
A6	0.01	0.39	0.01	0.00	0.00	0.02	0.00	0.06
A7	0.09	0.04	0.01	0.00	0.01	0.20	0.03	0.06
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	14.878137

Consistency Index

n (size of comparision matrix)	7
CI	1.313

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.995

Objective 3

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1/6	7	9	9	9	5
A2	6	1	9	9	9	9	9
A3	1/7	1/9	1	9	9	9	9
A4	1/9	1/9	1/9	1	1/7	9	1/9
A5	1/9	1/9	1/9	7	1	9	1/9
A6	1/9	1/9	1/9	1/9	1/9	1	1/9
A7	1/5	1/9	1/9	9	9	9	1
SUM	7 2/3	1 5/7	17 4/9	44 1/9	37 1/4	55	24 1/3

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.13	0.10	0.40	0.20	0.24	0.16	0.21	0.21
A2	0.78	0.58	0.52	0.20	0.24	0.16	0.37	0.41
A3	0.02	0.06	0.06	0.20	0.24	0.16	0.37	0.16
A4	0.01	0.06	0.01	0.02	0.00	0.16	0.00	0.04
A5	0.01	0.06	0.01	0.16	0.03	0.16	0.00	0.06
A6	0.01	0.06	0.01	0.00	0.00	0.02	0.00	0.02
A7	0.03	0.06	0.01	0.20	0.24	0.16	0.04	0.11
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	12.667569

Consistency Index

n (size of comparision matrix)	7
CI	0.945

A1	0.03	0.01	0.63	0.16	0.01	0.01	0.05	**0.13**
A2	0.30	0.07	0.01	0.16	0.04	0.24	0.20	**0.15**
A3	0.00	0.63	0.07	0.16	0.04	0.24	0.20	**0.19**
A4	0.00	0.01	0.01	0.02	0.01	0.00	0.05	**0.01**
A5	0.30	0.14	0.14	0.16	0.09	0.24	0.05	**0.16**
A6	0.07	0.01	0.01	0.16	0.01	0.03	0.05	**0.05**
A7	0.30	0.14	0.14	0.16	0.79	0.24	0.41	**0.31**
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	**1.00**

Consistency

λ_{max}	13.836665

Consistency Index

n (size of comparision matrix)	7
CI	1.139

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.863

Response 2

Goal

To select the most important factors affecting the decommissioning process

Demographics

Core Activities	other	Senior Lecturer
Years Experience	5 - 10 years	
Role	Other	Researcher
Expertise	Maritime Engineering	
Highest Qualification	Doctorate	
Chartered?	No	
Incorporated?	No	

Criteria

C1	Understanding onshore regulations
C2	Understanding offshore regulations
C3	Reduction in length of waste stream
C4	Reduction in volume of waste

Alternatives

A1	Reducing costs of decommissioning process
A2	Knowledge & best practice sharing
A3	Understanding of liability throughout waste stream
A4	Knowledge of offshore processes by onshore personnel
A5	Understanding of legislative compliance along waste stream
A6	Identification of older equipment
A7	Reuse of recertified/ remanufactured equipment

Objectives

Objective 1	To ensure sustainable and successful decommissioning of offshore installations
Objective 2	To ensure onshore legislation and regulations are understood.
Objective 3	To ensure offshore legislation and regulations are understood.
Objective 4	To reduce the length of the waste stream.
Objective 5	To reduce the volume of waste.

Objective 1

Pairwise Matrix

	C1	C2	C3	C4
C1	1	7	7	7
C2	1/7	1	8	8
C3	1/7	1/8	1	8
C4	1/7	1/8	1/8	1
SUM	1 3/7	8 1/4	16 1/8	24

Normalised Matrix

	C1	C2	C3	C4	Criteria Weights
C1	0.70	0.85	0.43	0.29	0.57
C2	0.10	0.12	0.50	0.33	0.26
C3	0.10	0.02	0.06	0.33	0.13
C4	0.10	0.02	0.01	0.04	0.04
SUM	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	6.0246

Consistency Index

n (size of comparision matrix)	4
CI	0.675

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.750

Objective 2

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1	7	3	1	9	9
A2	1	1	1	1	1	7	7
A3	1/7	1	1	7	1	7	8
A4	1/3	1	1/7	1	1/3	7	8

