A Multi-attribute Quantitative Assessment System for Offshore Facilities' Decommissioning Options Decision-making

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Abstract

Since offshore oil and gas resources have been developed widely worldwide for decades, some facilities have reached the end of their service lives and need to be decommissioned. However, due to the constraints of relevant regulations, technologies, costs, potential risks, and environmental impacts, what options should be taken for decommissioning offshore facilities and whether the chosen method can be convincing have always been puzzling the offshore industry. This research is devoted to developing a multi-attribute quantitative evaluation system called MADM-Q (Multi-attribute Decision Making-Quantitative), which can quickly provide decision makers with reliable quantitative evaluations in the engineering planning stage and choose the most reasonable decommissioning options. The proposed system refers to the current comparative assessment method in the UK and sets up three assessment sub-modules: cost, risk, and impact. The first sub-model, Engineering Cost Evaluation System (ECES) is the first bottom-up approaches cost assessment model in offshore facility decommissioning research. This project uses 26 reports, including 32 facilities' historical data of decommissioned platforms in the North Sea to establish two cost assessment models and compares the model performance. The comparison results show that the ECES used more data categories (7 categories minimum) than top-down approach (5 categories minimum) and has better accuracy than top-down framework model built by other researchers. The second sub-model, innovative Hierarchical Analyst Domino Evaluation System (HADES) acts as a risk assessment module, considering Domino Effect Accidents (DEAs) and providing accurate and rapid quantitative risk assessment results. The HADES is a quasi-dynamic quantitative risk assessment system constructed by combining the core idea of AHP with traditional QRA. It defines the trigger mechanism of DEAs in two sufficient and necessary principles and builds a new accident scene generation mechanism based on the two principles. This method is different from the scenario hypothesis method used by traditional QRA but allows the system generate accident scenarios dynamically according to the accident situation and build the DEAs causality network. The third sub-model, Composite Impact Evaluation System (CIES) assesses the environmental and socioeconomic impacts of the project as one of the cost modifiers. This part mainly considers the marine environmental and social impact caused by the hydrocarbon leakage accident and converts the impact results into monetary form as part of the project reserve cost that energy companies need to prepare. In addition, there are also data exchanging among the three modules:

- The ECES results will serve as the basis.
- The HADES results will be incorporated to remind decision-makers to prepare for reserve cost.

- The HADES results will be fed into the CIES to quantify the project's negative impacts, which may increase reserve cost.

According to the requirements of decision makers for different decommissioning options, the system can quickly obtain the basic cost range and the Individual Risk Per Annum (IRPA) value of the project by only using the basic information of the offshore facility itself and the location information as input. The three modules in this system have a mature framework, and the detailed methods used are based on physics and general-purpose industrial equations. It can be applied to different regions of the world only by regional adaptation of commercial data. Among them, after comparing the evaluation results of ECES and HADES with the actual results of the case report, it reflects the excellent accuracy of the ECES and HADES systems - 12% cost evaluation average deviation and 1.43E-04 IRPA Evaluation bias. In addition, the three modules provide many access ports, allowing users to use more optimized methods, such as the results obtained by finite element analysis as input values to obtain more accurate accident scene development models and evaluation results. Among them, although the HADES method is currently only a quasi-dynamic risk assessment method, it can be developed into a real-time dynamic risk monitoring and assessment system by combining advanced technologies such as digital twin technology and sensor technology, which has excellent development potential.

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Author's Declaration

I have read and understood the rules on cheating, plagiarism and appropriate referencing as outlined in the ethics handbook and I declare that the work contained in this thesis is my own, unless otherwise acknowledged. I wish to further declare that some parts of this thesis may contain relevant texts and/or data from my published and unpublished works which were either quoted verbatim or further analysed to new revealing depths.

Signed: Yihong Li

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List of Publications

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Abbreviations

AHP	Analytic Hierarchy Process
ALARP	As Low As Reasonably Practicable
ARO	Asset Retirement Obligations
ASCOPE	ASEAN Petroleum Council
ASEAN	Association of Southeast Asian Nations
BAT	Best Available Technology
BBN	Bayesian Belief Network
BEIS	Department for Business, Energy and Industrial Strategy
BEP	Best Environmental Practice
BLEVE	Boiling Liquid Expanding Vapor Explosion
BOP	Blowout Preventers
BORA	Barrier and Operational Risk Analysis
BSEE	Bureau of Safety and Environmental Enforcement
BYOD	Bring Your Own Device
CA	Comparative Assessment
CBD	Convention on Biological Diversity
CCS	China Classification Society
CFD	Computational Fluid Dynamics
CGBS	Concrete Gravity Base Structures
CIES	Composite Impact Evaluation System
CITES	Convention on International Trade in Endangered Species
COBSEA	Coordinating Body on the Seas of East Asia
COG	Centre of Gravity
DAPSI(W)R(M)	Drivers, Activities, Pressures, State changes, Impacts (on Welfare), and Responses (as Measures)
DEAs	Domino Effect Accidents
DMI	Direct Material Input
DSV	Diving Support Vessel
DTI	Department of Trade and Industry
EA	Economic Appraisal
EBRD	European Bank for Reconstruction and Development
EC	European Community

ECES	Engineering Cost Evaluation System
EEZ	Exclusive Economic Zone
EFTA	European Free Trade Association
EHS	Environmental, Health, and Safety
EIA	Environmental Impact Assessment
EIF	Environmental Impact Factor
ELECTRE	Elimination and Choice Expressing the Reality
ETA	Event Tree Analysis
FEM	Finite Element Method
FMEA	Failure Mode and Effect Analysis
FPSO	Floating Production, Storage, and Offloading
FTA	Fault Tree Analysis
GOM	Gulf of Mexico
HADES	Hierarchical Analyst Domino Evaluation System
HAZID	Hazard Identification
HAZOP	Hazard and operability study
HCL	Hybrid Causal Logic
HLV	Heavy Lift Vessel
HOF	Human and Organizational Factors
ICF	International Coaching Federation
IRPA	Individual Risk Per Annum
LTM	Logarithm Transformation Model
MADM-Q	Multiple Attribute Decision Making - Quantitative
MAUT	Multi-attribute Utility Theory
MCDA	Multi-criteria Decision Analysis
MEFA	Material and Energy Flow Analysis
MIP	Mixed Integer Programming
MIRA	Miljørettet RisikoAnalyse
MOPU	Mobile Offshore Production Units
MPA	Marine Protect Area
MTO	Man, Technology and Organization
NCS	Norwegian Continental Shelf
NEBA	Net Environmental Benefit Analysis
NORM	Naturally Occurring Radioactive Materials

NRC	Nuclear Regulatory Commission
NWH	North West Hutton
OECD	Organisation for Economic Cooperation and Development
OMT	Risk Organizational, Human and Technology Project
OWF	Offshore Wind Farm
OMEGA	Oracle Multicriterial General Assessment of Decommissioning
PAES	Platform Abandonment Estimating System
PHA	Preliminary Hazard Analysis
PRA	Probabilistic Risk Assessment
PROMETHEE	Preference Ranking Organization Method
QRA	Quantitative Risk Analysis
RNNP	Risk level in the Norwegian petroleum activity
ROV	Remotely Operated underwater Vehicle
SAFOP	Safe operations study
SAW	Simple Additive Weighting
SEMI	Semi-submersible Platforms
SIA	Social Impact Assessment
SLM	Settled Liability Model
SLV	Single Lift Vessel
SMART	Simple Multi-Attribute Rating Technique
SMARTER	Simple Multi-Attribute Rating Technique Exploiting Ranks
SMARTS	Simple Multi-Attribute Rating Technique with Swing weight
SQ	Semi-quantitative and Qualitative Methodologies
SSCV	semi-submersible Crane Vessel
SSTMP	Subsea Templates
STL	Submerged Turret Loading System
SWOT	Strengths Weakness Opportunities and Threats
TCD	Targets Criteria Database
TFO	Total Field Output
TLP	Tension Leg Platforms
TMR	Total Material Requirement
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TST	Technical Safety Condition
TTS	Technical Condition Safety

U/LFL	Upper/Lower Flammable Limit
UKCS	United Kingdom Continental Shelf
UKNEAFO	UK National Ecosystem Assessment Follow-On
VCE	Vapor Cloud Explosion
VECs	Valued Environmental Components
Well P&A	Well Plug & Abandonment
WP	Well Protector

Chapter 1. Introduction

From establishing the first offshore oil and gas facility in 1897 (Howard B & W, 1987) to nearly 7,500 oil wells in the world in beginning the 21st century (ICF International, 2015), the technology of offshore oil and gas facilities has been developed for more than a hundred years, and the technology of oil and gas exploration, exploitation and storage has been significantly expanded (Tang et al., 2018). It is only in recent years that the decommissioning of offshore facilities has begun to be taken seriously by the world's major offshore oil producers due to a growing emphasis on environmental protection, a desire for cost reduction, and several catastrophic offshore facility accidents (Bull & Love, 2019). According to estimation (Fowler et al., 2014), within the next few decades, 85% of the world's offshore facilities will be decommissioned after reaching a design life of up to 30 years. In the UK North Sea, there will be more than 350 facilities with about 3 million tons of superstructures by 2040 and more than one million tons of substructures to be decommissioned, requiring a total of about 30 billion decommissioning costs (OGUK, 2018). The world's other major offshore oil producers, such as Norway, the Netherlands, Germany, the United States, Thailand, Malaysia, and Brazil, face the similar situation (Ruivo & Morooka, 2007). The global wave of decommissioning of offshore facilities has begun to wash over energy companies and national governments. Environmental groups, the media, the public, and stakeholders such as fishing groups are looking at what energy companies do with decommissioned platforms. Once mishandled, the aftermath of the Brent Spar incident remains yesterday (Löfstedt & Renn, 1997). Such a situation undoubtedly puts enormous pressure on energy companies and government decision-makers: to control the acceptability of costs and construction risks, maintain their social image, and protect other stakeholders' claims for marine rights and interests.

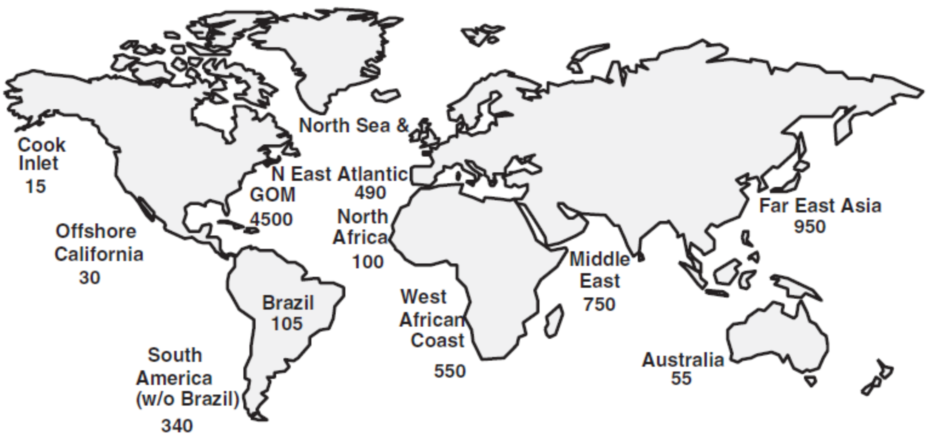


Figure 1. Global platform distribution in 2003 (Parente et al., 2006)

However, the current technology cannot satisfy the decision-makers of offshore industry and governments to obtain the effective and reasonable decision-making results. Excessive qualitative analysis and the use of expert scoring techniques make the assessment reports lack sufficient objectivity and reliability. Similarly, too subjective assessment results cannot convince the public and stakeholders to support the decision-making of energy companies and governments, thus creating contradictions, increasing decommissioning project expenses in disguise, and affecting energy companies' credibility and stock price (Li & Hu, 2022).

Therefore, it is of crucial importance to develop a multi-attribute evaluation system that takes quantitative analysis as the core, qualitative analysis, and expert scoring as the auxiliary, fully integrates the three aspects of cost, risk and impact evaluation and can make them affect each other. The system should be modular, and the detailed approach used for each module should lean towards more general physical and industrial equation to ensure the system can use in different areas. At the same time, the system should be hierarchical, which is convenient for non-professionals or semi-professionals to use, construct and modify parameters, and combine artificial intelligence or other advanced algorithms to improve the computing speed in the future. Finally, the system should strive to obtain results that are close to reality based on the above. Then the system modules are able to interact with each other to revise the results.

1.1 Offshore Decommissioning Basic Knowledge

Identifying options and steps for decommissioning offshore facilities is the basis for studying this issue. The decommissioning scheme determines the costs and risks of decommissioning and the reaction of society to the scheme. The decommissioning steps are related to the category of cost calculation, the content and the sequence of risk assessment. Due to regional and national regulations, some decommissioning options are not feasible and will be input as primary boundary conditions in the decision-making model. Furthermore, different decommissioning options will also miss some decommissioning steps, thereby reducing costs and quantitative risk assessment results.

There are many categories of offshore facilities: Concrete Gravity Base Structures (CGBS), compliant towers, fixed platforms, Floating Production, Storage, and Offloading (FPSO) vessels, Mobile Offshore Production Units (MOPU), Tension Leg Platforms (TLP), Semi-submersible platforms (SEMI), Spars, Well Protectors (WP), Subsea Templates (SSTMP)(Walker & Roberts, 2013). Typically, these facilities have a design life of 15-30 years, depending on their size, and not all these facilities are oil and gas extraction facilities. Some are living platforms, refining platforms, storage facilities or control facilities. Therefore, to evaluate the pros and cons of a facility's decommissioning plan, it is necessary to have a detailed understanding of the facility's function, scale, location type, and area et al.

1.1.1 Decommissioning Options

Decommissioning options refer to the disposal options during and after the decommissioning of a facility. The decommissioning process options for these facilities usually fall into three categories: complete remove, the partial remove of varying degrees, and leaving situ. There are four types of disposals after decommissioning: reuse, renovation, onshore dismantling and sinking. Combining the above options yields a total of eleven categories of decommissioning options, as shown in the Table 1 (Bull & Love, 2019). For fixed platforms, the decommissioning options are shown in Figure 2. It should be mentioned that due to the OSPAR 98/3 resolution(OSPAR Commission, 1998), submersion of media into artificial reefs is temporarily not allowed in Europe, but this option has already been practiced in other countries in the world (Picken et al., 2000; Kaiser & Pulsipher, 2005).

Table 2. Offshore Decommissioning Options.

Procedure options	Process options	Combination			
A. Completely removal	1. Reuse	A1	A2	A3	A4
B. Partly removal	2. Transformation	B1	B2	B3	B4
C. Leave situ	3. Onshore recycle	C1	C2	C4	
	4. Sink situ. or other place				

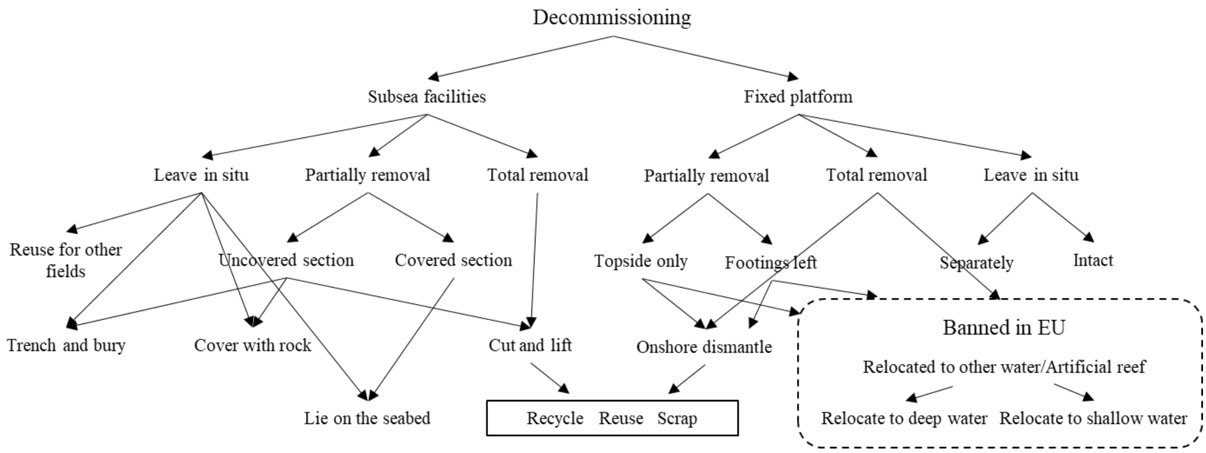


Figure 2. Decommissioning options for fixed platforms and subsea facilities (Fowler et al., 2014; Ekins et al., 2006)

As mentioned above, decommissioning options are influenced by facility type, location, and water depth. Some unique structures, such as CGBS, are too costly and risky to remove entirely due to their excessive weight. Only the topside can be removed, and the underwater part is left in place after cleaning. This rationalization scheme may also have social implications. The original decommissioning plan for the Brent Spar was to tow the buoy part to sink in the deep North Sea. This option has been evaluated by several experts and has no impact on the environment. However, the social chain reaction caused by the strong reaction of environmentalists forced the project team to drag the attached parts to shore for dismantling, which significantly increased the cost of decommissioning (Löfstedt & Renn, 1997). Social repercussions are likely to affect the final decommissioning option. Effective communication and strict relevant legislation and regulations are effective ways to prevent such incidents from happening.

1.1.2 Decommissioning Procedures

The decommissioning options for offshore facilities are usually used as the primary boundary condition of the evaluation model, and the steps for decommissioning the offshore facilities are arranged according to the decommissioning options as the framework backbone of the evaluation model. It is generally believed that the decommissioning phase of an offshore facility is the reverse engineering of its installation step (ICF International, 2015). Still, according to Figure 3, the decommissioning phase is not a simple reverse installation.