A5	1	1	1	3	1	6	3
A6	1/9	1/7	1/7	1/7	1/6	1	1/5
A7	1/9	1/7	1/8	1/8	1/3	5	1
SUM	3 2/3	5 2/7	10 2/5	15 1/4	4 5/6	42	36 1/5

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.27	0.19	0.67	0.20	0.21	0.21	0.25	0.29
A2	0.27	0.19	0.10	0.07	0.21	0.17	0.19	0.17
A3	0.04	0.19	0.10	0.46	0.21	0.17	0.22	0.20
A4	0.09	0.19	0.01	0.07	0.07	0.17	0.22	0.12
A5	0.27	0.19	0.10	0.20	0.21	0.14	0.08	0.17
A6	0.03	0.03	0.01	0.01	0.03	0.02	0.01	0.02
A7	0.03	0.03	0.01	0.01	0.07	0.12	0.03	0.04
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	8.9751989

Consistency Index

n (size of comparision matrix)	7
CI	0.329

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.249

Objective 3

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1	6	3	1	8	8
A2	1	1	1	1	1	6	6
A3	1/6	1	1	6	1	6	7
A4	1/3	1	1/6	1	1/3	7	8
A5	1	1	1	3	1	7	4
A6	1/8	1/6	1/6	1/7	1/7	1	1/5
A7	1/8	1/6	1/7	1/8	1/4	5	1
SUM	3 3/4	5 1/3	9 1/2	14 1/4	4 5/7	40	34 1/5

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.27	0.19	0.63	0.21	0.21	0.20	0.23	0.28
A2	0.27	0.19	0.11	0.07	0.21	0.15	0.18	0.17
A3	0.04	0.19	0.11	0.42	0.21	0.15	0.20	0.19
A4	0.09	0.19	0.02	0.07	0.07	0.18	0.23	0.12
A5	0.27	0.19	0.11	0.21	0.21	0.18	0.12	0.18
A6	0.03	0.03	0.02	0.01	0.03	0.03	0.01	0.02
A7	0.03	0.03	0.02	0.01	0.05	0.13	0.03	0.04
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	8.6215494

Consistency Index

n (size of comparision matrix)	7
CI	0.270

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.205

Objective 4

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	3	1/2	1/3	1/2	1/4	1/3
A2	1/3	1	3	1	2	6	6
A3	2	1/3	1	1	1	4	4
A4	3	1	1	1	1/4	1/3	1/3
A5	2	1/2	1	4	1	3	3
A6	4	1/6	1/4	3	1/3	1	4
A7	3	1/6	1/4	3	1/3	0.25	1
SUM	15 1/3	6 1/6	7	13 1/3	5 2/5	14 5/6	18 2/3

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.07	0.49	0.07	0.03	0.09	0.02	0.02	0.11
A2	0.02	0.16	0.43	0.08	0.37	0.40	0.32	0.25
A3	0.13	0.05	0.14	0.08	0.18	0.27	0.21	0.15
A4	0.20	0.16	0.14	0.08	0.05	0.02	0.02	0.09
A5	0.13	0.08	0.14	0.30	0.18	0.20	0.16	0.17
A6	0.26	0.03	0.04	0.23	0.06	0.07	0.21	0.13
A7	0.20	0.03	0.04	0.23	0.06	0.02	0.05	0.09
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	10.061423

Consistency Index

n (size of comparision matrix)	7
CI	0.510

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.387

Objective 5

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1/4	1/3	1/3	1/2	5	4
A2	4	1	6	6	7	6	7
A3	3	1/6	1	1/3	1	4	5
A4	3	1/6	3	1	5	2	1
A5	2	1/7	1	0.2	1	1/3	1/3
A6	1/5	1/6	1/4	1/2	3	1	1/3
A7	1/4	1/7	1/5	1	3	3	1
SUM	13 4/9	2	11 7/9	9 3/8	20 1/2	21 1/3	18 2/3

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.07	0.12	0.03	0.04	0.02	0.23	0.21	0.10
A2	0.30	0.49	0.51	0.64	0.34	0.28	0.38	0.42
A3	0.22	0.08	0.08	0.04	0.05	0.19	0.27	0.13
A4	0.22	0.08	0.25	0.11	0.24	0.09	0.05	0.15

A5	0.15	0.07	0.08	0.02	0.05	0.02	0.02	0.06
A6	0.01	0.08	0.02	0.05	0.15	0.05	0.02	0.05
A7	0.02	0.07	0.02	0.11	0.15	0.14	0.05	0.08
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	9.0772437