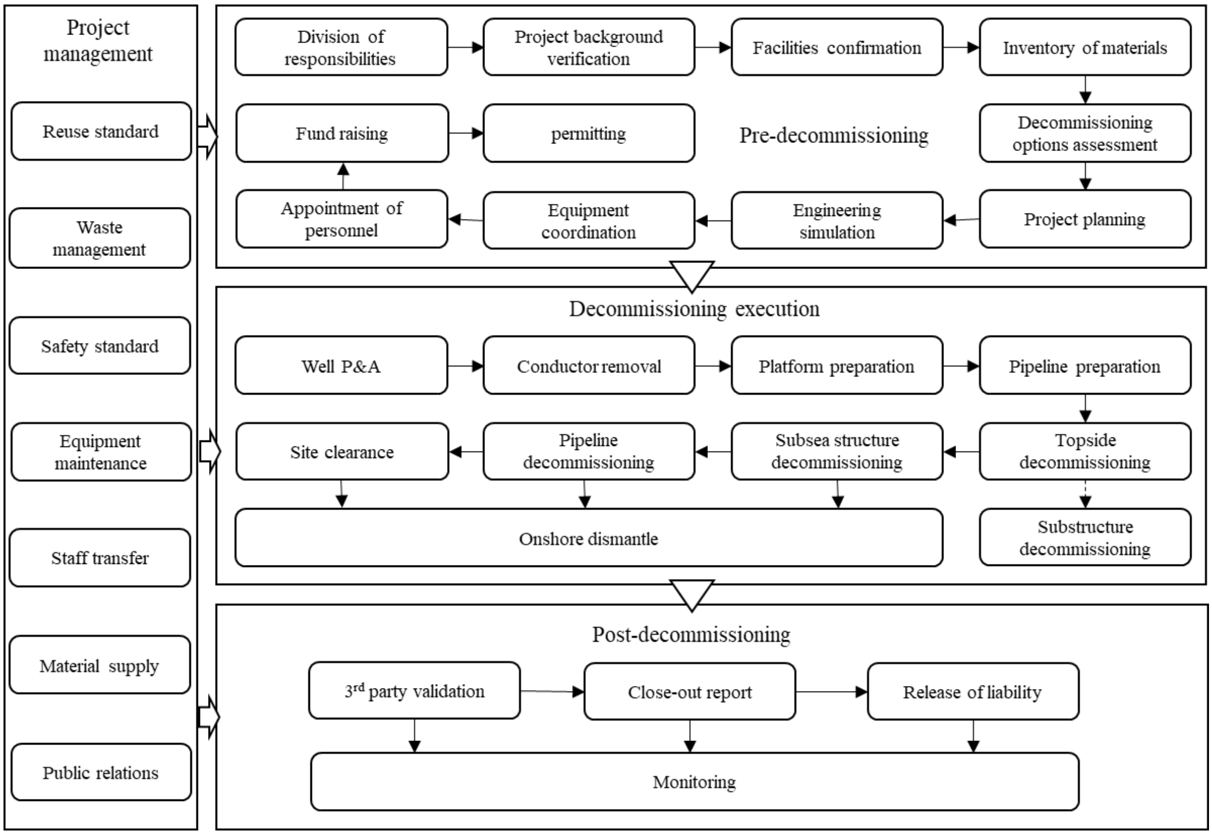


Figure 3. General decommissioning procedures for offshore oil and gas facilities (Fam et al., 2018; Ruivo & Morooka, 2007)

The decommissioning steps for completely removing a fully functional platform are very complex. It consists of four parts:

- The project management plays a role in planning, controlling, constraining, and monitoring the entire project. Governance includes numerous provisions for decommissioning options and details - considered in the assessment system as boundary conditions, waste management, safety standards, equipment and personnel use and maintenance, material usage, and responsibility for dealing with any potential or unexpected incidents. Issued public relations issues, produced reports, and completed applications for relevant government departments.
- The pre-decommissioning stage is the preparation stage for the decommissioning project, including responsibility division, background investigation, facility status confirmation, material inventory, evaluation of decommissioning options, construction schedule, necessary engineering simulation, equipment mobilization, personnel recruitment, fundraising and solicitation license. The content of this part of the work overlaps with the project management part, and the difference is that the project management work will keep dynamic updates according to the construction situation. Currently, most of the models developed for offshore decommissioning are

concentrated in the decommissioning options assessment section because it includes the assessment of cost, risk, environment, technology, society, and other aspects. Decision makers need a convincing Evaluate result to support their decision-making, thereby avoiding negative social impacts that damage government credibility and business interests.

- The decommissioning execution steps refer to the engineering steps of the decommissioning project. Figure 3 is a standard decommissioning procedure for a fixed oil or gas production platform that can be entirely removed. The restrictive words to describe the application scenarios of this step due to some offshore facilities, for example, living platforms do not involve decommissioning wells and pipelines; FPSOs can be towed back to the port without topside and substructure decommissioning, the steps in the Figure 3 can be omitted.
- After the decommissioning construction is completed, it enters the post-decommissioning stage. The content of this stage is relatively simple, mainly including third-party verification, submission of reports, transfer of responsibility, and continuous monitoring. Third-party verification is usually an inspection of decommissioning for environmentally hazardous materials, such as drilling cuttings rich in hydrocarbons or radioactive materials. The close-out report summarises the decommissioning project submitted to the government to declare the task accomplished by following the standard. Thus, the responsibility for the area can be transferred to the government department or the next developer. The accident is no longer primarily responsible. Continuous monitoring is necessary, mainly in two aspects: whether legacy facilities are causing damage to the environment; and closed oil wells are leaking.

The decommissioning process has been clarified by introducing the decommissioning process framework for offshore facilities. As mentioned above, most of the technologies that have been developed are applied in the decommissioning option assessment step of the pre-decommissioning stage because this part requires the most pre-assessment content. According to the Multi-criteria Decision Analysis (MCDA) technology adopted in the UK (Palandro & Aziz, 2018), there are mainly five parts: cost, risk, technology, environment, and society. Typically, assessments of the decommissioning implementation phase focus only on dynamic risk assessments without regard to evaluations of involved costs and environmental or social impacts.

1.1.3 Hazards of Offshore Decommissioning

From the first introduction to QRA and the second chapter on Hazard Identification (HAZID), one of the foundations of QRA is to determine the hazards that need to be studied. The types of hazards faced by decommissioning projects of offshore facilities are similar to those in the operation phase of the facilities. The physical effects and probabilities of the consequences are quite different. Moreover, determining hazards will require extensive experience and knowledge so that there is no overlapping area between the obtained hazards as much as possible, resulting in an overestimation of the overall risk.

Unfortunately, there are limited amount of existing data and information available on HAZID. Table 2 shows the current judgments of different scholars and institutions on offshore decommissioning hazards. It can be seen from the table that several hazards are commonly mentioned. Others are unique and carefully categorized.

Table 2. Hazards for decommissioning in literatures.

Hazards	Source
Release of flammables Release of toxics Release of asphyxiates Release of LSA radioactive scale Fire and explosion Blowback from entrained gases in pipework Gas freeing Additional ignition sources Hot work Collision Dropped object Heavy and major lifting activities Incomplete cut Risks posed by presence of barges Handling and securing loads Weight/COG uncertainty Sudden redistribution of loads within the structure Structural failure Loss of stability Loss of position/buoyancy Hazards posed by helicopter transportation Handling cutting equipment Electrocution	(Lloyd's Register System Integrity and Risk Management, 1997)

Isolation Breathable atmosphere/confined space entry Decommissioning of safety systems Occupational health Access and egress Diving activities Severe weather and weather changes Environmental loading on remaining structure Handling and loading unfamiliar equipment Loading and unloading onto a moving barge Handling of explosives Work over water Work at height Waste control	
Process releases Riser/pipeline related hydrocarbon release Blowouts Ship collisions-passing vessels Ship collision-visiting vessels Dropped objects Extreme weather/earthquake Helicopter accidents	(Myrheim et al., 2005)
Blowout Process Riser/pipeline Fire load and smoke Explosion load Collision Dropped object Structural failure	(Vinnem & Røed, 1999)

According to the types of hazards listed in the table 2, considering the engineering volume and difficulty of modelling the risk assessment system, this study selects eight common hazards as the research objects shown in Table 3. These hazards are distributed in each stage of decommissioning, distinct stages will correspond to different numbers of hazards, and even if the same hazards are in different construction stages, there may be discrepancies in the evaluation content. The correspondence between Hazards and decommissioning steps are shown in Tables 3 and 4.

Table 3. Major hazards for offshore facilities' decommissioning.

Major Hazards	1. Hydrocarbon releases	2. Fire and explosion	3. Ship collisions	4. Dropped objects
	5. Helicopter accidents	6. Diving	7. Mechanical damage	8. Structural failure

Table 4. Hazards for each decommissioning procedure.

Procedure	Well p&a	Conductor removal	Platform preparation	Pipeline preparation
Hazards No.	1,2,3,4,8	3,4,8	1,2,3,4,5,6,7,8	1,3,6
Procedure	Pipeline decommissioning	Topside decommissioning	Substructure decommissioning	Onshore dismantle
Hazards No.	3,4,6	3,4	3,4	4,7

Briefly explain table 4 according to the decommissioning procedure and corresponding major hazards:

- In the UK, well plug & abandonment is usually put together with conductor removal. The major hazards faced in this step include hydrocarbon releases (mainly blowouts), fires and explosions, ship collisions, dropped objects when using crane, and structural failure due to fire or collision. At this stage, thermal cutting equipment will not be used for the time being, so there is no need to worry about the leakage and explosion of the gas cylinder. Only need to pay attention to the well blowout during plugging.
- The platform preparation steps involve the most human resources, equipment, and material usage, mainly involving the cleaning, dismantling, and division of platform equipment. Therefore, this step involves the most types of major hazards, including all eight major hazards. Among them, the main form of hydrocarbon release is gas cylinder leakage, so the leading cause of fire and explosion is also caused by the accident of gas cylinders. The forms of other major hazards are the same as those in the well p&a stage. It is necessary to consider the possibility that the container for collecting waste may injure people or fall after sliding due to collision.
- The pipeline preparation step is easy to understand, and it is not mainly carried out on the platform but by DSV and other engineering vessels as the main character. Cleaning pipelines may result in the leakage of hydrocarbons or cleaning fluid, which does not lead to fire or explosion accidents but is more likely to pollute the marine environment.

Therefore, this step mainly needs to consider hydrocarbon release, ship collision and diving accidents.

- The major hazards faced in pipeline decommissioning differ slightly from pipeline preparation stages. Hydrocarbon release will not reoccur due to clean up in the last stage, but pipe cutting, and hoisting diversion must make dropped objects and diving a major hazard. In addition, DSV and engineering ships are still used at this stage, so ship collision is also one of the main hazards. But it also depends on the option of pipeline decommissioning. It may only need to be trenched and buried, so there is no need to consider the issue of dropped objects.
- The main types of hazards faced by topside and substructure decommissioning are the same, and the work content of these two steps is generally the same. Only ship collisions and falling objects need to be considered. In addition, since there are no workers on the platform at this time, the object's falling will not cause death, but economic loss caused by structural and equipment damage.
- The work involved in onshore dismantling is similar to other onshore structural industries, so it is only necessary to consider the hazards of falling objects and mechanical injuries.

The above are the hazards mainly studied when conducting QRA in this study. The evaluation methods of these hazards will be modularized into HADES, a novel method newly proposed in this project. Please refer to Chapter 5 for details.

1.2 Statement of the Problem

Although the research on decision-making tools for decommissioning offshore installations has progressed since the last century, the quantity, efficiency, and reliability of these studies still need improvement.

Research into offshore oil and gas facilities decommissioning has been processed in many years. Assessment systems still need to be developed specifically for the planning and construction phases of decommissioning offshore oil and gas facilities. Most of the assessment systems used by other industries have been modified and adapted or are the same as those used by other industries. No fully quantitative decision tools are explicitly developed for decommissioning offshore installations. Only some qualitative or quantitative decision aids exist.

Furthermore, even with decision support systems from other industries, most techniques rely on qualitative rather than quantitative methods. Especially if decision-makers need a reliable risk assessment numerical result, they must either use a qualitative assessment system or a complex and time-consuming simulation analysis system. Qualitative systems are quick and easy to get results, but the public often questions their reliability. The results of the simulation system are accurate, but the efficiency could be higher, and it takes time for 3D modelling and equipment support of high computing power computers. What decision-makers need is a decision-making aid tool that can quickly and accurately obtain quantitative evaluation results. The shortcomings of the above-mentioned current technologies lead to the conduct of this research.

1.3 Research Aim and Objectives

This study aims to construct a quantitative evaluation system for decision-making of decommissioning options for offshore facilities that are fast, accurate and does not require expert participation. The system mainly includes three modules of cost, risk, environment, and socio-economic assessment and considers the interaction between the modules to refine the assessment results.

The main objectives of this research are:

- Clarify the requirements of international conventions, regional regulations, UK law on decommissioning options, risk standards and environmental protection standards applicable to the decommissioning of North Sea Connect facilities.
- Based on the top-down and bottom-up frameworks, a cost assessment module for decommissioning connected facilities in the North Sea is constructed, and the advantages of the two are compared.

- Using the quantitative risk assessment method as the basic framework and only the primary data of offshore facilities, a quantitative risk assessment system for decommissioning offshore facilities considering domino risk accidents is constructed.
- Based on the quantitative assessment, additional economic losses are calculated according to the events with negative environmental and socio-economic impacts obtained from the risk assessment.
- Set the basic parameters of facilities under different decommissioning options, integrate the assessment results of the three modules, compare them, and provide decision-makers with a reliable basis for decommissioning options based on the quantitative assessment results.

1.4 Structure of Thesis

The structure of this thesis is arranged as follows.

Chapter 1: Introduction. The first chapter mainly introduces the certainty of the decommissioning of offshore facilities, the strong demand for decommissioning of offshore facilities around the world today, and the current development of related technologies. The core of this part is to introduce the options and steps of decommissioning offshore facilities in detail so that readers can have a basic understanding of the steps and contents of decommissioning research of offshore facilities. In addition, this part also clarifies the primary source of boundary conditions and the research backbone of the evaluation system.

Chapter 2: Literature review. The second chapter is divided into five parts, focusing on the essential knowledge for decommissioning offshore facilities. The first part is the relevant international conventions, regional and national regulations and laws, classification society regulations and other standards for decommissioning options, engineering safety, and environment protection. These rules are used as the filter of decommissioning options at the beginning and comparing assessment results after the evaluation. Eliminate non-compliant decommissioning options. Then there is the introduction and induction of decision-making methods to build the basic framework used by this system. The last three parallel parts are the introduction and inauguration of the methodologies corresponding to the three modules in the system to determine which method should be used for each evaluation module.

Chapter 3: Framework and inputs. The third chapter shows the overall framework of the system, three main modules, the content of the modules, and the workflow. And then introduces the data types of inputs and outputs, and the reasons for choosing those types. This chapter is a general guide before introducing the whole system so that readers can clearly understand the functions of each part, where they belong, and the connections between modules. Readers can have an overall understanding of the entire multi-attribute quantitative decision-making evaluation system based on the content of this chapter.

Chapter 4: Cost assessment methodology. This chapter mainly introduces the research framework, detailed methods and mathematical expressions used in the cost assessment module for decommissioning North Sea offshore facilities based on the top-down and bottom-up frameworks. And the problems encountered when building the cost assessment module and the solutions.

Chapter 5: Risk assessment methodology. This part is the core part of the whole system. It introduces each module in the Hierarchical Analyst Domino Evaluation System (HADES) innovatively developed in this study, the specific methods of each module for quantitative risk assessment calculations, and the Events Tree Analysis method upgraded for HADES. This chapter will also initially deal with the environmental pollution caused by the engineering process. Bring pollution evaluation results into the next module as one of the fundamental input values.

Chapter 6: Impact assessment methodology. This chapter mainly introduces the construction process's possible environmental and socio-economic impacts to correct the range of the results obtained by the quantitative assessment of cost and risk so that the final assessment results are more accurate.

Chapter 7: Including cases of study introduction, the establishment of the Targets Criteria Database, two cost assessment models and their results of case of study, risk assessment results of case of study by using HADES, compound impact assessment results of case of study, summary of all assessment results and three decommissioning options assessment results of NWH platform decommissioning.

Chapter 8: Conclusion. Summarize the findings of this study. Clarify the main highlights and innovations of this research. Finally, the shortcomings of this study and the work to improve this study in the future.

Chapter 2. Literature Review and Theoretical Basis

2.1 Convention, Law, and Regulations for Offshore Decommissioning

Generally considered that offshore oil and gas facilities decommissioning mainly has three basic purposes: equipment recovery (Jiang et al., 2011), environmental recovery (Xiangyu, 2013) and liability release (Bull & Love, 2019). However, different from the supervision of platform construction, classification societies of various countries play a vital role. For the platform decommissioning projects, the major classification societies in the world like DNV GL, ABS and CCS have not put forward separate and detailed regulations on the management, technology and engineering planning and processing of decommissioning. At present, the main laws and regulations of decommissioning are all drafted by countries or relevant international organizations. Such a way of decision-making has great freedom and risk. The methods used by the whole industry are basically based on the existing cases for analogy, induction, statistics, prediction and planning (OGUK, 2018; Repsol, 2017). It is speculated that this is because decommissioning activities involve more related issues such as environment, risk, responsibility and impact on other industries, while technical issues do not occupy the main position. Therefore, countries are more inclined to coordinate and control such projects rather than leave them to the market.

Figure 4 shows the laws and regulations applicable to different major decommissioning areas worldwide. Ten key international conventions have provisions for decommissioning offshore oil and gas facilities, including marine environmental protection, marine life protection, hazardous waste disposal, waste transfer and detailed engineering requirements (OSPAR Commission, 1998; United Nations, 1958; IMO, 1958; Peet, 2003; Maritime Organization, 2006; Robbins, 2014; CITES, 2015; Kirkman, 2006). Combined with relevant laws and regulations issued by various regions and countries, such as the Petroleum Act and Energy Act (Gov.UK, 1998; Parliament UK, 2008), issued by the British government, it is currently the code of conduct and guidance for offshore decommissioning industry.

Figure 4. Laws and regulations about offshore decommissioning in the world.

2.1.1 Global Conventions

Regulations and conventions at the international level give many restrictions and relatively basic guidance to offshore decommissioning projects. Since the Geneva Convention in 1958, marine protection has been initiated to prevent secondary pollution caused by offshore decommissioning projects. Although the provisions of the Geneva Convention may not fully consider the decommissioning of offshore platforms at the very beginning, but only for the safety of maritime navigation and the prevention of the spread of hazardous pollutants, its definition of dumping is ground-breaking, and has been used for reference and improved by many relevant conventions. According to Geneva Convention in 1958, dumping has two means (United Nations, 1958):

(1) Intentional disposal of waste or other substances from man-made objects at sea.

(2) The deliberate abandonment of an artificial structure at sea.