Consistency Index

n (size of comparision matrix)	7
CI	0.346

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.262

Response 3

Goal

To select the most important factors affecting the decommissioning process

Demographics

Core Activities	onshore
Years Experience	1 - 5 years
Role	Supply Chain
Expertise	Project Management
Highest Qualification	Doctorate
Chartered?	No
Incorporated?	No

Criteria

C1	Understanding onshore regulations
C2	Understanding offshore regulations
C3	Reduction in length of waste stream
C4	Reduction in volume of waste

Alternatives

A1	Reducing costs of decommissioning process
A2	Knowledge & best practice sharing
A3	Understanding of liability throughout waste stream
A4	Knowledge of offshore processes by onshore personnel
A5	Understanding of legislative compliance along waste stream
A6	Identification of older equipment
A7	Reuse of recertified/ remanufactured equipment

Objectives

Objective 1	To ensure sustainable and successful decommissioning of offshore installations
Objective 2	To ensure onshore legislation and regulations are understood.
Objective 3	To ensure offshore legislation and regulations are understood.
Objective 4	To reduce the length of the waste stream.
Objective 5	To reduce the volume of waste.

Objective 1

Pairwise Matrix

	C1	C2	C3	C4
C1	1	1	1	9
C2	1	1	9	9
C3	1	1/9	1	1/6
C4	1/9	1/9	6	1
SUM	3 1/9	2 2/9	17	19 1/6

Normalised Matrix

	C1	C2	C3	C4	Criteria Weights
C1	0.32	0.45	0.06	0.47	0.32
C2	0.32	0.45	0.53	0.47	0.44
C3	0.32	0.05	0.06	0.01	0.11
C4	0.04	0.05	0.35	0.05	0.12
SUM	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	6.2119

Consistency Index

n (size of comparision matrix)	4
CI	0.737

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.819

Objective 2

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1	1	1/7	1/7	1	1/4
A2	1	1	8	1/4	7	8	1
A3	1	1/8	1	5	1/4	1/5	1/5
A4	7	4	1/5	1	1/6	1/7	1/5

A5	7	1/7	4	6	1	7	7
A6	1	1/8	5	7	1/7	1	1/4
A7	4	1	5	5	1/7	4	1
SUM	22	7 2/5	24 1/5	24 2/5	8 5/6	21 1/3	10

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.05	0.14	0.04	0.01	0.02	0.05	0.03	0.05
A2	0.05	0.14	0.33	0.01	0.79	0.37	0.10	0.26
A3	0.05	0.02	0.04	0.20	0.03	0.01	0.02	0.05
A4	0.32	0.54	0.01	0.04	0.02	0.01	0.02	0.14
A5	0.32	0.02	0.17	0.25	0.11	0.33	0.71	0.27
A6	0.05	0.02	0.21	0.29	0.02	0.05	0.03	0.09
A7	0.18	0.14	0.21	0.20	0.02	0.19	0.10	0.15
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	13.297453

Consistency Index

n (size of comparision matrix)	7
CI	1.050

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.795

Objective 3

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	9	9	9	1	9	9
A2	1/9	1	5	6	1	8	9
A3	1/9	1/5	1	1	1	3	1
A4	1/9	1/6	1	1	6	1	1
A5	1	1	1	0.1666667	1	1	7
A6	1/9	1/8	1/3	1	1	1	1
A7	1/9	1/9	1	1	1/7	1	1
SUM	2 5/9	11 3/5	18 1/3	19 1/6	11 1/7	24	29

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.39	0.78	0.49	0.47	0.09	0.38	0.31	0.41
A2	0.04	0.09	0.27	0.31	0.09	0.33	0.31	0.21
A3	0.04	0.02	0.05	0.05	0.09	0.13	0.03	0.06
A4	0.04	0.01	0.05	0.05	0.54	0.04	0.03	0.11
A5	0.39	0.09	0.05	0.01	0.09	0.04	0.24	0.13
A6	0.04	0.01	0.02	0.05	0.09	0.04	0.03	0.04
A7	0.04	0.01	0.05	0.05	0.01	0.04	0.03	0.04
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	10.16659