Which means dumping isn't just about waste material, it's also about related behaviour. Compared with the later London Dumping Convention (Peet, 2003), it is not perfect, but at least a basic requirement for countries to carry out marine development.

This flaw was largely remedied by the 1982 Law of the Sea, resolution UNCLOS III (United Nations, 1989). It well defines the rights and obligations of countries in the ocean, and sets the guidelines for enterprises, the environment, and the management of Marine natural resources.

The IMO, as the most important world-class organization related to oceans, was founded in 1948 and its guidelines entry into force in 1958. The IMO Guidelines 1989 (Youna, 2013) provide the most detailed regulations on decommissioning of offshore structures to date: any abandoned facilities or structures on the continental shelf or in the Exclusive Economic Zone (EEZ) must be completely removal. If it is not possible to do so due to technical or other problems, the UNCLOS III criteria must be complied with, and any decision not to do so must be assessed case-by-case by the state to which the structure belongs.

According to IMO regulations:

(1) Any structure below 75 m water depth, except for decks and superstructures, structures with a structural height of less than 4,000 tons above the sea level must be completely removed.

(2) After January 1, 1998, in less than 100 meters of water, the weight in the air < 4,000 tons, excluding decks and superstructures, completely dismantle all structures laid on the seabed.

(3) Removal cannot cause significant adverse effects on navigation and the marine environment.

(4) Any structure exposed to the sea surface should be adequately maintained to prevent the structure from aging and damage; for partially demolished structures, the height must be 55 m or less below the surface after removal.

(5) Artificial reefs must be far from the navigation.

(6) Newly installed offshore facilities must be completely removed after January 1, 1998.

The IMO Guidance are currently the most versatile world-class regulation and are accurate to the depth of the water and the weight of the platform. Compared with the content of other international conventions that are already more straightforward and instructive, this guidance is also available to most countries around the world as the most basic guidance for offshore decommissioning.

The London Dumping Convention 1972 and Protocol 1996 (Peet, 2003; Maritime Organization, 2006) are the most recent and widely applicable international maritime conventions relating to the decommissioning of offshore platforms in UK. The London Dumping Convention was signed in Intergovernmental Conference on the Convention on the Dumping of Wastes at Sea in 1972. After the revision in 1993, it become the 1996 London Protocol. The main content of these two conventions is to require countries to protect the marine environment, either individually or collectively, within their own capabilities, to prevent, reduce and eliminate as much as possible the pollution caused by dumping or burning wastes at sea. But the main countries that signed the two conventions are European countries. Many countries in Southeast Asia are not signatories to the treaty. The United States has only signed the London Dumping Convention 1972 and has not participated in the Protocol 1996. Therefore, the Convention has strong limitation force on the North Sea area (Zou & Zhang, 2017). In addition, the Conventions has a cross-cutting definition of harmful pollutants and does not quantify its pollution. Such flexible arrangements have made the implementation of the Convention too flexible and controversial (Yidan, 2019).

The Convention on the transboundary movement of wastes is the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, known as the 1989 Basel Convention. This Convention is the only convention on the international transport and disposal of hazardous wastes. It regulates environmentally sound management standards and prohibits the export or import of hazardous wastes or other wastes in non-licensed situations. A two-layer control system is used to control the cross-border movement of waste, namely (Robbins, 2014):

(1) Green control procedures for general non-hazardous waste
(2) Amber control procedures for hazardous waste

The import and export of waste must have written agreements between the importing and exporting countries and inform the relevant countries about the cross-border movements so that they can be assessed and prepared. Cross-border transportation of waste can only be approved if the waste is moved, and the disposal is not accompanied by a hazard. The 1995 amendment to the Basel Convention prohibits developed countries from exporting any hazardous waste to less developed countries. Although it has not yet entered into force, it has been written into the relevant import and export laws of the EU and Norway. For Africa and the South Pacific, based on the Basel Convention, there are Bamako Convention (Eguh, 1998) and Waigani Convention (Hoogstraten & Lawrence, 2003) for similar cross-border transport of waste.

2.1.2 Regulations for North Sea

For the EU region, there are mainly two regional conventions that restrict the transport of waste across borders. The first one is OECD (Organisation for Economic Cooperation and Development) Resolution 107 (Ction, 1995) and EC (European Community) 1013/2006 (European Community, 2006); the other is Naturally Occurring Radioactive Materials (NORM) (Arpansa, 2008). These two agreements make it possible to transport and trade waste between EFTA (European Free Trade Association), OECD, EC, and Basel Convention signatories, but exclude countries that are not members of the above; and enhance how the radioactive material not mentioned in the Basel Convention should be governed and dealt with.

The same applies to the European region, but the more influential OSPAR is more likely to be followed as European countries in the retirement of offshore facilities. OSPAR has six major working strategies (UNICPOLOS, n.d.):

- Biodiversity and ecosystem
- Eutrophication
- Hazardous substances
- Offshore industry
- Radioactive substances
- Joint assessment and monitoring programme.

The implementation of the Convention mainly has the following three principles:

- Polluter pays principle.
- Continue to reduce pollution.
- Best Available Technology (BAT) and Best Environmental Practice (BEP).

For decommissioning, European countries mainly followed OSPAR Decision 98/3- OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations, which is an alternative to Decision 95/1 and entered into force in February 1999. The decision fully takes into account the difficulty of decommissioning when moving the footing of large steel jackets who is more than 10,000 tons and concrete gravity platforms, the following provisions have been made (OSPAR Commission, 1998; OGP, 2012):

- All or part of the footings of a steel installation in a category listed in Annex 1, placed in the maritime area before 9 February 1999, to be left in place.
- A concrete installation in a category listed in Annex 1 or constituting a concrete anchor base, to be dumped or left wholly or partly in place, and
- Any other disused offshore installation to be dumped or left wholly or partly in place, when exceptional and unforeseen structural damage or deterioration, or from some other cause presenting equivalent difficulties, can be proven.

It should be noted that interference with drill cuttings during decommissioning is not considered to be the reason for leaving all or part of the structure in place.

The OSPAR 98/3 Annex 1 mentioned above lists offshore facilities that do not have to be fully removed:

(1) Steel installations weighing more than 10000 tonnes in air.
(2) Gravity based concrete installations.
(3) Floating concrete installations.
(4) Any concrete anchor-base which results, or is likely to result, in interference with other legitimate uses of the sea.

In Annex 2 of Decision 98/3, a framework had been given for offshore decommissioning to do the Comparative Assessment (CA). The assessment needs to consider the potential impact of the proposed installation and disposal on other legitimate uses of the environment and the ocean, as well as considering practical reuse, recycling, and disposal options for decommissioning installations.

In addition, OSPAR is the only regional decision to make detailed requirements for drilling cuttings. Drilling cuttings contain low toxic oil-based mud, water-based mud, and even low radioactive mineral cuttings. OSPAR developed more detailed control measures through recommendations such as 2000/3 (Series, 2007), and 2006/5 (OSPAR Commission, 2009b). The first phase is assessed by measuring the rate of oil loss (leaching), persistence (sea floor area where oil concentration remains above 50mg/kg) and duration. If the assessment results exceed any of these measurement thresholds, a second stage is initiated, which includes determining the cuttings pile location, area, topography, hydrology, volume, physical characteristics, chemical content, and biological characteristics.

So far, OSPAR has no detailed guidelines for the sampling of cuttings, and only has a certain limit on the oil content, and does not consider the problem of reflective substances, that is, other dangerous substances.

Regarding the prevalence of artificial reefs in recent years, OSPAR has also made relevant regulations. In OSPAR 1999 (Comission, 2013), artificial reefs were defined. Artificial reefs in European waters are mainly used for aquaculture, recreation and research, and their structures are mainly concrete and natural rocks. In 2009 (OSPAR Commission, 2009a), OSPAR evaluated artificial reefs and concluded that the negative impacts of artificial reefs were localized and conducive to coral reefs. The positive significance is far greater than the negative ones (Dolly, 2012).

Nevertheless, at present, there are no regulations related to artificial reefs in the European region, whether at the international, regional, or national levels. However, according to the London Convention/Protocol and OSPAR 98/3, artificial reefs progress is slow in Europe (OSPAR, 2013).

2.1.3 Regulations for Other Regions

Coordinating Body on the Seas of East Asia (COBSEA) is a regional convention in the East Asian Seas. Ten participating countries jointed in except Brunei and Myanmar. The Convention is based on the Association of Southeast Asian Nations (ASEAN), approved in 1983 and expanded to 10 members in 1994 China and Australia also joined. However, the content of this convention has little to do with the decommissioning of offshore projects, but is more related to the flow and trade of waste (Kirkman, 2006).

Nevertheless, there is another organization, the ASEAN Petroleum Council (ASCOPE), which has made several provisions for oil and gas platforms (ASCOPE, 2012):

(1) Do not interfere with the use of the ocean by others.
(2) Each platform requires a safe area of 500 meters, which must be respected by other industry staff.
(3) Dismantle any abandoned platform (no removal requirements are specified).
(4) Protect marine life.

Currently, two international conventions on the protection of species affect the decommissioning of offshore facilities. The first is Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (CITES, 2015), which aims to ensure that international trade in wildlife specimens does not threaten their survival. The second is Convention on Biological Diversity (CBD) (Adrew et al., 2005), primarily to protect biodiversity, to make sustainable use of biodiversity components, and to share the benefits of using genetic resources fairly and equitably.

The World Bank and the European Bank for Reconstruction have invested in many energy companies' projects, so there are related requirements for the retirement of offshore facilities to ensure their own interests.

The World Bank requires that long-term decommissioning, the relevant responsible company should prepare the decommissioning plan, fundraising plan, budget, etc. of the platforms and facilities to be decommissioned, and negotiate with the sponsors as soon as possible.

The World Bank's guidance includes:

- IFC General and Project Specific Environmental, Health, and Safety (EHS), provides general and industry-specific guidance (Rodriguez, 2009).
- Towards Sustainable Decommissioning and Closure of Oil Fields and Mines: A Toolkit to Assist Government Agencies, provides a set of tools that complement other World Bank guidelines for assessing decommissioning issues (World Bank Multistakeholder Initiative, 2010).
- The Equator Principle, which includes an agreed decommissioning plan, and, where applicable and appropriate, sign a consent form for decommissioning (IFC, 2013).
- The IFC Stakeholder Engagement Good Practice Handbook for Companies Doing Business in Emerging Markets, a tool for private companies and governments to plan and implement sustainable projects (IFC, 2007).
- The IFC Environment, Health and Safety Guidelines, emphasize that decommissioning projects must follow IMO standards and OSPAR decisions (IFC, 2014).

In contrast, the standards of the EBRD vary from place to place, but the basic requirement is to establish a decommissioning plan as soon as possible for the responsible country or company, establish a dedicated fund for decommissioning, and implement it as planned (IOGP, 2017).

In general, although the conventions and regulations are different, they all require that decommissioning does not cause harm to the marine environment and other users. At present, UNCLOS III is basically considered as the basic criterion. However, UNCLOS III is only applicable to the EEZ and continental shelf areas and does not apply to the 12 nautical mile territorial sea. That is to say, the decommissioning of offshore facilities in the territorial waters of each country can be decided by governments. All conventions do not require submarine piping systems and submarine cables. This is currently lacking in international norms. In contrast, some national regulations and classification society norms, such as DTI (Ekins et al., 2006) and China Classification Society (CCS), have mentioned some of the decommissioning of submarine pipeline systems, but their attention is obviously insufficient (CCS, 2016).

2.2 Decision Making Approaches

Decision-making approaches are set of complex scientific method followed by decision-makers. When such methods face different focuses, they usually cause changes in detailed methods to suit decision-makers' requirements. The complexity and quantification of the decision-making event will be divided into quantitative, qualitative, and composite methods for complex decision-making.

Quantitative methods refer to decision-making reference results derived from scientific calculations or widely recognized equations. The advantage is that the decision-making reference results are more objective and reliable. No sensitivity analysis is required to avoid any interference of subjective consciousness in the decision-making, so it is compelling. First, the quantitative process of many things is a big problem. Second, in many cases, the quantitative process will be affected by subjective consciousness and cannot guarantee absolute objectivity. Finally, quantitative results may not be consistent or intuitive for decision-makers. These three flaws are unavoidable and can only be continuously improved with technology development.

Qualitative methods are artificially assigning a numerical value or grade according to the degree of development of things, which is then used as a reference for decision-making. Qualitative methods are usually used in conjunction with expert rating methods to ensure the reliability and authority of their assessment results. This type of method can be widely adopted because it can solve the problem of the inability to quantify things. However, its excessive subjective participation makes its results easily questionable. Some current techniques use sensitivity analysis to avoid the undue influence of subjective perception on the results. Even with revisions, but there may still be unconvincing situations in which decision-making assessments for some projects with broad interests are involved.

The composite decision-making method formed by combining the above two methods seems to be able to avoid the defects of the above two and build a decision analysis model with generality and reliability. Nevertheless, how to convincingly combine quantitative and qualitative results is the biggest problem faced when constructing and using such methods. There is no mutual conversion bridge between the two. The commonly used method divides the quantitative results into a specific range to obtain qualitative results and then integrates all the qualitative results as the basis for decision-making. This process requires users to be proficient in the first two types of methods, the threshold for use is high, and the process may be longer.

2.2.1 Quantitative Approaches

For the decommissioning of offshore oil and gas facilities, quantitative methods are widely used in cost assessment, energy use and gas emissions, risk assessment, and material statistics. These methods include but are not limited to theoretical method, equivalent cost method, regression analysis, material, and energy flow method. Table 5 describes the use of these methods in the decision-making model for the decommissioning of offshore oil and gas facilities. In many cases, these methods are just a sub-method among the main methods of evaluating models and will be used in combination with qualitative methods. When used alone, it is often used to calculate the cost and the probability of loss of life.

Table 5. Methods and their descriptions.

Methodology	Description	Application
Theoretical Method (Havbro Faber et al., 2002; Bennear, 2015; Fam et al., 2021)	Theoretical equation Data substitution High reliability Not flexible enough Universal	Cost evaluation Risk evaluation Energy use and gas emission Commercial fishing Passenger transport Employment status
Equivalent Cost Method (McCann et al., 2016)	Connectivity Regression analysis	Cost evaluation
Regression Analysis (Amila Wan Abdullah Zawawi et al., 2015; Kaiser et al., 2003; Groves & Hannan, 1968)	Connectivity Universally applicable High data demand Simple process	Cost assessment Risk assessment Sea state forecast
Material and Energy Flow Analysis (Ekins et al., 2006; Sokolović, 2011)	Boundary conditions Strong reliability High data demand Cross-domain application	Cost evaluation Energy use and gas emission Environmental assessment

Theoretical method refers to the method of calculation using the theoretical equation that already exists in the industry. The industry has already derived calculation methods such as gas emissions, energy use, and hydrocarbon permeability based on the theoretical basis of physics or chemistry and can further calculate some costs based on market details. Although the results of this method will have small drawbacks, the theoretical framework is basically reliable, and the results used for evaluation are also easy to convince the public. But this method cannot calculate items that have not been clearly related, so it has obvious limitations. This type of methods will be widely used in the estimation of gas emissions, energy use, structural strength and other related cost estimation and risk assessment parts in decision-making models (Havbro Faber et al., 2002).

Equivalent cost method is a method that connects multiple physical quantities and costs. For example, the water depth, weight, number of structures, etc. are linked to the cost currency. This method is very similar to regression analysis, and the method actually used is also a regression method, so it will be explained in detail in the regression analysis (McCann et al., 2016).

Regression analysis is widely used, and its specific theory will not be repeated in this thesis. For details, please refer to (Angelini, 2018). This thesis mainly discusses the application of regression analysis in the decommissioning of offshore oil and gas facilities. Regression analysis is mainly used to find the relationship between variables, especially the relationship between variables that have not been determined by theory. In decommissioning, regression analysis is often used after logical relationship analysis, such as: looking for the relationship between decommissioning costs and engineering time, water depth, module weight, etc. (Kaiser et al., 2003). There must be a logical relationship between these variables, and similar conclusions can be drawn from the analysis of the data correlation. But, due to many unknown variables, traditional theoretical analysis cannot completely determine what the relationship between these variables is. At this time, regression analysis can be based on historical data, through mathematical calculations and modern computer technology, to give the most likely relationship curve between the two and the expression of the curve. The application of regression analysis in decommissioning is not only to estimate costs, but also to estimate construction time, or to predict sea conditions to reduce construction risks (Groves & Hannan, 1968). However, the basis of reliable regression analysis is based on sufficient historical data. In other words, if there is not enough historical data, the use of regression analysis is meaningless and inaccurate. This is also the reason why the evaluation accuracy of the Platform Abandonment Estimating System (PAES) mentioned below was low in the early stage of establishment (Kaiser & Liu, 2014).

In addition, for the regression analysis of the decommissioning of offshore oil and gas facilities, there is a common problem among scholars who currently use this method, that is, the historical data of all studies is insufficient in quantity, even for studies with a large amount of data, no more than 100 group reliable data (Bernstein, 2015b). And the regression model established by using these historical data, the verification process often one or two groups of the same historical data which establishes a major potential problem with the prior models is that the original regression analysis is likely to be over-fitting (Cawley & Talbot, 2010). Although the argument of over-fitting is usually used in the field of machine learning rather than decommissioning, in the author's actual research, it is found that this phenomenon often occurs when the sample data of the research decommissioning cost evaluation is small. Under such potential problems, several indicators used to test the results of regression analysis, such as the coefficient of determination R^2, no longer have reference value, because even if R^2 performs well, like reaching 0.8 or 0.9, the results of the regression analysis may be excessive fitted, so it cannot be used. The expression of R^2 is as follows:

$$R^2 = 1 - \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \Big/ \sum_{i=1}^{n}(y_i - \hat{y})^2 \qquad (1)$$

Where y_i is the actual value; $\hat{y}_i$ is the mean of the actual value; $\hat{y}$ is the estimated value obtained by linear regression.

The basic principle of Material and Energy Flow Analysis (MEFA) is that energy and matter do not live or die and will only be transferred in other forms. The characteristic of this method is to establish a boundary, and then calculate all the energy and matter entering and leaving the boundary to obtain the required information, such as emissions, heat radiation, workmanship, pollution, etc. (Jeremy, 2000). Figure 5 shows a schematic diagram of MEFA. This method is more used in the research of urban systems rather than in the industry (Decker et al., 2000). A innovatively application of this method to the decommissioning of offshore oil and gas facilities (Ekins et al., 2006; Sokolović, 2011). This method can estimate many values related to decommissioning, and make it link with costs, gas emissions, energy use, material statistics, etc. The difficulty is that it requires a high degree of information control. Generally, only the institution that implements decommissioning can grasp the first-hand and most detailed material flow data, and third-party researchers will not be able to obtain these data. This is also the biggest limitation of the method.

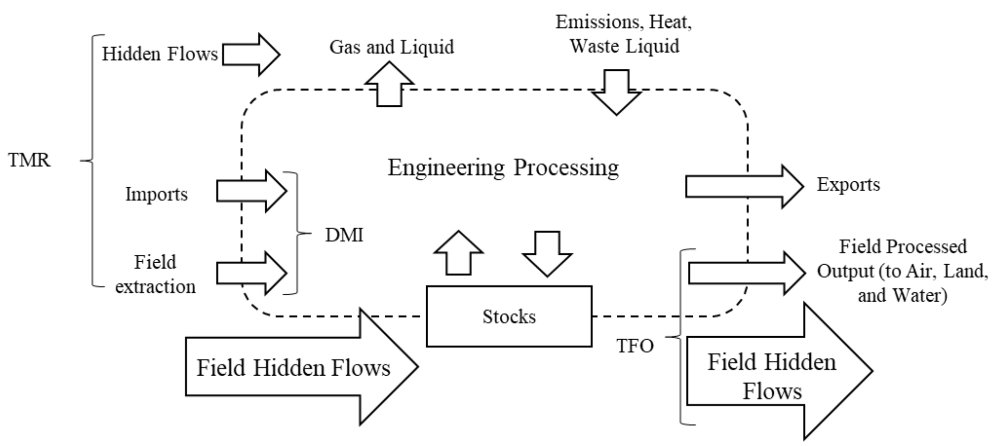


Figure 5. Material and Energy Flow Analysis. Adapted from Kirchain and Ekins content (Jeremy, 2000).

Where TMR means Total Material Requirement; DMI means Direct Material Input, TFO means Total Field Output.

The above are the quantitative methods that have been used in the decision-making model for the decommissioning of offshore oil and gas facilities. These methods are mainly used in cost assessment and risk assessment, as well as in the calculation of energy use and gas emissions. It is not difficult to see that since other aspects cannot be quantified well, qualitative methods will be used for evaluation.

2.2.2 Qualitative Approaches

Since many aspects cannot be quantitatively analyzed to obtain results, the use of qualitative methods is very common when making option decisions. These qualitative methods are the same as quantitative methods. They will only be used alone in certain assessments. In most cases, they are combined with quantitative methods as part of comprehensive analysis.

There are many types of qualitative methods used in decommissioning, including but not limited to: expert scoring method, comparative evaluation method, case study method, risk matrix method, etc. Even many evaluation methods do not have specific names but are collectively referred to as qualitative evaluation methods. These methods generally use three qualitative evaluation systems, the first is weighting, the second is scoring matrix, and the third is comparative appraisal (Bernstein et al., 2007; Kruse et al., 2015; Na et al., 2017; Suddle, 2009). Many qualitative methods are based on these three systems, adding the latest technology and integrating the needs of related fields to form new methods. It needs to be particularly pointed out that the weighting method can be either a quantitative method or a qualitative method according to the way it is used. The main difference lies in whether the weighting selection is subjectively determined by the decision maker. If the weight is set according to the proportion of each attribute value in the total, there is no subjective intervention, which is a quantitative method; if the weight value is determined subjectively by the decision maker, a qualitative method is preferred. Therefore, the detailed description of this method is placed in the explanation of Simple Multi-Attribute Rating Technique with Swing weight (SMARTS) below. This part will mainly focus on the scoring matrix system and the method of comparative appraisal system.

The first is the scoring matrix system. The characteristic of this type of qualitative analysis method is to establish a matrix that includes all the options that need to be evaluated, the assessment criteria applicable to each option, and a set of unified degree evaluation lists. This list can be in the form of a score from 0-100, or it can be in the form of a grade from the worst to the best. The following of this paper will mention MCDA as an example, for five criteria and their sub-criteria, and all parts of decommissioning options, combined with the evaluation indicators, show as the Table 6. Decision makers only need to fill in the identified scores in the blanks according to their own needs, then the results are weighted and added, and other data processing methods, to the final total score, to decide which option to choose. The method of this system is often used in combination with the weighting method and the expert evaluation method. The advantage is that it helps to play the role of experts, can well reflect the preferences of decision makers, and can prevent improper behavior. The shortcomings are obvious. Experts are not necessarily familiar with the required scoring field and the scoring is not effective. The introduction of weights also substitutes the shortcomings of the weight method that the weight cannot be set well, and it is difficult to eliminate subjective and emotional evaluation negative effects of results (Carbon Disclosure Project, 2020; Department for Business Energy & Industrial Strategy, 2018).

Table 6. Scoring matrix example (Department for Business Energy & Industrial Strategy, 2018).

		Decommissioning Options											
Assessment Criteria	Sub-criteria	Complete removal to land			Partial removal to land			Leave wholly in place			Disposal at sea		
Safety	Risk to personnel												
	Risk to other users of the sea												
	Risk to those on land												
Environmental	Marine impacts												
	Other environmental compartments												
	Energy/resource consumption												
	Other environmental consequences												
Technical	Risk of major project failure												
Societal	Fisheries impacts												
	Amenities												
	Communities												
Economic													
Sum		24			26			26			21		
Ranking		2			3			3			1		
Scores		High=3				Medium=2				Low=1			

The Comparative appraisal system is widely used. It can be said that any similar part of any decommissioned project can be evaluated using comparative appraisal methods. Such methods include, but are not limited to, the ranking method, the mandatory classification method, the key point allocation method, the pairwise comparison method, the critical event comparison method, the target management method and the comprehensive method (David, 1991). The core idea of comparative appraisal is similar to control variables and proportional scaling. In decommissioning, for example, when the same type of platform is like the water depth, the energy company will base on the weight ratio of the platform, the offshore distance, the number of wellheads, the length of pipelines and other different quantities, to evaluate the decommissioning cost range of un-decommissioned oil and gas facilities. In terms of risk assessment, these methods can assess the likelihood and consequences of similar accidents in different scenarios based on the scenes and consequences of accidents that have occurred. The use of such methods is flexible and diverse, and often does not require the cooperation of many experts. But due to the executors of the comparative appraisal system may not have sufficient knowledge of the project, they may be underestimated or over-evaluated, and the results obtained are often inaccurate and, in many cases, not strong convincing. In addition, this method requires a large amount of historical sample data, especially for comprehensive and complex projects such as the decommissioning of offshore oil and gas facilities. There are often only one or two comparable data in the hands of energy companies, and the evaluation results can be imagined.

The above is a brief summary of the qualitative analysis methods used in the decommissioning of offshore oil and gas facilities. It is undeniable that the use of qualitative methods is inevitable and necessary in decommissioning. This kind of method has strong applicability and easy to use. So far, many scientific methods have been incorporated to avoid and reduce the influence of excessive subjective consciousness on the evaluation process. Although there are still widespread hidden dangers of excessive subjectivity, and sometimes it is necessary to set basic thresholds for the quality of evaluators, so that the efficiency of the implementation of some methods is still not high but returning to the decommissioning decision-making itself is also based on the subjective concerns of all parties. It has formed five criteria generally applicable in the field of decommissioning. Therefore, it can be said that the use of qualitative methods is necessary in the field of decommissioning decision-making and evaluation. Related decision-makers and decision-making tool developers need to pay attention to that such methods should be gradually reduced after the gradual increase in historical decommissioning data in the future, and try to use quantitative methods to measure objective variables, such as cost, risk and environmental pollution assessment.

2.2.3 Comprehensive Approaches

In the decision-making model, it is rare to use a simple quantitative and qualitative method alone. In many cases, the method used in the model is a combination of quantitative and qualitative methods. This type of method pioneered the combination of quantitative and qualitative methods to obtain evaluation results.

Such methods used in multi-attribute decision making models include but are not limited to: Decision Tree Method, Goal Programming (Ekins et al., 2006), Semi-quantitative and Qualitative Methodologies (SQ) (Cripps & Aabel, 2002), Analytic Hierarchy Process (AHP) (Na et al., 2017), Elimination and Choice Expressing the Reality (ELECTRE) (Soltanmohammadi et al., 2008), Multi-Attribute Utility Theory (MAUT) (Kim & Song, 2009), Mixed Integer Programming (MIP) (Thompson & Sessions, 2010), Net Environmental Benefit Analysis (NEBA) (Kanmkamnerd et al., 2016; Kankamnerd et al., 2018), Oracle Multicriterial General Assessment of Decommissioning (OMEGA) (Zachar et al., 2011), Preference Ranking Organization Method (PROMETHEE) (Soltanmohammadi et al., 2009), Simple Additive Weighting (SAW) (Fowler et al., 2014), Strengths Weakness Opportunities and Threats (SWOT) (Smyth et al., 2015), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Narrei & Osanloo, 2011), Simple Multi-Attribute Rating Technique with Swing weight (SMARTS) (Ward & F.Hutton, 1994), Comparative Assessment (CA) (Ekins et al., 2005), Multi-Criteria Decision Analysis (MCDA) (Palandro & Aziz, 2018) and many other methods. The application of these methods in the industrial field includes but is not limited to the oil and gas field, wind power generation field, mining, nuclear power, road and bridge, transportation, etc. The decision-making models used in the decommissioning of offshore oil and gas facilities are mainly AHP, SAW, SMARTS, MCDA and CA. Although these methods have different names, they overlap to some extent in the field of offshore oil and gas facility decommissioning. For example, MCDA is currently the core method of CA, and AHP and SMARTS are the most used methods of MCDA. Therefore, AHP, SAW, SMARTS and MAUT will be briefly introduced next. As for the application of other methodologies, readers are requested to understand by themselves based on references.

Analytical Hierarchy Process (AHP) is a structured technology used to analyze complex decisions. The content of the method is to classify and layer the targets, assign weights to them according to the importance of the targets and the preferences of decision makers, then analyze the weights based on pairwise comparisons between the targets, and finally use linear algebra to calculate the results for each target calculate the score (Saaty, 1990). The Figure 6 shows how to use AHP (Leal, 2020). This method is intuitive and simple. After a long period of development, a quantitative scale was used instead of a qualitative scale (Xodus, 2017). It is used to make decommissioning decisions for subsea structures.

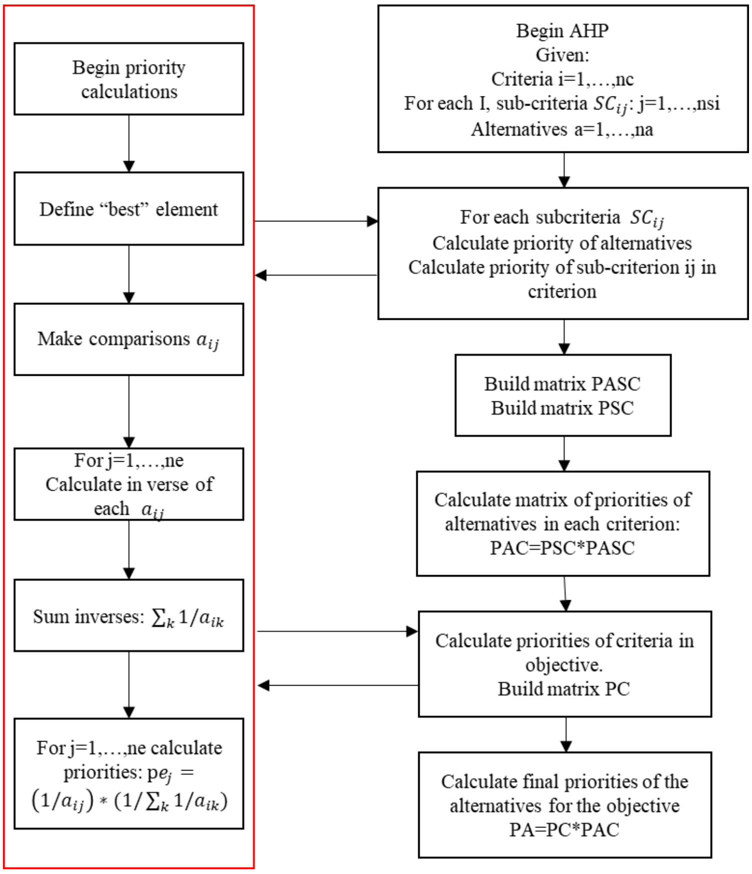


Figure 6. Steps to use AHP, PASC is Priorities of the Alternatives in each Sub-criterion, PSC is the Priorities of the Sub-criteria for each Criterion, PAC is the Priorities of the Alternatives in each Criterion, PC is the Priorities of each Criterion, PA is the final Priorities of the Alternatives (Leal, 2020).

Simple Additive Weighting (SAW) is also called scoring method or weighted linear combination method. The simple explanation is to find the weighted sum of the performance levels of each alternative on all attributes. Its mathematical expression is as follows (Dede & Adrian, 2018):

$$R_{ij} = \begin{cases} x_{ij} / Max\ x_{ij} \\ Min\ x_{ij} / x_{ij} \end{cases} \tag{2}$$

$$V_i = \sum_{j=1}^{n} W_j r_{ij} \tag{3}$$

Where R_{ij} is the qualified performance level; $Max\ x_{ij}$ is the maximum value of each row and column; $Min\ x_{ij}$ is the minimum value of each row and column; x_{ij} is the rows and columns of the matrix; with R_{ij} is the normalized performance rating of Ai alternatives; V_i is the final value of the alternative; W_j is the Specified weight; A larger value of V_i indicates that Ai's alternatives are preferred.

The simplicity of SAW can greatly improve the efficiency of decision-making, and this method has a significant advantage, that is, due to preset preferences and weights, the SAW method can perform more accurate judgments. In the decommissioning of oil and gas, this method does not appear to be accepted by all decision-making participants and stakeholders, because the preferences of all parties are different. Therefore, further requirement had been proposed for flexibility that can cover all decommissioning options and backup options the importance of method (Fowler et al., 2014).

Simple Multi-Attribute Rating Technique with Swing weight can be seen from the name that SMART is improved by adding the swing weight method. The SMART method was first proposed by Edwards in the 1970s and is a simple and intuitive decision-making method. After improvement, there were SMARTS and SMART Exploiting Ranks (SMARTER). At present, SMART has been eliminated and no longer used, and SMARTS and SMARTER methods are more widely used, because the latter two can better improve the phenomenon of excessive subjective decision-making in the SMART method (Transport, 2014; Ward & F.Hutton, 1994). The use of SMARTS is mainly divided into nine steps, except that the swing weighting method is applied in the seventh and eighth steps, the other steps are the same as SMART. The SMARTER is similar, except that the weight is directly calculated using equation (4) in the eighth step.

$$w_k = {}^{1}/_{K} \sum_{i=k}^{K} (1/i) \quad (4)$$

Where K is the number of attributes.

The SAMRTS method was first used by Bernstein in the decision-making model for the decommissioning of offshore oil and gas facilities, mainly in the PLATFORM mentioned above. The use of this method makes the weight distribution in decision making more flexible, and its subjective influence is reduced (McCann et al., 2016; Max et al., 2015).

The Multi-Attribute Utility Theory method was first established in the 1970s (Peter C, 1970). It follows the same logic as the traditional utility theory. The criteria are normalized within the range of [0,1] according to their purpose, and then a weighted score for each available alternative can be obtained (Hwang & Yoon, 1981). The feature of this method is additive independence, which means that a person's preferences have no interaction between attributes, and the value of one attribute is not affected by other attribute levels. In this way, the utility function of each attribute can be evaluated separately and evaluated according to the weight of combining them into a multi-attribute utility function. The specific method is as follows (Kidd et al., 1977):

(1) Identification and organizational attributes.
(2) Define a scale for each attribute.
(3) Define a single attribute utility function, and divide the possible ratings of each attribute from the worst 0 to the best 100%
(4) Choose swing weight or equivalent cost to construct the stakeholder's relative value or cost preference model for each attribute. SMARTS is used here to get the weighting.
(5) Integrate swing weights and attribute scores into the overall multi-attribute utility of each decision option.

The specific mathematical expression is shown in equation (5).

$$U(x_1, x_2, \dots, x_n) = \sum_{i=1}^{n} w_i u_i(x_i) \quad (5)$$

Where $0 \leq U(x_1, x_2, \dots, x_n) \leq 1, 0 \leq u_i(x_i) \leq 1, \sum_{i=1}^{n} w_i = 1$.

The MAUT method has been used in the decommissioning of nuclear (Kim & Song, 2009)and offshore oil and gas platform decommissioning (Max et al., 2015; McCann et al., 2016). Some scholars have compared AHP and MAUT in the field of nuclear energy and found that the potential disadvantage of the latter is that it is difficult to generate a utility function for each criterion, while AHP requires a method of generating a comparison matrix for each criterion and sub-criterion is very troublesome (Kim et al., 2006).

2.2.4 Multi-attribute Decision-making Models for Offshore Decommissioning

The decision-making model for the decommissioning of offshore oil and gas facilities is an important part in offshore decommissioning project, this framework can give decision makers and relevant information demanders an intuitive decision basis. It is generally believed that this type of model has five major categories, namely environmental, economic, social, health and safety (risk), and others. Although according to the requirements of the British government, it is necessary to include technical feasibility in the model, in fact, the purpose of technical feasibility analysis mainly serves the selection of equipment, so that the result can be aggregated into the cost and risk part. In this paper, there is no discussion, readers can refer to relevant British government documents according to their needs. The contents of these categories are shown in the Table 7 (Fowler et al., 2014).The ultimate goal of these decision-making models is to use qualitative or quantitative methods, or MCDA (multi-criteria decision analysis) method

(Weber & Borcherding, 1993; Martins et al., 2020), as the main method, this comparative support tool mixed by methods such as weighting or expert review, to perform calculations based on the focus of the model, so as to arrive at the most appropriate decommissioning plan under the model. However, it should be noted that the results obtained by the MCDA method are not the so-called optimal solution but one of an acceptable solution (Martins et al., 2020), which will be expanded in section 2.2.

Table 7. The five criteria and some of their contents were obtained by the author based on the literature of multiple scholars (Lloyd's Register System Integrity and Risk Management, 1997).