Consistency Index

n (size of comparision matrix)	7
CI	0.528

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.400

Objective 4

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	8	6	6	5	7	3
A2	1/8	1	8	1	1	9	1
A3	1/6	1/8	1	1	1	1	5
A4	1/6	1	1	1	1	1	1
A5	1/5	1	1	1	1	1	7
A6	1/7	1/9	1	1	1	1	6
A7	1/3	1	1/5	1	1/7	0.1666667	1
SUM	2 1/7	12 1/4	18 1/5	12	10 1/7	20 1/6	24

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.47	0.65	0.33	0.50	0.49	0.35	0.13	0.42
A2	0.06	0.08	0.44	0.08	0.10	0.45	0.04	0.18
A3	0.08	0.01	0.05	0.08	0.10	0.05	0.21	0.08
A4	0.08	0.08	0.05	0.08	0.10	0.05	0.04	0.07
A5	0.09	0.08	0.05	0.08	0.10	0.05	0.29	0.11
A6	0.07	0.01	0.05	0.08	0.10	0.05	0.25	0.09
A7	0.16	0.08	0.01	0.08	0.01	0.01	0.04	0.06
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	9.6413455

Consistency Index

n (size of comparision matrix)	7
CI	0.440

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.334

Objective 5

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	8	4	6	1	1	1
A2	1/8	1	9	1	1	6	5
A3	1/4	1/9	1	1	6	1	1
A4	1/6	1	1	1	1	1	1
A5	1	1	1/6	1	1	1	1
A6	1	1/6	1	1	1	1	1
A7	1	1/5	1	1	1	1	1
SUM	4 1/2	11 1/2	17 1/6	12	12	12	11

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.22	0.70	0.23	0.50	0.08	0.08	0.09	0.27
A2	0.03	0.09	0.52	0.08	0.08	0.50	0.45	0.25
A3	0.06	0.01	0.06	0.08	0.50	0.08	0.09	0.13
A4	0.04	0.09	0.06	0.08	0.08	0.08	0.09	0.07

A5	0.22	0.09	0.01	0.08	0.08	0.08	0.09	0.09
A6	0.22	0.01	0.06	0.08	0.08	0.08	0.09	0.09
A7	0.22	0.02	0.06	0.08	0.08	0.08	0.09	0.09
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	10.394973

Consistency Index

n (size of comparision matrix)	7
CI	0.566

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.429

Response 4

Goal

To select the most important factors affecting the decommissioning process

Demographics

Core Activities	both
Years Experience	More than 10 years
Role	Consultancy
Expertise	Well plugging and aba
Highest Qualification	Master's Degree
Chartered?	No
Incorporated?	No

Criteria

C1	Understanding onshore regulations
C2	Understanding offshore regulations
C3	Reduction in length of waste stream
C4	Reduction in volume of waste

Alternatives

A1	Reducing costs of decommissioning process
A2	Knowledge & best practice sharing
A3	Understanding of liability throughout waste stream
A4	Knowledge of offshore processes by onshore personnel
A5	Understanding of legislative compliance along waste stream
A6	Identification of older equipment
A7	Reuse of recertified/ remanufactured equipment

Objectives

Objective 1	To ensure sustainable and successful decommissioning of offshore installations
Objective 2	To ensure onshore legislation and regulations are understood.
Objective 3	To ensure offshore legislation and regulations are understood.
Objective 4	To reduce the length of the waste stream.
Objective 5	To reduce the volume of waste.

Objective 1

Pairwise Matrix

	C1	C2	C3	C4
C1	1	1/4	1/2	1/2
C2	4	1	5	5
C3	2	1/5	1	1
C4	2	1/5	1	1
SUM	9	1 2/3	7 1/2	7 1/2

Normalised Matrix

	C1	C2	C3	C4	Criteria Weights
C1	0.11	0.15	0.07	0.07	0.10
C2	0.44	0.61	0.67	0.67	0.60
C3	0.22	0.12	0.13	0.13	0.15
C4	0.22	0.12	0.13	0.13	0.15
SUM	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	4.1621

Consistency Index

n (size of comparision matrix)	4
CI	0.054

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.060

Objective 2

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	1	1/3	1/3	1/3	1	1/3
A2	1	1	1/3	1/3	1	1	1
A3	3	3	1	3	1	3	3
A4	3	3	1/3	1	1/3	2	3