Environmental	Financial	Socioeconomic	Health and safety	Technic/Feasibility
Gas emissions	Mobilization of support vessels	Taxation concessions	Navigation	Cutting equipment
Energy use	Personnel	Employment opportunities	Fishing	Diving equipment
Contamination	Onshore processing	Economic stimulus	Crushing accidents	Transportation
Production of exploitable biomass	Landfill	Cultural impingements	Exposure to drilling mud	HLV lifting capacity
Provision of reef habitat	Replacement of construction materials	Public access	Exposure to toxic construction materials	Transport barge capacity
Enhancement of diversity	Monitoring of structures left	Public sentiment	Fire and explosion	Modular transportation technology
Protection from trawling	Maintenance of structures left.	Corporate reputation	Radiation	Structural resistance
Spread of invasive species.	Liability for property damage	Legal and regulatory	Falling	Accident early warning
Loss of the developed community	Liability for personal injury	Commercial fishing access	Collision	Sudden disaster prevention and control
Facilitation of disease	Well abandonment	Recreational fishing opportunities	Helicopter transport	Dynamic risk assessment and monitoring
Alteration of trophic webs	Equipment renting fee	Diving opportunities Clear seabed	Extreme weather and sea conditions	Feasibility of blasting use
Alternation of hydrodynamic regimes	Application license fee	Unobstructed ocean views	Structural failure at extreme temperatures	Artificial reef feasibility
Habitat damage from scattering of debris		Use of other marine industry sites		Reuse feasibility
Smothering of soft-bottom communities				

The existing decision-making model has been developed specifically for the decommissioning of offshore oil and gas facilities (Bernstein, 2015a), but more of it is borrowed and modified from other field like onshore oil and gas industry (Lakhal et al., 2005), and marine environmental industry (Timothy, 1989; Atkins et al., 2011), but these models generally take the decommissioning option as the basic logical route which mentioned in Figure 2. According to the selection of different options, the corresponding evaluation results are obtained. Finally, according to the different weight arrangements for each focus, the evaluation results are summed to obtain the overall performance evaluation is to compare the pros and cons of the results and arrive at a suitable oil and gas facility decommissioning decision. The Table 8 shows the names, established year, main contents and characteristics of some decision-making models.

Table 8. Models' information.

Model name	Main content	Advantages	Disadvantages
PLATFORM(Bernstein, 2015a)	Used in the Gulf of Mexico software support More quantitative methods used Excellent cost evaluation component Government organizations assist in development High reliability	Efficient Intuitive Mathematical Mature User interface	Restrictive Incomplete consideration The mathematical method is too simple
DAPSI(W)R(M)(Burdon et al., 2018)	Originated from DPSIR Focus on environmental protection Novel theoretical framework Software support	Environmental and social considerations Technical feasibility considerations Excellent theoretical framework Novel evaluation mechanism Dynamically expandable	Excessive limitation Poor mathematics More qualitative assessment The compatibility with decommissioning needs to be strengthened
BPEO(Bond & Brooks, 1997)	Mature Historical Good compliance assessment Lay the foundation for modern decommissioning	Multi-attribute Quantitative results Mature Strong applicability Versatile	Excessive bias towards environmental and social impact Outdated cost assessment methods Relatively low efficiency No software support
Comparative Assessment(Oil & Gas UK, 2015)	Five criteria Multi-attribute evaluation Advanced and comprehensive concept Richer experience Mature and stable	Easy to use Multiple attributes Stable and reliable Mature system Industry support Sensitivity check	Standard overlap More qualitative methods Lack of randomness Relatively low efficiency No software support

The PLATFORM is a decision-making model dedicated to the decommissioning of offshore oil and gas facilities. This model is currently for comprehensive evaluation. The method used is the MCDA method mentioned above, which combines the weight method, quantitative method and qualitative method. The developed tool uses historical data from decommissioned platforms in the Gulf of Mexico in the United States to obtain parameters and weight values suitable for offshore installations in the Gulf of Mexico. The model has been developed in multiple versions, from being only used for fixed shallow water platforms to deep water floating platforms and CGBS (Bernstein, 2015b; Kruse et al., 2015; Cantle & Bernstein, 2015; Max et al., 2015). And this model is currently known to the author, and the only model for interactive software exists. But the model did not consider engineering risks, marine wind and wave risks, etc., when making decision-making assessments, and provided more room for cost surplus. Therefore, its decision-making ability needs to be improved at present.

DAPSI(W)R(M) represents the basic concerns of the framework, namely: Drivers, Activities, Pressures, State changes, Impacts (on Welfare), and Responses (as Measures) (Burdon et al., 2018).The framework was enhanced by DPSIR, Drivers-Pressures-State-Impact-Response, and the purpose of the initial development was to establish a causal model to describe the relationship between society and nature (Elliott et al., 2017; Kristensen, 2004). Just like the original DPSIR, DAPSI(W)R(M) is also a framework that focuses on causality and response. It was used to manage environmental systems. Later, through the Cooper (Cooper, 2013), UK National Ecosystem Assessment Follow-On (UKNEAFO) project (Turner et al., 2014, 2015), Elliot (Elliott, 2014), Smyth (Smyth et al., 2015) and others further developed (Wolanski & Elliott, 2015; Atkins et al., 2011; de Jonge et al., 2012; Cooper et al., 2013). The purpose of this framework is to answer eight questions. Correspondingly, there are 7 corresponding resources to solve these problems. See the Table 9. For the decommissioning of oil and gas platforms, the Table 10 can give the decommissioning content corresponding to the relevant elements of the framework.

Table 9. DAPSI(W)R(M) core questions and resources (Burdon et al., 2018).

Questions	Resources
What oil and gas structures require decommissioning?	Inventory of available decommissioning options
What are the potential decommissioning approaches for the structure?	Activities-Pressures matrix for decommissioning
What potential decommissioning activities are required?	Inventory of protected features in UK marine waters
What pressures are likely to result from decommissioning activities?	Assessment of feature sensitivities to Pressures
What MPA features are present within the sit?	Intermediate ecosystem services (IES)-MPA matrix
What is the potential loss or damage to the designated features?	Goods/ Benefits (G/B)- MPA matrix
What is the potential for the loss or gain of ecosystem services?	Underlying scientific evidence relating to decommissioning in the marine environment
What is the potential for the loss or gain of societal goods/ benefits?	

Table 10. Elements of the DAPSI(W)R(M) framework of relevance to decommissioning (Burdon et al., 2018).

Element	Relevance to decommissioning
Drivers	Legal and societal demand for a clean, safe, productive, diverse and healthy environment.
Activities	Appropriate decommissioning options and their associated activities e.g., removal of rigs, burying or removal of pipelines, removal of rock protection.
Pressures	Wide-scale pressure list: above-water noise, abrasion, siltation, collision risk, contamination by chemicals, litter, light, etc.
State changes	Potential biological loss, gain or damage to the hydrodynamics, ecology, ecosystem services, such as smothering of the benthos, resuspension of sediments and re-liberation of contaminants.
Impacts (on Welfare)	Potential loss or gain of societal goods and benefits; commercial, recreational and cultural aspects, such as increase or decrease in fisheries, changes to recreation near developments.
Responses (as Measures)	Management measures such as legal controls, technological advances or economic instruments to further enhance the provision of ecosystem services; mitigation and/or compensation measures to minimize effects.

The framework was established to deal with the decommissioning in the Marine Protect Area (MPA), so it pays more attention to environmental and social response. Nevertheless, newer data cannot be applied, and security, social impact, technical and cost issues cannot be combined. This framework provides decision results and play a role of consultation, but it cannot make decisions by its own. The DAPSI(W)R(M) framework (Burdon et al., 2018) mentioned a number of tools and frameworks related to the decommissioning of offshore oil and gas facilities for MPAs. However, according to the author's own inspection, development of these frameworks or the original purpose of the tool was only for the protection of marine life, and its function overlapped with the decommissioning of offshore facilities but could not be completely relied upon. But the related research results about Net Gain mentioned by it are no longer available.

BPEO, Best Practicable Environmental Option, together with ALARP (As Low As Reasonably Practicable) (Jackson & Stone, 2004), is the basic decision-making framework and risk control framework currently adopted for the decommissioning of offshore oil and gas facilities in the UK. BPEO was applied by the UK RCEP (Royal Commission on Environmental Pollution) in 1995 to manage industrial waste (Jackson & Stone, 2004). It is defined as "the outcome of a systematic and consultative decision- making procedure which emphasizes the protection and conservation of the environment across land, air and waste" (Hanan, 2012). In terms of actual decommissioning issues, EIA (Environmental Impact Assessment), EA (Economic Appraisal), SIA (Social Impact Assessment) (Bond & Brooks, 1997; Bond, 1995). will be combined for decision-making, and the whole is called Integrated Assessment. The decision-making process of BPEO is mainly divided into 5 steps, corresponding to 7 methodologies, to integrate the environmental and social assessment results. The process and corresponding methodology are shown in Figure 8. The methodology will be explained in detail in the later section. Based on the BPEO framework, the Environmental Impact Assessment (EIA) method currently adopted by the British government and industry, as well as the comparative assessment method, has been very mature. According to the requirements of BEIS (Department for Business, Energy and Industrial Strategy) (Department for Business Energy & Industrial Strategy, 2018), these two methods integrate five aspects of cost, environment, risk, social impact, and technical feasibility. They are currently the mainstream methods. Although the five aspects are treated equally in the evaluation method (equal weights are given), in actual use, their subjective components still have an impact on the decommissioning decision. Secondly, these two methods do not consider the impact of risks on costs, environment, and society. In actual operations, industrial methods are still used to calculate the risks separately. In my opinion, this aspect needs to be improved.

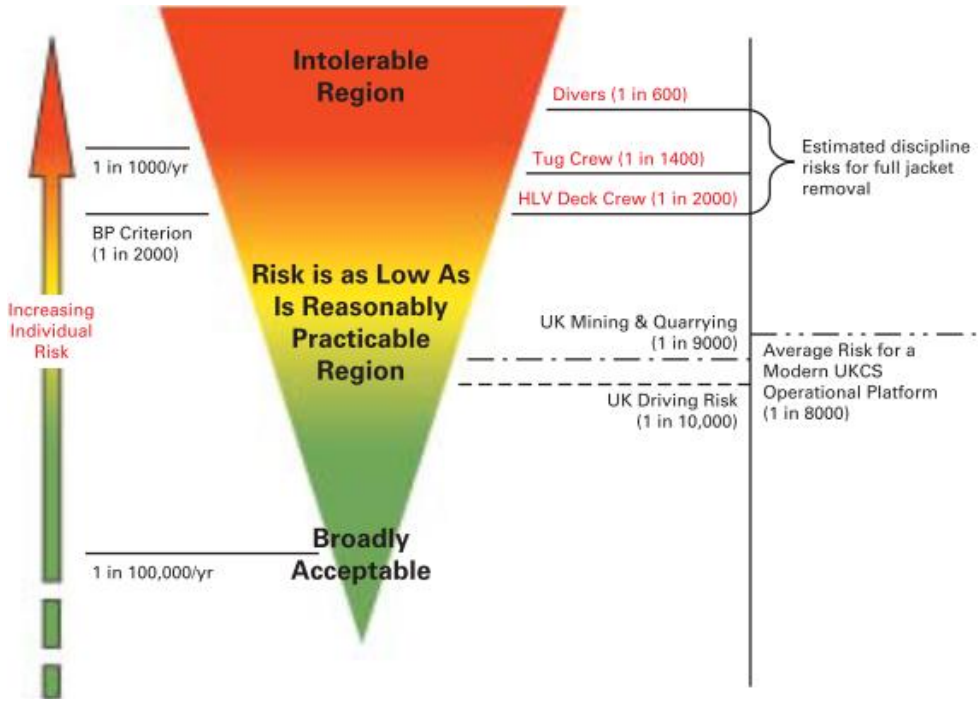


Figure 7. ALARP individual risk criterion and other data.

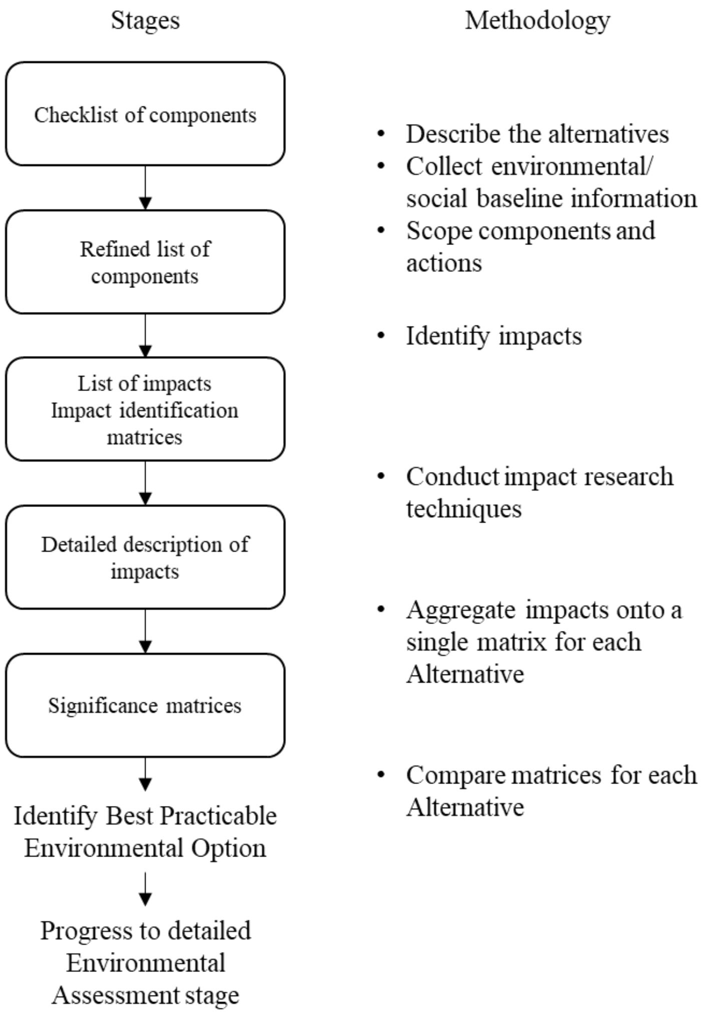


Figure 8. BPEO procedure (Bond & Brooks, 1997).

Comparative Assessment is an assessment model widely used in many fields. In the United Kingdom, the CA model used in the evaluation of the decommissioning of offshore oil and gas facilities is a model developed after integrating the frameworks of BPEO, ALARP, and EIA. This is the first model that uses five criteria as the evaluation criteria at the structural level. It is also the decision-making model used for the decommissioning of offshore oil and gas facilities, which is more mature using MCDA so far. The main focus of CA is the five criteria, and its evaluation process is shown in Figure 9 (Oil & Gas UK, 2015). Many methods are used to evaluate the five criteria, including quantitative methods such as theoretical equations, qualitative methods based on comparison, and expert evaluation methods. The more advanced point of CA is the addition of sensitivity analysis to weaken the subjective bias caused using more qualitative methods and expert assessments. This is not available in other decision-making models, so this model can be considered more advanced.

However, since the formulation of criteria and sub-criteria is artificial, there may be overlap or high correlation between the criteria, which leads to multiple evaluations of a certain criterion. Secondly, there are many qualitative methods and expert evaluation methods used in the evaluation process. The use of quantitative methods is also relatively traditional and cannot reflect the uncertainty and randomness of actual projects (Martins et al., 2020).

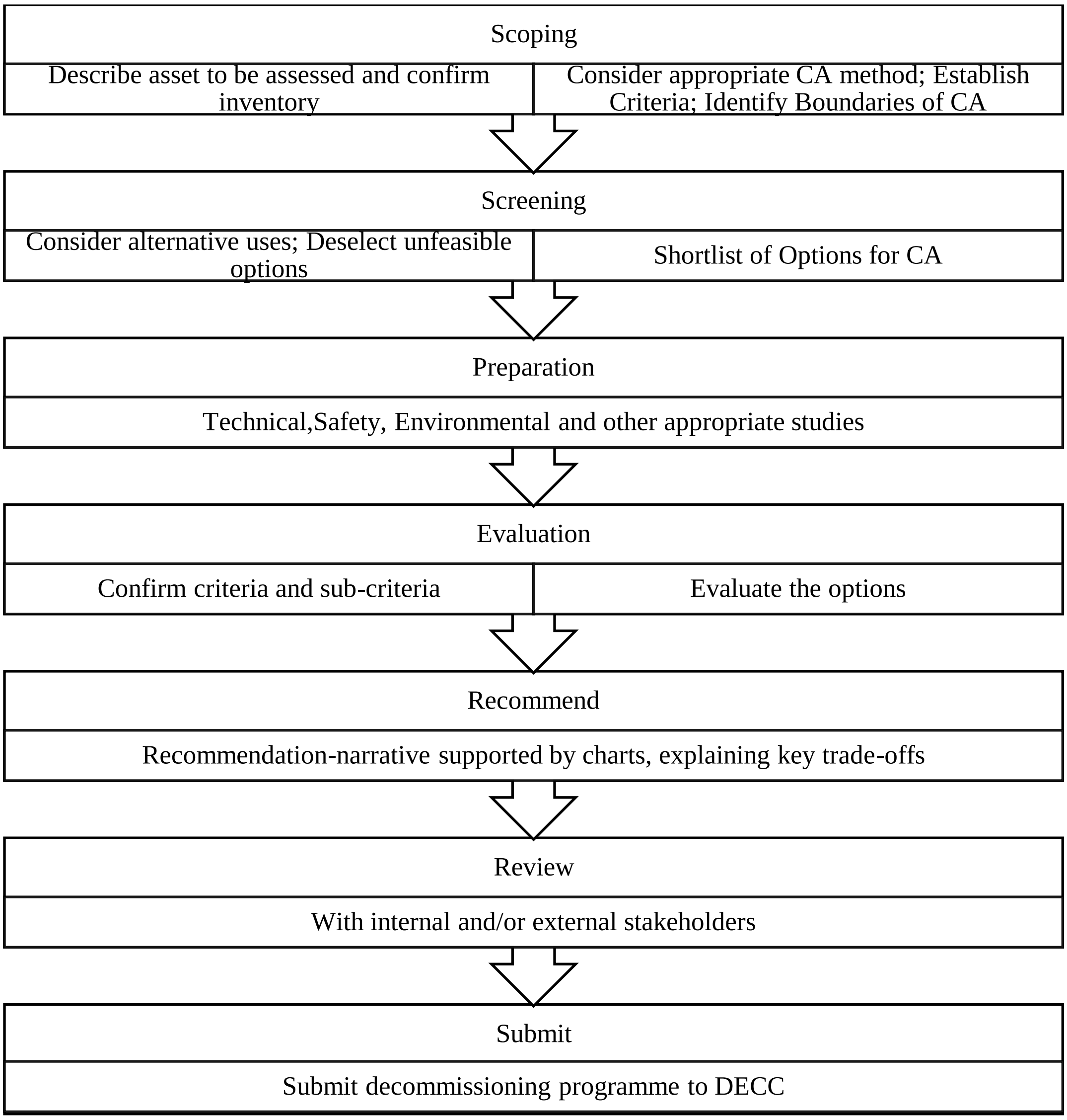


Figure 9. The CA phases (Ekins et al., 2006).

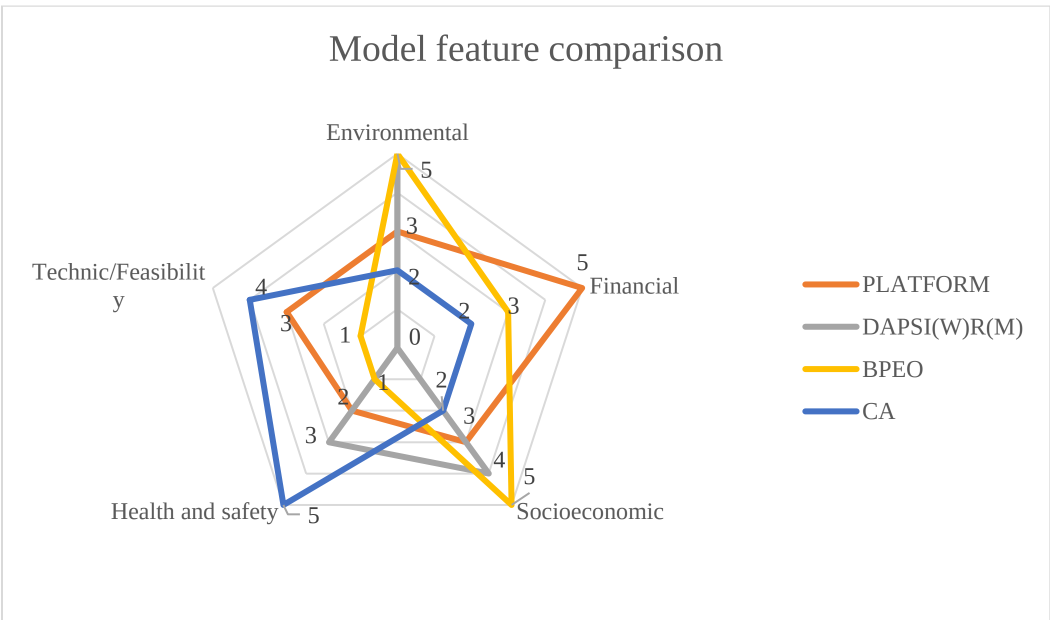


Figure 10. Models' features comparison.

According to the description of each frame in the Table 8, combined with the five criteria classification of the decommissioned frame in the Table 7, the radar chart in Figure 10 is obtained to visually show the performance of each decision frame in the five criteria. This part is more subjective and designed by the author based on the understanding of the three models. It is true that this type of model is scientific and intuitive, but based on actual conditions, it is not widely accepted. Different from the decommissioning of onshore facilities, it is not only the traditional risks and costs, but the decommissioning of offshore oil and gas facilities will have an impact in many areas. The marine environment and the impact on other users are also valued by the public. Brent Spar, which was decommissioned by Shell in 1995, is a typical example (Pulsipher & Daniel Iv, 2000; Osmundsen & Tveterås, 2003). Although this example has been widely mentioned by scholars in the field of offshore oil and offshore platforms, it also has a strong position in the history of marine environmental protection. It must be said that the initial decommissioning decision of Brent Spar is scientific, low-risk and low-cost of. But the public's concern is that the decision poses a potential threat to the marine environment and may harms the benefit of other water users. As a result, after a long negotiation, Shell compromised with environmental protection organizations and dragged the submerged body of brent spar onshore for disposal at any cost.

2.3 Cost Assessment

As an important part of the decision-making model, the cost evaluation model is also an important part of the decommissioning decision-makers. The accuracy of the assessment results not only affects the duration of the project, but also affects the environment, risks, government approvals and many other aspects. Therefore, academia and industry have always paid great attention to more accurate and versatile cost evaluation models. However, the cost assessment of the decommissioning of offshore oil and gas facilities is different from the decommissioning of onshore oil and gas facilities. Its data sufficiency (Murray et al., 2018; Kaiser, 2015), uncertainty, and insufficient historical experience make it difficult to develop accurate cost assessment tools and cannot guarantee stable accuracy. It is known that among the currently published models, the higher accuracy can only be controlled at an average of about 35% (the weather impact is directly assessed as 20% of the total cost, while providing an error space of 15%) (Bernstein et al., 2007). Especially with increasing emphasis on marine environmental protection, an accurate cost assessment model means that the further optimization of project schedule, environmental impact, and risk control is very important and valuable.

At present, the U.S. and U.K. offshore industries have each developed a set of cost assessment models based on their own technology and conditions. The U.S. model is the PAES tool which is mainly developed by ProServ Offshore (Kaiser & Liu, 2014). In the United Kingdom, a model form combining CA and EIA is adopted (Oil & Gas UK, 2015; Bond & Brooks, 1997), that is, based on the historical data of decommissioning of similar facilities, evaluation is performed to estimate the cost of decommissioning and the environmental impact.

The models used by the two countries are like some extent, because according to PAES development records, the model also uses comparative assessment methods in some parts of the evaluation, such as gas emissions, energy use, waste management and other aspects (Smith et al., 2016). The main difference between these two models is the assessment of detailed costs. The United States uses a compound regression method to establish an empirical equation to estimate the cost. There is no empirical equation in the method presented in the UK. The evaluation method is still developed by various energy companies and oil service companies based on the data they have, and the framework is the same.

Back to the beginning, the academia has already given a more authoritative explanation on how to establish a cost evaluation model. Two mainstream frameworks show as Figure 11, which are top-down and bottom-up frameworks (Kaiser, 2015). The top-down framework mainly uses historical data, starting from a larger level of data, ignoring part of the cost accounting that is too detailed, after data processing-such as standardization-and then regression, there are various regression methods, and the following methods are mainly the method used in data analysis. For example: get the topside structure decommissioning cost, total emissions, construction duration and other data of some decommissioned platforms, as well as the basic parameters of the topside structure’s weight, scale, number of modules, etc., through the aggregation of the same type of data on these platforms, data processing, data analysis, get its functional relationship, and then use it to evaluate the cost of topside retirement of other structures. This method requires a large amount of accurate historical data and is a framework based on data analysis methods. And bottom-up focuses on the detail level, that is, starting with each task of the decommissioning project, cost estimation is carried out separately, and then summarized. From a theoretical perspective, a theoretical model is established for each step of the decommissioning of oil and gas facilities, combined with engineering guidelines and engineering data, and from the perspective of man-hours or unit volume, the relationship with the cost is established to conduct cost evaluation.

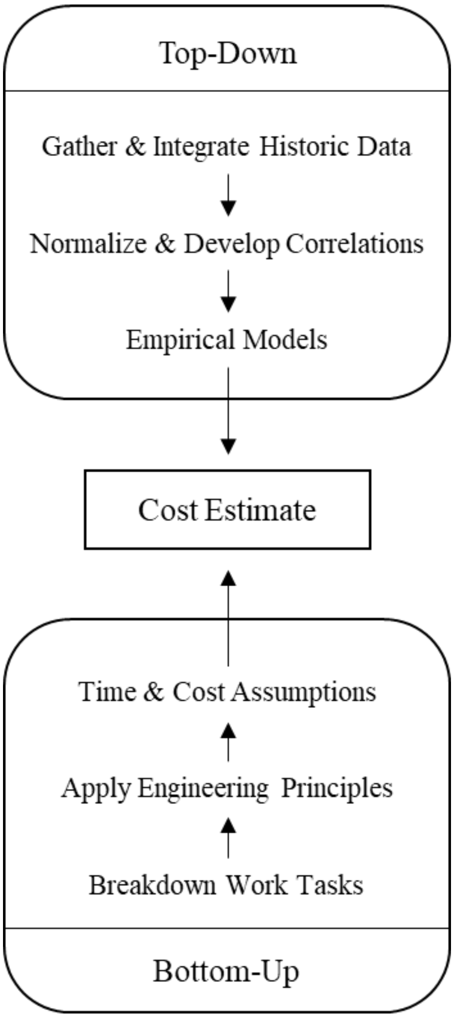


Figure 11. Two cost model frameworks(Kaiser, 2015).

These two types of frameworks currently have their own advantages, but it is difficult to achieve a better unification in form. From a theoretical point of view, the model built by the bottom-up framework is more pertinent. For a certain type of oil and gas facility in a certain area of the sea, the cost can be estimated in detail and accurately without the need for similar historical data of decommissioning projects. However, the establishment process requires the collaboration of multiple experts to evaluate engineering standards, parameter settings, etc. The process is cumbersome and complex and does not have wide applicability. The top-down framework is simpler, which is conducive to the industry’s own development, and the versatility of the resulting model will be more advantageous. But first, the framework requires more historical data of decommissioned projects as a database, and the degree of data sufficiency will directly affect the accuracy of the evaluation results. However, the sharing of such information is taboo in the industry because it involves issues such as antitrust laws and trade secrets. At the national level, such as the British BEIS, although such data can be obtained, it cannot be granted the right to share such data (Lake & John R, 2006). Secondly, the model evaluation results under this framework are often not as accurate as the model evaluation results under the bottom-up framework. Although in the future, ample data may improve the accuracy, it is still difficult to match the accuracy of the bottom-up framework. The model is comparable.

In recent years, some scholars have used economics or other industry methods to innovate the decommissioning cost assessment framework from different perspectives (Sandra Santa & Ernesto Heredia, 2011; Kaiser, 2015), mainly based on the decommissioning methods of nuclear industry facilities and chemical industry facilities. Cost assessment for the decommissioning of offshore facilities. But its model framework does not deviate from the two modes mentioned above. We look forward to the emergence of more novel and effective models to solve this urgent problem.

2.3.1 Top-Down Framework

The most significant feature of the cost assessment model estimated according to the Top-Down framework is that mathematical regression analysis is generally used as the primary methodology, a large amount of data is used as the research source. Finally, the regression equations between several categories of data and costs are obtained as experience—a equation to estimate the cost of decommissioning an offshore facility. The following models are built according to Top-Down framework.

Platform Abandonment Estimating System (PAES)

Based on the decommissioning data of three platforms in the Gulf of Mexico, ProServ Offshore developed a simple algorithm for the decommissioning of oil and gas platforms in the GOM region in 2000 (Twachtman Snyder & Byrd Lnc., 2000). The main content of this algorithm is to fix some costs, such as HLV mobilization/demobilization costs, and daily costs. And part of the cost, such as the cost of the mobile platform is returned. The sum of all values is the method of decommissioning cost of oil and gas facilities to estimate the cost of platform decommissioning. At the beginning of the model establishment, due to the small amount of data, the accuracy of this algorithm is not good enough, and the estimated value is often more than 25% lower than the actual cost.

Later, as the sample data gradually increased, the PAES system was also improved. Especially with the addition of Mark J. Kaiser and Brock B Bernstein, as well as organizations such as ICF and BSEE (Bressler & Bernstein, 2015; ICF International, 2015; Proserv Offshore, 2010), the model now has even better performance. The model determines that the management cost of platform decommissioning accounts for 8% of the total cost, the weather factor is preset to 20%, and the cost flexible interval is 15%. This is a cost evaluation model that is very suitable for rough estimation by industry and government agencies. Although it has been improved so far, the definition of its accuracy is still large fluctuation, between 6% and 258% (ICF International, 2015), but it is still the best in the cost evaluation mathematical model. This mathematical model is also used in the decision model PLATFORM mentioned above.

Mark J. Kaiser's Models

Mark J. Kaiser has made many optimizations based on the PAES model and established a variety of cost evaluation mathematical models from different angles. It has a very high reference value and use value. Although the scope of application of the model is partially restricted, it is not applicable to all offshore oil and gas facilities at present, and the actual parameters have regional differences. For different countries and regions, it needs to be re-studied. But the template he provided is worthy of in-depth study by related scholars.

In Kaiser's 2003 model (Kaiser et al., 2003), he innovatively classified the platforms according to four legs less than or equal to four legs and greater than four legs, and concluded that in each of the six main decommissioning activities, four leg platforms and eight legs The average cost of the leg platform and the standardized data. And get the key parameters of the six main activities of the four-leg and eight-leg platform, such as: water depth, number of wells, deck weight, maximum module weight, integrity, etc., and get regression equations. But the disadvantage is that the coefficient determination R^2 value of some of the regression equations is too low, many of which are even lower than 0.5, which is not unavailable for regression analysis. Perhaps because of this, the accuracy of the model is not specified in the original text.

Later, in his 2006 thesis (Kaiser, 2006), a multi-parameter model was developed. This model provides even as many as seven parameters for the cost of each process in the decommissioning process, including but not limited to: water depth, number of wells, work category, well development degree, workboat deployment, season, waiting season, number of construction period days, etc., Some of the parameters are two-dimensional, that is, only 0 and 1 are used to distinguish whether to use the parameter. This model is a standard top-down model, which requires a lot of data and is very detailed, and at least three models have been developed for each activity to choose from. Although the accuracy of this model is not clearly stated in the original text, it is known that it must be very high. However, the data required for this model is too detailed, which is unrealistic for researchers or model users without data support.

In 2014, Kaiser developed a dedicated decommissioning cost assessment model for the GOM deep water fixed platform and the compliance tower platform (Kaiser & Liu, 2014). Deep water means a platform with a depth of more than 400ft. The model uses data from 53 deep-water fixed platforms and compliance towers. The decommissioning costs of such platforms are often very high, so the impact is huge. In this model, more detailed platform decommissioning division and decommissioning options are applied. In this model, regression analysis is further used. Except for wet tree retirement costs and riser removal costs, which are determined according to unit prices, regression methods are used for other parts. The difference is that in the regression analysis of each part, they are classified according to the number of wells, conductors' number, water depth, etc., to obtain a more accurate regression equation. It is worth mentioning that not only linear regression analysis is used, but nonlinear regression analysis is also used more frequently.

The model largely draws on the results of Kaiser and applies data from the decommissioning of offshore oil and gas facilities in Malaysia, making the model localizable. In this model, regression analysis is widely used, but unlike other models that mostly use linear regression analysis, this model uses a lot of nonlinear regression analysis. When substituting data, calculations are made based on Malaysia's own working hours and efficiency. The entire model also deals with the decommissioning project step by step. Unlike the model of PAES and Kaiser, this model also makes an empirical equation for the project management part of the cost to make a more detailed cost estimate, which is undoubtedly conceptually An improvement to improve accuracy, but for the actual effect, although R^2 and correlation analysis data are given, because the amount of data cannot be determined, and the verification part of the entire model only uses one example, whether the regression equation is over Saturation is not known. Because it is well known that the Top-Down mode uses historical data for fitting. It is a posterior model, so the over-fitting situation cannot be ignored. Even if R^2 performs well, it is very likely to have occurred. Fitting situation, so only a good prediction for one case, and cannot be applied to the prediction of other cases (Sarle, 1995).

2.3.2 Bottom-Up Framework

Although Kaiser put forward two basic frameworks for cost evaluation very early, most scholars tend to build the cost evaluation model of the top-down framework. Although there are cost assessment models based on Bottom-Up, they are not dedicated to decommissioning offshore facilities. This section will introduce several bottom-up framework cost assessment systems developed for other industries, which can be used as a reference.

Milne's approach (Milne et al., 2021)

Milne et al. developed a bottom-up framework cost assessment mathematical model for offshore wind turbine decommissioning. The model divides Offshore Wind Farm (OWF) decommissioning into ten steps, from project management to monitoring. However, the model evaluation part only includes the fourth step - wind turbine generator removal, to the seventh step - cable removal. In his model, the unit decommissioning price of components mentioned in many reports (PCCI, 2014) and papers (Ioannou et al., 2020; Quintana, 2016) of others is used as the unit decommissioning price of its components. The cost evaluation results of this model are acceptable and can maintain an average deviation of about 20% when applied to some models.

PETRONAS approach (Lah, 2021)

Developed by Petronas, the model is now mainly used in Malaysia for the annual budget assessment of more than 300 terminals, more than 600 pipelines and other assets. This method is a relatively mature method for decommissioning cost assessment, and after a long period of use and optimization, it seems to have an excellent overall prediction effect.

Approaches for assessing the cost of decommissioning nuclear power facilities (OECD & NEA, 2010)

Although it is a cost assessment method for decommissioning nuclear power facilities, the Bottom-up framework is still used. Their decommissioning models have many correlations between offshore and nuclear power facilities. Therefore, this paper also refers to the cost assessment method for nuclear facility decommissioning. The thesis mentioned that many countries had developed decommissioning assessment models based on the bottom-up framework, including AIF/NESP-036 and DECCER in the United States, ONDRAF in Belgium, OMEGA in Slovakia, and France, the Netherlands, Germany, and other countries developed model.

Briefly summarize the characteristics of the framework approach and the reasons for its current status. The author’s artificial Bottom-Up framework is theoretically a method with high versatility and accuracy. Still, it is the worst in ease of use and requires the highest degree of professionalism. The builder must have a good understanding of the industrial details of the industry and master the newer market cost data to build a better model under the bottom-up framework. This is not difficult for experts working in energy companies, but it is very difficult for academics in universities and other non-industry researchers. However, the time and labor cost of building this framework model is much higher than the top-down framework, which involves other stakeholders’ commercial secrets. So, even if the energy company makes such a model, it will not open its model to others.

2.3.3 Uncategorized

Comparative Assessment (CA)

Although CA is a decision-making model, it also includes the cost assessment part. As the most intuitive, simple, no software calculation, and can consider multiple evaluation methods, the cost assessment part of CA can be considered as the most versatile and reliable model in the current mature technology.