A5	3	1	1	3	1	2	2
A6	1	1	1/3	1/2	1/2	1	1
A7	3	1	1/3	1/3	1/2	1	1
SUM	15	11	3 2/3	8 1/2	4 2/3	11	11 1/3

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.07	0.09	0.09	0.04	0.07	0.09	0.03	0.07
A2	0.07	0.09	0.09	0.04	0.21	0.09	0.09	0.10
A3	0.20	0.27	0.27	0.35	0.21	0.27	0.26	0.26
A4	0.20	0.27	0.09	0.12	0.07	0.18	0.26	0.17
A5	0.20	0.09	0.27	0.35	0.21	0.18	0.18	0.21
A6	0.07	0.09	0.09	0.06	0.11	0.09	0.09	0.08
A7	0.20	0.09	0.09	0.04	0.11	0.09	0.09	0.10
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	7.5938115

Consistency Index

n (size of comparision matrix)	7
CI	0.099

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	✅ 0.075

Objective 3

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	3	1	1	3	3	3
A2	1/3	1	1/3	1/3	1/3	1	1
A3	1	3	1	2	3	3	3
A4	1	3	1/2	1	1	3	3
A5	1/3	3	1/3	1	1	1	1
A6	1/3	1	1/3	1/3	1	1	1
A7	1/3	1	1/3	1/3	1	1	1
SUM	4 1/3	15	3 5/6	6	10 1/3	13	13

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.23	0.20	0.26	0.17	0.29	0.23	0.23	0.23
A2	0.08	0.07	0.09	0.06	0.03	0.08	0.08	0.07
A3	0.23	0.20	0.26	0.33	0.29	0.23	0.23	0.25
A4	0.23	0.20	0.13	0.17	0.10	0.23	0.23	0.18
A5	0.08	0.20	0.09	0.17	0.10	0.08	0.08	0.11
A6	0.08	0.07	0.09	0.06	0.10	0.08	0.08	0.08
A7	0.08	0.07	0.09	0.06	0.10	0.08	0.08	0.08
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	7.2308006

Consistency Index

n (size of comparision matrix)	7
CI	0.038

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.029

Objective 4

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	3	1	1	3	3	3
A2	1/3	1	1/3	1/2	1	1	1
A3	1	3	1	3	3	4	4
A4	1	2	1/3	1	1	3	3
A5	1/3	1	1/3	1	1	3	2
A6	1/3	1	1/4	1/3	1/3	1	1
A7	1/3	1	1/4	1/3	1/2	1	1
SUM	4 1/3	12	3 1/2	7 1/6	9 5/6	16	15

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.23	0.25	0.29	0.14	0.31	0.19	0.20	0.23
A2	0.08	0.08	0.10	0.07	0.10	0.06	0.07	0.08
A3	0.23	0.25	0.29	0.42	0.31	0.25	0.27	0.29
A4	0.23	0.17	0.10	0.14	0.10	0.19	0.20	0.16
A5	0.08	0.08	0.10	0.14	0.10	0.19	0.13	0.12
A6	0.08	0.08	0.07	0.05	0.03	0.06	0.07	0.06
A7	0.08	0.08	0.07	0.05	0.05	0.06	0.07	0.07
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	7.2334416

Consistency Index

n (size of comparision matrix)	7
CI	0.039

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.029

Objective 5

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	3	1/3	1/2	3	3	3
A2	1/3	1	1/3	1/3	1/2	1/2	1/3
A3	3	3	1	3	3	3	3
A4	2	3	1/3	1	1	1	1
A5	1/3	2	1/3	1	1	1	1
A6	1/3	2	1/3	1	1	1	1
A7	1/3	3	1/3	1	1	1	1
SUM	7 1/3	17	3	7 5/6	10 1/2	10 1/2	10 1/3

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.14	0.18	0.11	0.06	0.29	0.29	0.29	0.19
A2	0.05	0.06	0.11	0.04	0.05	0.05	0.03	0.06
A3	0.41	0.18	0.33	0.38	0.29	0.29	0.29	0.31
A4	0.27	0.18	0.11	0.13	0.10	0.10	0.10	0.14

A5	0.05	0.12	0.11	0.13	0.10	0.10	0.10	0.10
A6	0.05	0.12	0.11	0.13	0.10	0.10	0.10	0.10
A7	0.05	0.18	0.11	0.13	0.10	0.10	0.10	0.11
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	7.5399177

Consistency Index

n (size of comparision matrix)	7
CI	0.090

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.068

Response 5

Goal

To select the most important factors affecting the decommissioning process

Demographics

Core Activities	other	Education
Years Experience	More than 10 years	
Role	Other	Lecturer
Expertise	Waste management	
Highest Qualification	Doctorate	
Chartered?	No	
Incorporated?	No	

Criteria

C1	Understanding onshore regulations
C2	Understanding offshore regulations
C3	Reduction in length of waste stream
C4	Reduction in volume of waste

Alternatives

A1	Reducing costs of decommissioning process
A2	Knowledge & best practice sharing
A3	Understanding of liability throughout waste stream
A4	Knowledge of offshore processes by onshore personnel
A5	Understanding of legislative compliance along waste stream
A6	Identification of older equipment
A7	Reuse of recertified/ remanufactured equipment

Objectives

Objective 1	To ensure sustainable and successful decommissioning of offshore installations
Objective 2	To ensure onshore legislation and regulations are understood.
Objective 3	To ensure offshore legislation and regulations are understood.
Objective 4	To reduce the length of the waste stream.
Objective 5	To reduce the volume of waste.

Objective 1

Pairwise Matrix

	C1	C2	C3	C4
C1	1	1	1/2	1/2
C2	1	1	1/2	1/2
C3	2	2	1	1
C4	2	2	1	1
SUM	6	6	3	3

Normalised Matrix

	C1	C2	C3	C4	Criteria Weights
C1	0.17	0.17	0.17	0.17	0.17
C2	0.17	0.17	0.17	0.17	0.17
C3	0.33	0.33	0.33	0.33	0.33
C4	0.33	0.33	0.33	0.33	0.33
SUM	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	4.0000

Consistency Index

n (size of comparision matrix)	4
CI	0.000

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.000

Objective 2

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	9	1	7	1	5	5
A2	1/9	1	1/5	1/3	1/5	1/6	1/6
A3	1	5	1	1	1	5	5
A4	1/7	3	1	1	1/2	1/5	1/5

A5	1	5	1	2	1	3	3
A6	1/5	6	1/5	5	1/3	1	1
A7	1/5	6	1/5	5	1/3	1	1
SUM	3 2/3	35	4 3/5	21 1/3	4 3/8	15 3/8	15 3/8

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.27	0.26	0.22	0.33	0.23	0.33	0.33	0.28
A2	0.03	0.03	0.04	0.02	0.05	0.01	0.01	0.03
A3	0.27	0.14	0.22	0.05	0.23	0.33	0.33	0.22
A4	0.04	0.09	0.22	0.05	0.11	0.01	0.01	0.08
A5	0.27	0.14	0.22	0.09	0.23	0.20	0.20	0.19
A6	0.05	0.17	0.04	0.23	0.08	0.07	0.07	0.10
A7	0.05	0.17	0.04	0.23	0.08	0.07	0.07	0.10
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	8.5483362

Consistency Index

n (size of comparision matrix)	7
CI	0.258

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.195

Objective 3

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	5	3	6	1	1/2	1/2
A2	1/5	1	1/4	1/3	1/5	1	1
A3	1/3	4	1	7	1	8	8
A4	1/6	3	1/7	1	1/2	1/5	1/5
A5	1	5	1	2	1	8	8
A6	2	1	1/8	5	1/8	1	1
A7	2	1	1/8	5	1/8	1	1
SUM	6 5/7	20	5 2/3	26 1/3	4	19 2/3	19 2/3

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.15	0.25	0.53	0.23	0.25	0.03	0.03	0.21
A2	0.03	0.05	0.04	0.01	0.05	0.05	0.05	0.04
A3	0.05	0.20	0.18	0.27	0.25	0.41	0.41	0.25
A4	0.02	0.15	0.03	0.04	0.13	0.01	0.01	0.06
A5	0.15	0.25	0.18	0.08	0.25	0.41	0.41	0.25
A6	0.30	0.05	0.02	0.19	0.03	0.05	0.05	0.10
A7	0.30	0.05	0.02	0.19	0.03	0.05	0.05	0.10
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	9.9652773

Consistency Index

n (size of comparision matrix)	7
CI	0.494

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.374

Objective 4

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	8	1	9	1	8	8
A2	1/8	1	1/2	1/3	1/6	3	3
A3	1	2	1	7	1	9	8
A4	1/9	3	1/7	1	1/7	1/5	1/6
A5	1	6	1	7	1	9	8
A6	1/8	1/3	1/9	5	1/9	1	1
A7	1/8	1/3	1/8	6	1/8	1	1
SUM	3 1/2	20 2/3	3 7/8	35 1/3	3 5/9	31 1/5	29 1/6