In the CA, a strict assessment process is the key to ensuring the reliability of the result. Figure 9 shows the CA process and its explanation. In the entire process, the setting of criteria and sub-criteria is the most important part (Oil & Gas UK, 2015). Strictly speaking, the cost assessment part of the CA cannot be called a model, but is only a part of the comprehensive assessment, which requires relevant experts to evaluate according to Asset Retirement Obligations (ARO), and the result is often reported as a percentage of the lowest cost to the highest cost of options or report the difference in orders of magnitude. The accuracy of this assessment method is compared with the Decommissioning Programme and Close Report reports of the decommissioned offshore oil and gas facilities in the UKCS area. It can be concluded that the accuracy fluctuates greatly. The better evaluation results only differ by several million pounds (Spirit Energy, 2018a), and there are individual actual costs that exceed the expected results by 100% (Shell, 2014; PremierOil, 2015).

Settled Liability Model (SLM)

Settled Liability Data Model is the latest research result of Kaiser in 2015 (Kaiser, 2015). He broke away from the original top-down and bottom-up frameworks, but used economic statistics, which is refreshing. The reason for the development of this cost assessment model is that more professional and detailed oil and gas facility decommissioning data cannot be easily obtained. These sensitive data are related to the commercial secrets of energy companies. Often these data are only available to energy companies, oil and gas service companies hired, and relevant government departments. Such information opacity is important to researchers or policy makers in other related fields, extremely unfriendly. Therefore, in this model, the physical characteristics of oil and gas facilities are no longer important, while Settled Liabilities, Working Interest, the number of decommissioned wells, and the number of various types of facilities of related companies are more important and easier to obtain from the public. Obtained from the data. After equation (6) to equation (7) are calculated, the average annual decommissioning cost can be obtained, in units of millions of dollars per structure. The model is loaded with data every year, and the coefficients are different every year. It is not difficult to know the development intention of this model. It is not to accurately provide energy companies or oil service companies with a more accurate decommissioning cost assessment, but to the government. Policy and strategy makers such as institutions and market analysts provide reference. This is a very novel model that combines the knowledge of statistical economics and offshore oil engineering.

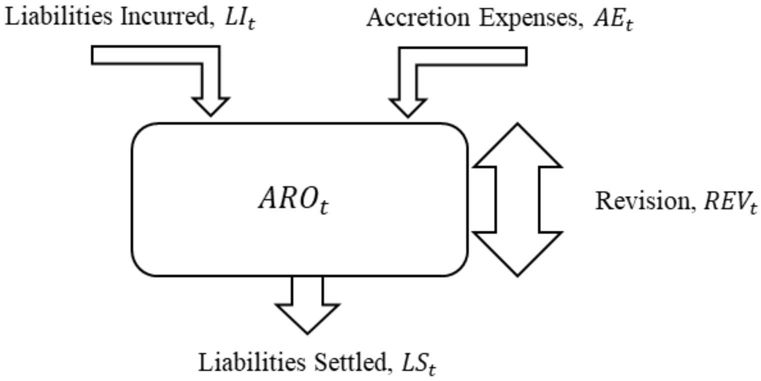


Figure 12. Asset retirement obligation balance equation (Kaiser, 2015).

$$ARO_{t+1} = ARO_t + LI_t - LS_t + AE_t \pm REV_t \quad (6)$$

$$DEC_t(C_i) = \alpha_0 + \sum_{j=1}^{k} \alpha_i ACTIVITY_{j,t}(C_i) \quad (7)$$

Where, ARO_t means Asset Retirement Obligations at the beginning of year *t*; LI_t means Liabilities Incurred in year *t*; LS_t means Liabilities Settled in year *t*; AE_t means Accretion Expense in year *t*; REV_t means Revisions in Estimated Liabilities in year *t*; $DEC_t(C_i)$ means Decommissioning Cost of company C_i in year *t*; α_i is coefficients; $ACTIVITY_{j,t}(C_i)$ means Ownership position of company C_i performing decommissioning ACTIVITY *j* in year *t*.

2.3.4 Summary of Cost Assessment Models

It can be seen from the above introduction that there are still few models or tools for decommissioning cost assessment of offshore facilities, and they are mainly concentrated under the top-down framework. Under the bottom-up framework, there is no mathematical model dedicated to the evaluation of the decommissioning cost of offshore facilities, and the reason is also made by the author above. Some models built beyond the two basic frameworks are basically composite or are temporarily more idealized and do not fully match the industrial system.

In fact, through the study of the above-mentioned cost assessment models and tools, it can be found that the method construction mode used by these models partially follows the two frameworks mentioned by Kaiser. The makers of related models usually use the coexistence of two frameworks to build models with appropriate data. For example, the step cost after work decomposition is listed as a mathematical expression, but its actual parameters are obtained by regression on existing data. This approach conforms to the bottom-up framework in structure but also uses the regression method of the top-down framework in methodology.

In addition, the most significant difference between the decommissioning of offshore facilities and the decommissioning of onshore facilities is the estimation of the decommissioning project time. By reading the relevant decommissioning reports, we know that a facility's decommissioning time will significantly affect local sea conditions and weather! The actual engineering time at sea can often be as short as a few months, while the wait time can be years, which makes the cost estimation extremely uncertain. For the time being, there is no relevant literature to study whether there is a mathematical relationship between the scale of the platform and the decommissioning time and other cost details.

In general, the methods, models and tools required to estimate the cost of decommissioning offshore facilities are currently limited, and their accuracy needs to be improved.

2.4 Quantitative Risk Assessment (QRA)

Quantitative Risk Assessment is the primary risk assessment method used in this study. This section will introduce the general process of this methodology and related previous results. The core equation of QRA is:

$$R = F \times C \tag{8}$$

Where R is the assessment result, F is the accident frequency, and C is the quantitative consequence assessment. It is deduced that the core parts of QRA mainly include three, the first is the hazard identification technology HAZID, the second is probability estimation method, and the last is the consequence assessment method.

Since the 1950s, modern QRA technology has received attention and was first developed and applied in nuclear safety assessment to estimate the damage to the population within 30 miles caused by radiation leakage in three scenarios (Cooke, 2005). Based on this, nuclear installation continuously improves security and troubleshoots security risks. After the continuous development of the QRA in the field of nuclear safety, the Nuclear Regulatory Commission (NRC) published the Reactor Safety Study in 1975 to provide the earliest guidance on nuclear safety regulations (Rasmussen, 1975). The application of QRA in the aerospace field also started earlier in the United States. NASA developed Probabilistic Risk Assessment (PRA) technology after the 1967 Apollo spacecraft accident that killed three astronauts to ensure the spacecraft met its 1969 safety goals. It was not until after the Challenger accident in 1986 that the PRA was abandoned because it could not meet demand (Paté-Cornell & Dillon, 2001).

Figure 13 shows a flow chart of QRA, which clearly shows the main parts of QRA, the content of each part, and the general method used. The specific methods used by each module will vary due to different usage scenarios and applied technologies, which will be described in detail below. The output results of QRA also differ according to the type of risk assessed and application scenarios.

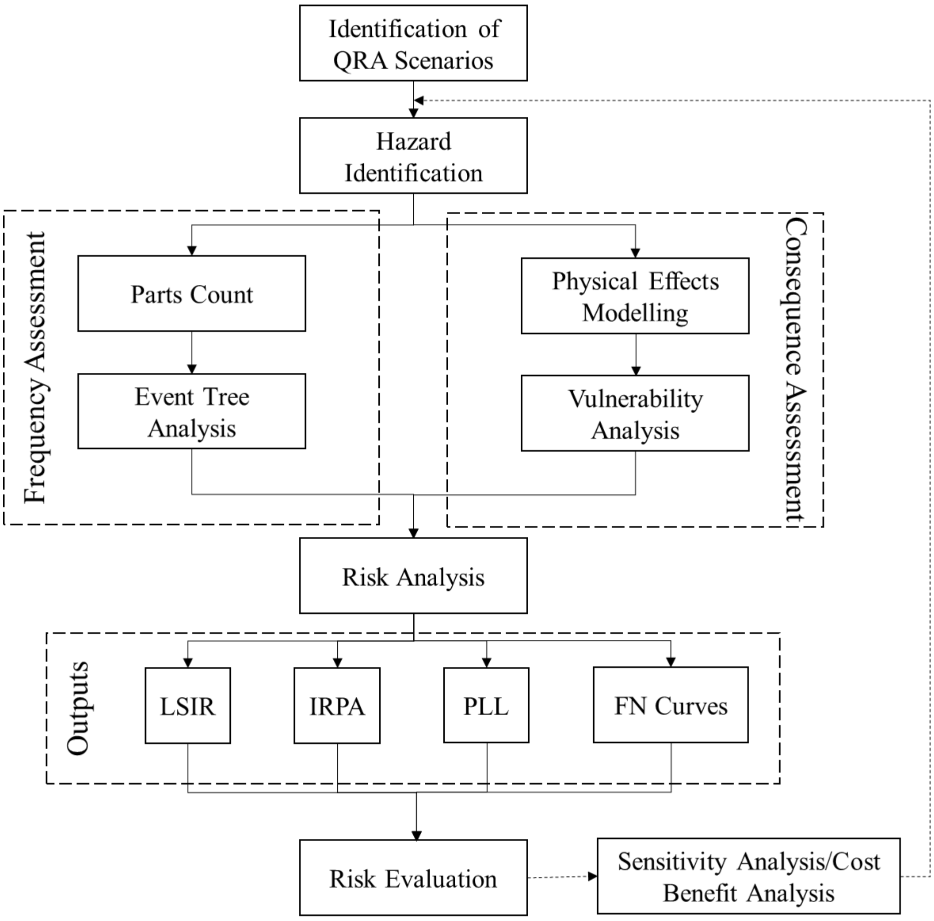


Figure 13. QRA flowchart.

The rest of this section will be introduced in terms of the main modules shown in the Figure. The details of the flow chart of QRA will be different for different scholars and for different scenarios and industry applications, but this does not affect the three core modules of QRA.

2.4.1 Hazard Identification (HAZID) Technologies

To clarify the content of the QRA, it is necessary to identify which hazards are worth evaluating and ignore those that do not cause relatively serious consequences, aiming to saving computing resources. Therefore, HAZID is an essential foundation of QRA, and its main contents are (Vinnem, 2014):

- Identify the hazards associated with the defined system, the sources of those hazards, and the events or series of situations that could lead to the hazard and its potential consequences.
- Generate a comprehensive list of hazards based on events and situations that could lead to possible adverse outcomes within the scope of the risk and emergency preparedness assessment process.
- Identify possible risk reduction measures. It is often claimed, especially by authorities, that more emphasis should be placed on hazard identification. This can lead to identifying only well-known hazards and nothing but those well-known hazards, in which case hazard identification fails.
- Look for unknown threats that have never happened but could lead to a significant accident.

The general HAZID technology will be divided into three levels according to different scenarios and needs. The classification of these three levels can generally reflect the level of detail and quantity of hazards that should be identified. The number of hazards at the system level is small, and the types of hazards are fewer. The number of hazards can be identified at the subsystem level, and the types of hazards are also relatively wide. For equipment level, multiple damage mechanisms of a component in a single accident or hazards caused by the same accident in multiple scenarios mean an enormous number of broadest hazard types. The three levels are explained as follows:

- Equipment level: that is, to identify equipment’s hazard in offshore decommissioning, such as valves, Blowout Preventers (BOP), vessels, etc.
- Subsystem level: Hazard identification is carried out at step in the operation of a system. For example, for well plug and abandonment, only the hazards that may occur when cement plugs are set are studied, and the hazards of other steps, such as mud extraction and mechanical plug setting, are not considered.
- System level: Hazard identification for a complete system, which can be large or small. Such as the fire protection system of the platform, the internal system of the oil acquisition system, the hazard identification of the entire platform operation, or the hazard identification of such large systems and processes as the platform decommissioning project.

In dealing with these HAZID, many specific and mature methods are used. Table 11 shows the most used specific methods for HAZID and a brief description.

Table 11. General HAZID methods.

Check lists (Taylor, 1974)	Listed by experts against existing project plans for review
Previous studies	Lists of hazards from similar cases used as start for a new object
Accident and failure statistics	Identify hazards based on accident and equipment failure statistics
Hazard and operability study (HAZOP) (Dunjó et al., 2010)	A technique for identifying in detail the sequence of failures and conditions that could lead to an accident
Safe operations study (SAFOP) (Tamil Selvan et al., 2015)	A technique for reviewing procedures to identify failure sequences and conditions that could lead to an accident
Preliminary Hazard Analysis (PHA) (Signoret & Leroy, 2021)	A method for hazards associated with the operation of a process or procedure used to identify, classify and screen systems initially in safety processes
Bow-tie (Ibrahim & Rao, 2017)	A method that can efficiently and visually display the operation process of the safety system

Some of the simple technologies in Table 11 will not be described in detail, and the following will describe the HAZOP, SAFOP, PHA and Bow-tie technologies appropriately for the convenience of readers.

Besides, HAZOP is an analytical technique for hazard identification and operational problems in complex processes. The technology has the characteristics of flexible usage scenarios and can be used as an interface between hardware, software and operators. Incident tree analysis is the core analysis method of HAZOP for identifying hazards.

HAZOP requires an experienced interdisciplinary team and sufficient design information to set up many evaluation nodes. For each node, the HAZOP team sequentially uses standardized guidewords and a list of process parameters to identify potential deviations from the design intent. For each deviation, the team determines possible causes and consequences and then decides (confirmed through follow-up risk analysis, if necessary) whether existing protections are adequate or whether steps need to be taken to install additional protections to reduce the risk to an acceptable level.

The parameter setting requirements should be simple enough to limit thinking and general to have no focus, so words such as flow, temperature, pressure, level, react, mix, isolate, drain, start-up, and shutdown are usually used. The guiding words usually express degree, relationship, sequence, time, logic, etc. For details, refer to the explanations of Crawley et al. (Crawley et al., 2008) and Lees (Frank P. Lees, 2012).

In addition, SAFOP, provided by Lloyd's Register Consulting—Energy AS (Scandpower Risk Management Inc, 2004) is an adaptation of the HAZOP technique for analyzing jobs and processes to identify hazards. SAFOP has advantages in the hazard assessment of planned and

changed projects and provides more detailed guidewords. Its usage is similar to that of HAZOP and will not be repeated here.
Furthermore, PHA, is an analytical technique used to identify hazards that could lead to a hazard event if not adequately prevented from occurring. Preliminary hazard analysis is typically used to assess hazards early in a project during the conceptual and front-end engineering stages. It does not require a fully detailed design but allows early identification of possible hazards, which aids in selecting the most advantageous facility and equipment arrangements. The general process includes the following:

- Define subsystems and modes of operation.
- Identify hazards associated with specific subsystems or operations.
- Define the hazardous event resulting from the hazard.
- Estimate the probability of an event occurring and the possible consequences of each hazardous situation and classify the probability and consequences using a specific set of rules.
- Identify and evaluate protective or mitigation measures to reduce the probability of an accident or limit the consequences.
- Evaluate the interaction effects of different hazardous events and consider the effects of common mode and common cause faults.

The preliminary hazard analysis is conducted in a structured manner, usually using some form of Tables. Each hazardous event corresponding to the subsystem or operation identified by the analysis is investigated and recorded in a row, resulting in a "risk level" for that particular hazardous event or subsystem or operation (Signoret & Leroy, 2021).
Finally, Bow-tie, essentially a combination of the traditionally used fault tree and event tree, with the fault tree forming the left side of the bow-tie and the event tree forming the right side. This method is characterized by using graphics to demonstrate how to implement a facility's safety management system effectively. It helps companies/operators analyze and manage the hazards and risks faced by their business, showing, and explaining the relationship between hazards, controls, and risk reduction measures.
Figure 14 is an example of a bow-tie diagram that depicts the relationships among hazards, threats, barriers, escalation factors, controls, consequences, recovery preparedness measures, and critical tasks. Currently, the most well-known tool is THESIS, conceived initially by Shell International and jointly owned and developed by ABS Consulting Ltd and Shell International (CCPS & Energy Institute, 2018).

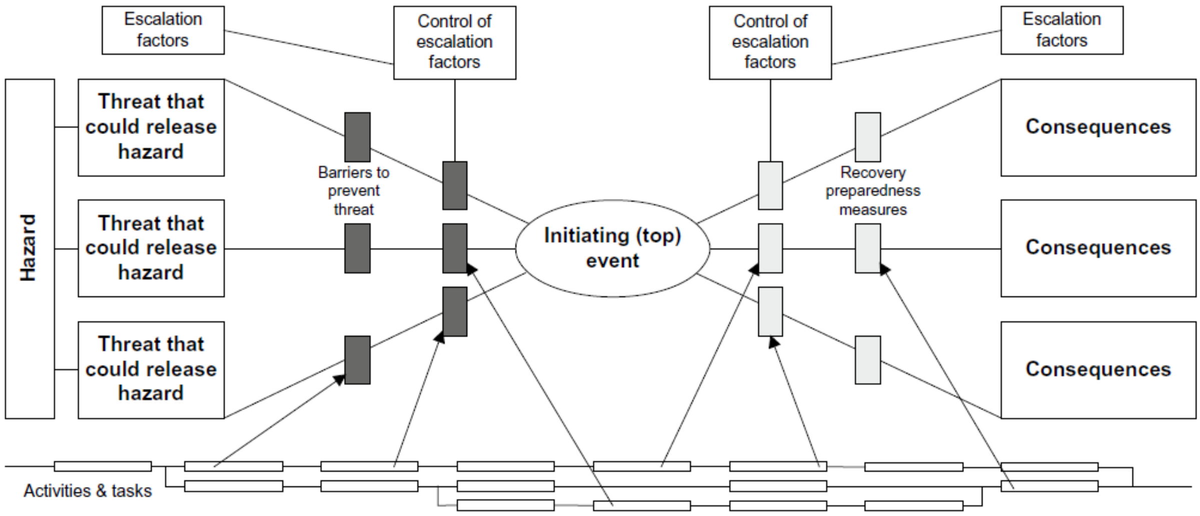


Figure 14. A typical bow-tie diagram.

2.4.2 Probability Evaluation Technologies

Accident probability assessment is a part of QRA that has the same important status as accident physical consequence assessment. Due to the diversity of probability theory development, the research on probability assessment is even more popular than the research on physical consequence assessment. Table 12 lists the basic methods of accident probability assessment used in the offshore industry. These methods are general, and their framework structure can be widely used in many fields, such as industry, economy, management, etc. However, there are differences in detailed methods.