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.29	0.39	0.26	0.25	0.28	0.26	0.27	0.29
A2	0.04	0.05	0.13	0.01	0.05	0.10	0.10	0.07
A3	0.29	0.10	0.26	0.20	0.28	0.29	0.27	0.24
A4	0.03	0.15	0.04	0.03	0.04	0.01	0.01	0.04
A5	0.29	0.29	0.26	0.20	0.28	0.29	0.27	0.27
A6	0.04	0.02	0.03	0.14	0.03	0.03	0.03	0.05
A7	0.04	0.02	0.03	0.17	0.04	0.03	0.03	0.05
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	8.6577389

Consistency Index

n (size of comparision matrix)	7
CI	0.276

Saaty's Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Consistency Ratio

CR	0.209

Objective 5

Pairwise Matrix

	A1	A2	A3	A4	A5	A6	A7
A1	1	7	1	9	1	1	1
A2	1/7	1	1/7	1/5	1/7	1/6	1/6
A3	1	7	1	9	1	8	8
A4	1/9	5	1/9	1	1/9	1/6	1/6
A5	1	7	1	9	1	8	8
A6	1	6	1/8	6	1/8	1	1
A7	1	6	1/8	6	1/8	1	1
SUM	5 1/4	39	3 1/2	40 1/5	3 1/2	19 1/3	19 1/3

Normalised Matrix

	A1	A2	A3	A4	A5	A6	A7	Criteria Weights
A1	0.19	0.18	0.29	0.22	0.29	0.05	0.05	0.18
A2	0.03	0.03	0.04	0.00	0.04	0.01	0.01	0.02
A3	0.19	0.18	0.29	0.22	0.29	0.41	0.41	0.28
A4	0.02	0.13	0.03	0.02	0.03	0.01	0.01	0.04

A5	0.19	0.18	0.29	0.22	0.29	0.41	0.41	0.28
A6	0.19	0.15	0.04	0.15	0.04	0.05	0.05	0.10
A7	0.19	0.15	0.04	0.15	0.04	0.05	0.05	0.10
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Consistency

λ_{max}	8.9733755

Consistency Index

n (size of comparision matrix)	7
CI	0.329

Saaty's Random Consistency Index (RI)

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
RI	*0*	*0*	*0.58*	*0.9*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*	*1.49*

Consistency Ratio

CR	0.249

APPENDIX .C: Conditional Probability Tables – Initial BN.

Decom Decision Made	
Yes	0.99
No	0.01

Decom Decision Made		Yes	No
Further Action	Yes	0.01	0.99
	No	0.99	0.01

Knowledge & Best Practice		Yes		No	
Decom Decision Made		Yes	No	Yes	No
Identification of Waste Materials	Yes	0.978	0.99	0.01	0.022
	No	0.022	0.01	0.99	0.978

Knowledge & Best Practice	
Yes	0.012
No	0.988

Identification of Waste Mat		Yes	No
Environmental Event	Yes	0.01	0.99
	No	0.99	0.01

Knowledge & Best Practice		Yes	No
Understanding of Offshore Legislation	Yes	0.099	0.099
	No	0.901	0.901

Identification of Waste Materials		Yes	No
Reduce Decom Cost	Yes	0.97	0.03
	No	0.03	0.97

Identification of Waste Materials		Yes	No
Reduce Volume of Waste	Yes	0.9476	0.0254
	No	0.0254	0.9476

Reduce Decom Cost		Yes		No	
Reduce Volume of Waste		Yes	No	Yes	No
Reduce Length of Waste Stream	Yes	0.97	0.46	0.54	0.03
	No	0.03	0.54	0.46	0.97

Understanding of Onshore Legislation	
Yes	0.0165
No	0.9835

Understanding of Offshore Legislation		Yes				No			
Knowledge & Best Practice		Yes		No		Yes		No	
Understanding of Onshore Legislation		Yes	No	Yes	No	Yes	No	Yes	No
Understanding of Liability Across Waste Stream	Yes	0.92	0.795	0.825	0.701	0.299	0.175	0.205	0.08
	No	0.08	0.205	0.175	0.299	0.701	0.825	0.795	0.92

Understanding of Liability Across Waste Stream		Yes	No
Liability Event	Yes	0.01	0.99
	No	0.99	0.01

APPENDIX .D: Conditional Probability Tables – Combined BN.

	Yes	No
N1 - Is Decom taking place?	0.99	0.01

N14 - Knowledge & best practice sharing	Yes	No
	0.01247	0.98753

N1- Is Decom taking place?		Yes	No
N2- Is there a complete inventory	Yes	0.254	0.746
	No	0.746	0.254

N3 - Survey	
Yes	0.403
Noe	0.597

N1- Is Decom taking place?		Yes	No
N3 - Has a detailed survey taken place?	Yes	0.403	0.597
	No	0.597	0.403

N2 - Inventory	
Yes	0.254
No	0.746

N14 - Knowledge & Best Practice Sharing		Yes				No			
N3 - Has a detailed survey taken place?		Yes		No		Yes		No	
N2- Is there a complete inventory		Yes	No	Yes	No	Yes	No	Yes	No
N4 - Has all the material been identified?	Yes	0.339416	0.526214	0.45628	0.643078	0.356922272	0.543720478	0.473786	0.660584
	No	0.660584	0.473786	0.54372	0.356922	0.643077728	0.456279522	0.526214	0.339416

N5 - Have all the correct permits been applied for?		Yes	No
E1 - Liability Event	Yes	0.01	0.99
	No	0.99	0.01

N4 - Has all the material been identified?		Yes	No
N6 - Reduce volume of waste	Yes	0.0141	0.5749
	No	0.9859	0.4251

N4 - Has all the material been identified?		Yes	No
N8 - Reduce Decom Cost	Yes	0.01691	0.5771
	No	0.98309	0.4229

N4 - Has all the material been identified?		Yes	No
N9 - Material tansported in tote tanks	Catastrophic	0.000113	8.72E-05
	Large Hole	0.000338	0.000262
	Small Hole	0.00141	0.00109
	None	0.562139	0.434561

N4 - Has all the material been identified?		Yes	No
N10 - Orignial Containment	seals	0.1325	0.1025
	valves	0.0564	0.0436
	pipes	0.0948	0.0732
	tanks	0.0451	0.0349
	machinery	0.0400	0.0310
	undefined	0.1122	0.0868
	None	0.0829	0.0641

N9 - Material transported in tote tanks		Catastophic						
N10 - Original Containment		Seals & Fittings	Valves	Pipes & Hoses	Tanks	Machinery	Undefined	None
N11 - Final Destination	Recycle Reuse	0.03	0.03	0.03	0.03	0.03	0.03	0.97
	Landfill	0.97	0.97	0.97	0.97	0.97	0.97	0.03

N9 - Material transported in tote tanks		Large hole						
N10 - Original Containment		Seals & Fittings	Valves	Pipes & Hoses	Tanks	Machinery	Undefined	None
N11 - Final Destination	Recycle Reuse	0.03	0.03	0.03	0.03	0.03	0.03	0.97
	Landfill	0.97	0.97	0.97	0.97	0.97	0.97	0.03

N9 - Material transported in tote tanks		Small hole						
N10 - Original Containment		Seals & Fittings	Valves	Pipes & Hoses	Tanks	Machinery	Undefined	None
N11 - Final Destination	Recycle Reuse	0.03	0.03	0.03	0.03	0.03	0.03	0.97
	Landfill	0.97	0.97	0.97	0.97	0.97	0.97	0.03

N9 - Material transported in tote tanks		None						
N10 - Original Containment		Seals & Fittings	Valves	Pipes & Hoses	Tanks	Machinery	Undefined	None
N11 - Final Destination	Recycle Reuse	0.03	0.03	0.03	0.03	0.03	0.03	0.97
	Landfill	0.97	0.97	0.97	0.97	0.97	0.97	0.03

N9 - Material transported in tote tanks		Catastrophic	Large Hole	Small Hole	None
E2 - Environmental Event	Yes	0.0002	0.0006	0.0025	0.9967
	No	0.9998	0.9994	0.9975	0.0033

N10 - Original Containment		Seals	Valves	Pipes	Tanks	Machinery	Undefined	None
E3 - Environmental Event	Yes	0.235	0.100	0.168	0.080	0.071	0.199	0.147
	No	0.765	0.900	0.832	0.920	0.929	0.801	0.853