Table 12. Probability evaluation technologies for offshore industry.

Fault Tree Analysis (FTA)(Lee et al., 1985)	Visually display the structural, logical causality of system failures and the application of safety barriers
Event Tree Analysis (ETA)(You & Tonon, 2012)	Visualize the structural causality of accident development trends, the corresponding consequences, and the application of safety barriers
Statistical Simulation Analysis(Koch, 2018)	Also known as the Monte Carlo method, it uses modern computer technology to simulate the number of random accident occurrences to obtain their statistical frequency
Analytical Methods(Zhao et al., 1994; Čorić et al., 2021)	Some basic statistical methods are collectively referred to. In most cases, the causes of accidents and the inclusion or inclusion attributes of specific characteristics of the target are studied, such as the geometric analysis method used in the study of ship collisions.

Since both statistical simulation and analytical methods are simple and easy to understand, we will not introduce too much in this part. Instead, we will focus on the FTA and ETA methods because they are widely used, and the Bow-tie diagram method as well obtained by their combination.

Fault Tree Analysis (FTA) is designed to determine the cause of equipment failure and is primarily used for reliability and availability assessment. The FTA is an intuitive tree-like graph showing various combinations of equipment failures and human error and the possible incidents caused by those combinations. These types of incidents are called top-level incidents in the FTA. The advantage of fault tree technology is its ability to combine hardware failures and human error to realistically represent the steps in which an accident occurred. This intuitive approach efficiently identifies prevention and mitigation measures and focuses on the underlying causes of accidents.

FTA is particularly suitable for analyzing complex and highly redundant systems compared to systems such as FMEA and HAZOP, where a single failure can lead to a hazardous event. Therefore, FTA is often used to analyses further the details of hazard events analyzed by other methods (e.g., HAZOP).

The output of fault tree analysis is a fault logic diagram based on Boolean logic gates (i.e., AND, OR), describing how different combinations of events lead to dangerous situations. In practical use, many fault trees may be required to fully consider all identified top events of an extensive industrial process. Furthermore, analysts need to exercise judgment in selecting the top events to consider at the event level to be analyzed to ensure adequate underlying data and use of computing resources (Rausand, 2013; Vesely et al., 1981; Aven & Heide, 2009).

An example presentation of an FTA is necessary. Figure 15 shows a simple fault tree that analyzes why a light bulb does not light up. The Figure shows the circuit diagram of the light bulb. According to the analysis of the circuit diagram, the reason why the light bulb does not light can be traced to the failure of four key components. If the light bulb is to light up, these four components must be kept in good condition simultaneously. Therefore, the logic gate currently uses an AND gate. Continue to pursue the switch problem. The reason for the switch working may be that there is no operator connecting the switch, or the switch itself may be faulty. The two basic events are independent, so the OR gate is used. In actual use, the establishment of FTA has high requirements on the user’s knowledge, experience, and understanding of the equipment. Users need to be aware of the series-parallel relationship in the process and the possibility of failure of each node. In addition, when using FTA, it is necessary to artificially limit the analysis level of basic events analyzed for large and complex systems to save workforce and computing resources. Otherwise, the fault tree is likely too large and difficult to analyze.

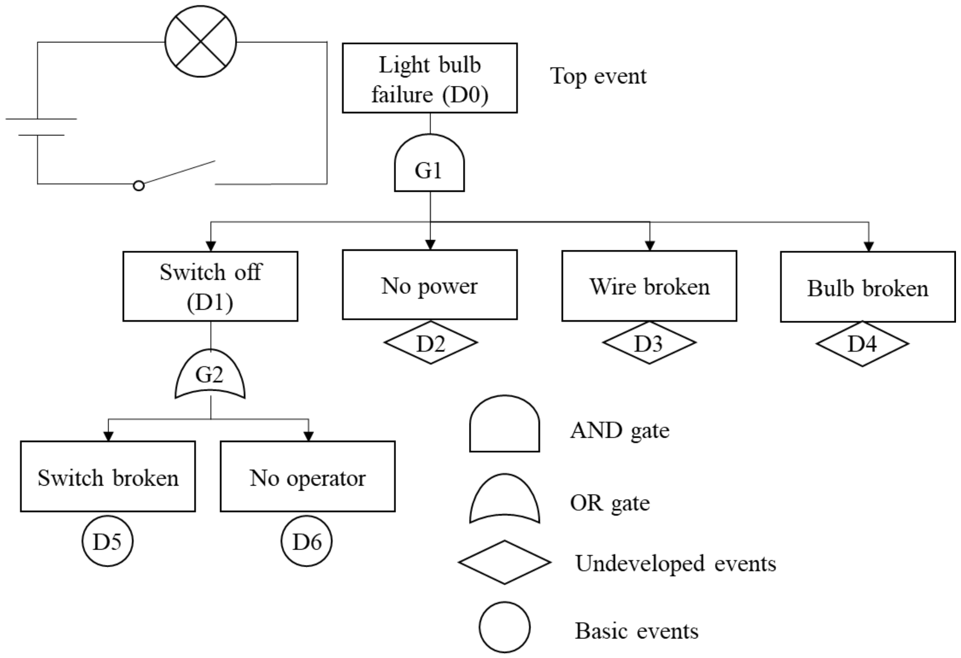


Figure 15. Fault tree analysis for light bulb does not light up.

Event Tree Analysis (ETA), an event tree is a visual model that describes a chain of possible events that may develop from a hazardous situation. Define initial events (also called top-level events to combine with FTA) and calculate their frequency or probability. The possible outcomes of initiating events are usually binary; the answer to each question is “yes” or “no”. These questions often correspond to safety barriers in the system, such as “failure to isolate or not”, so this approach reflects the designer’s way of thinking (Crawley, 2020).

In a dendrogram, each branch point gives the probability of that outcome. These branch points are often called “nodes” of the event tree. The probabilities or frequencies of terminal events are calculated from the probabilities or frequencies of the start event and the conditional probabilities associated with each branch. End events are collected in groups of similar consequences to give an overall risk map. The following actions are often performed from the event tree:

- Frequency calculation of consequence categories.
- Sensitivity analysis (effect of changes in specific parameters).
- Identify key contributions to each consequence category.

Figure 16 shows a binary ETA structure diagram, starting from the top event, to determine whether a directly related event occurs and the probability of occurrence to obtain the next layer of branches. Each layer operates in the same way and finally obtains the final event defined by the operator and obtains the probability or frequency of each final event according to the probability product of each branch from the top event to the final event (Andrews & Dunnett, 2000).

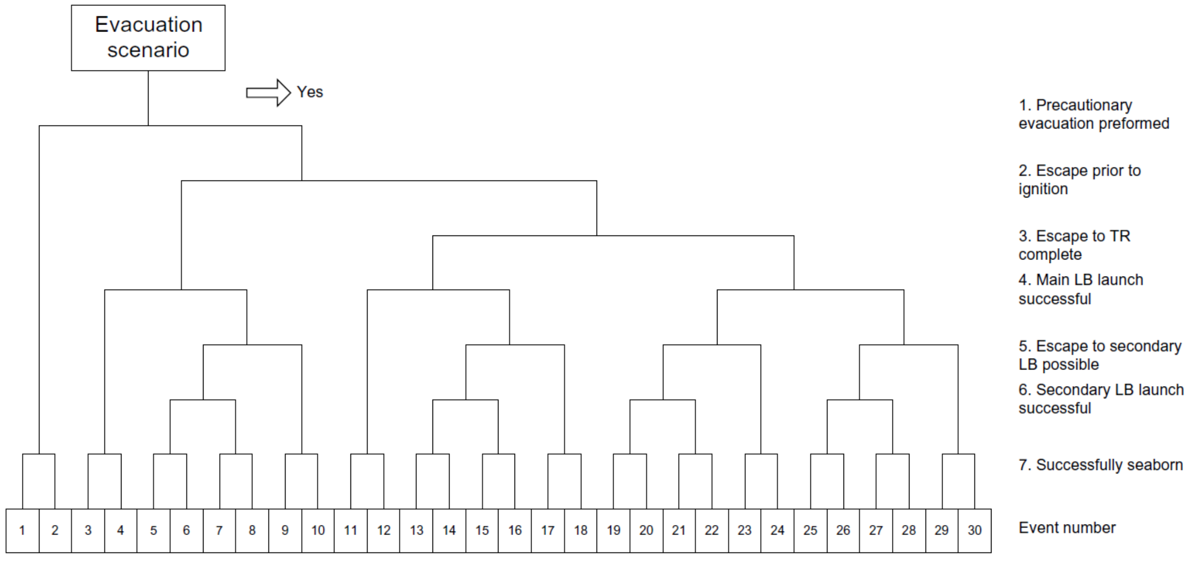


Figure 16. Basic framework of event tree.

It should be mentioned that combining FTA and ETA is more than just the Bow-tie method. Figure 17 shows a commonly used method combining FTA and ETA for industrial process analysis. Each branch node of ETA will be regarded as the top event of FTA, and the cause of the event will be analyzed. This method can establish extensive connections between events when some statistical data is insufficient. It is challenging to use fundamental data to obtain assessed accident probability (Paté-Cornell, 1984).

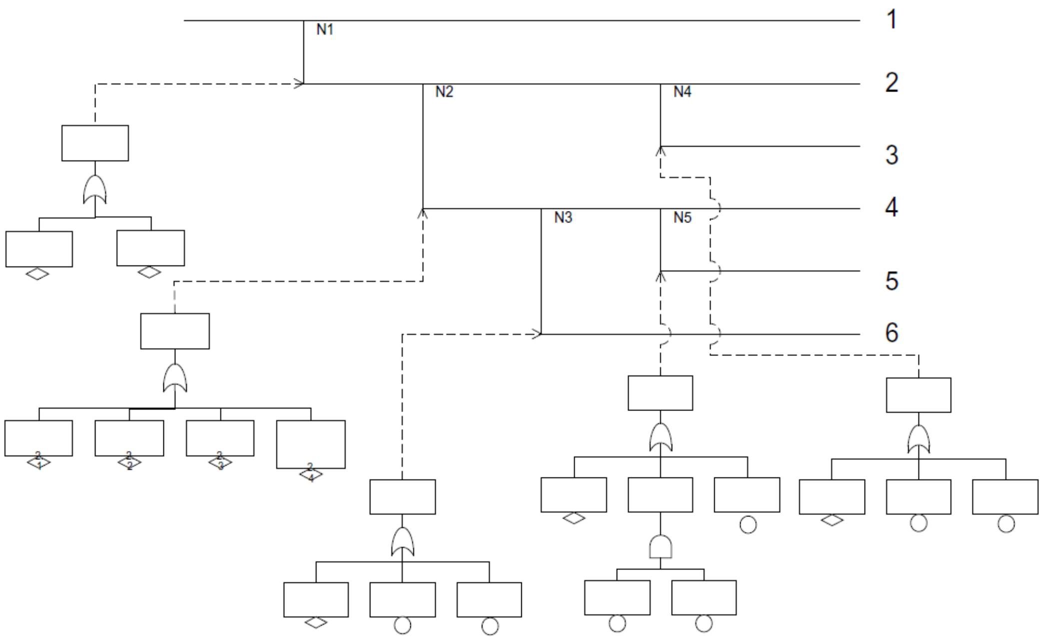


Figure 17. Combine ETA and FTA.

2.4.3 Consequence Assessment Technologies

At the outset of introducing consequences assessment techniques, the term "consequence" for QRA species should be explained. Consequences in a risk assessment typically have several attributes:

- Physical effects: physical-level consequences directly caused by accident, such as mechanical energy, temperature, radiation, visibility, etc.
- Human body reaction: the consequences obtained by physical effects on the human body, such as heat, smoke, poisonous gas, radiation, etc., damage to the human body and spirit
- Social reflection: the adverse impact on public opinion or among stakeholders after the accident, such as stakeholder protests, the decline in the company's social evaluation, etc.
- Environmental effects: The accident products have destructive consequences on the environment, such as the degree of environmental pollution, the difficulty of treatment, and the damage to other organisms.
- Economic effect: It can be directly or indirectly converted from the above attributes, resulting in economic damage to the party responsible for the accident or related organizations and the government.

Many attributes mean the number of consequence assessment techniques in QRA is vast. Some evaluation methods will go beyond the scope of engineering itself and involve evaluation techniques in many disciplines, such as medicine, socioeconomics, and business studies. Next, we will introduce the methods used in consequence assessment according to the above properties.

The physical effect is the most immediate consequence when an accident happens. These consequences include mechanical energy, chemical energy, heat flux/temperature, liquid/gas rate, accident duration, diffusion rate, etc. There are many calculation methods for evaluating these physical values, including theoretical equations, industrial empirical equations, standard value calculation equations developed by classification societies or corresponding values, etc., which will not be repeated. At present, the most popular technology in the industry is simulation technology, which mainly includes Finite Element Method (FEM) and Computational Fluid Dynamics (CFD): the former is used to analyze the damage and deformation process of the structure and the latter is used to analyze the behavior of liquids, gases, plasmas. The following Table provides a brief introduction to some software by using these techniques.

Table 13. Physical effect consequence assessment software by using FEM and CFD technologies in offshore industries.

Name	Function	Vendor
FLACS(Hansen & Johnson, 2015)	3D CFD software tool for gas and air flows.	Gexcon AS, Bergen, Norway
KAMELEON FireEx-KFX(Jang et al., 2015)	CFD tool for prediction of gas dispersion and fire characteristics and response in complex geometries.	DNV GL AS, Hovik, Norway
OLGA(Rugge et al., 2008)	Transient multiphase flow simulator about hydraulic and thermal accidents.	Schlumberger
PHAST/ER/EST(Arndt et al., 2018)	For hazardous material release consequence assessment.	DNV GL Limited, London, UK
FRED(Gexcon, 2020)	Including fire, release, explosion and dispersion prediction models.	Gexcon AS, Bergen, Norway
USFOS/FAHTS(Soreide & Amdahl, 1986)	Structural fire and explosion consequence analysis.	USFOS AS, Norway
PIPENET(Prisecaru et al., 2008)	Steady and dynamic fluid flow analysis in pipe and duct.	Sunrise System Limited, Cambridge, UK
VessFire(Vaillant et al., 2021)	Fire heat transfer, depressurization and stress consequence assessment model.	Petrell AS, Norway
HYENA(ACADS-BSG, 2019)	Fire sprinkler analysis.	ACADS-BSG
ANSYS Series(Manual, 2000)	Flow, turbulence, heat transfer, mechanical energy, force transfer etc. physical modeling.	ANSYS, USA
GASP(R. Batt, 2014)	Liquid pool spreading and evaporation on land or water modelling.	ESR Technology, UK
DRIFT(Chaplin et al., 2017)	Toxic and flammable gas dispersion modelling.	EST Technology, UK
EFFECTS(Melani et al., 2009)	Fire, explosion, dispersion due to toxic, flammable gases, liquefied gases and liquids release scenarios modeling.	Gexcon AS, Bergen, Norway

This thesis will not introduce the content and core methods of the software mentioned in the table due to space limitations. However, as mentioned above, in addition to classical physical methods, FEM and CFD methods are mainly used in these software to realize dynamic and visual simulation results using computer technology.

2.4.4 Comparative QRA system

Some technologies corresponding to the three main modules of QRA assessment are introduced above. These technologies are integrated and used when QRA is used to assess industrial risks, so introducing the hybrid QRA system is also very important. Composite QRA systems typically use several of the assessment techniques mentioned above to identify hazards, assess the probability of an accident, the reliability of the safety barrier, the consequences of the accident, and the mitigation of the safety barrier to the accident. However, due to the characteristics of industrial problems, some data cannot be ideally quantified. Instead, qualitative evaluation methods are used to consider that they are involved in quantitative calculation after assignment. Therefore, strictly speaking, some methods are quasi-quantitative risk analysis methods. However, this does not mean that the results obtained by these methods are not convincing. The following table introduces four relatively mature composites QRA systems, which are relatively mature technologies in offshore QRA.

Table 14. Comparative QRA system description.

Failure Mode and Effect Analysis (FMEA)(*Bow ties in risk management: A concept book for process safety*, 2018; Schneider & Stamatis, 1996)	A technology based on historical data to analyze accident frequency, consequences and aftermath through tabulation and qualitative classification
Barrier and Operational Risk Analysis (BORA)	A quasi-quantitative method for analyzing accident probability from the perspective of safety barriers and operations
Bayesian Belief Network (BBN)	Representing the correlation between accidents in a network diagram is often used in dynamic risk assessment calculations.
Risk Organizational, Human and Technology (OMT) Project	Developed from the BORA and Operational Condition Safety (OTS) methods, it uses OTS performance criteria and Risk Influencing Factors (RIFs) combined with fault trees and event trees for a detailed risk assessment of an operational process.

Failure Mode and Effect Analysis (FMEA) is a quasi-quantitative, simple technique that does not require discussion. The operation method of this technology is the same as its name, it is a technology for analyzing according to failure modes and effects, and FTA is mainly used as its analysis method (Schneider & Stamatis, 1996).

Barrier and Operational Risk Analysis (BORA) is a unique risk analysis method that focuses on security barriers. The founders of this method, Vinnem et al.(Vinnem & Vollen, 2003), believe that the key to risk assessment is the probability of risk occurrence and the mechanism of safety barrier failure. After all, only when the safety barrier fails will the accident cause consequences. A PSAM7 paper (Vinnem et al., 2004) also gives preliminary comments and suggestions.

Figure 18 illustrates the framework of BORA, and it proposes the following process to analyze the failure of operational barriers:

- Accident scenarios, underlying causes and qualitative RIF analysis (scores)
- Average Failure Frequency/Probability Quantification
- Quantification of failure frequency/probability for specific equipment

For a quantitative source of frequency and probability for a specific device, the following sources can be used:

- Technical Condition Safety (TTS)/ Technical Safety Condition (TST) verification
- Man, Technology and Organization (MTO) (People, Technology and Organization) Survey
- Risk level in the Norwegian petroleum activity (RNNP) (Risk Level Project) Questionnaire
- RNNP barrier performance data
- Experts' opinion
- Background Study

Two case studies of this method have been conducted, including the modelling and analysis of physical and non-physical barriers in offshore production facilities, and the results suggest that practitioners should improve the safety of production processes by:

- Research on Barrier Performance and Improvement.
- Investigate the need to strengthen the entire set of barriers during the operation.
- Identify effective risk mitigation measures, modification methods and configuration changes.

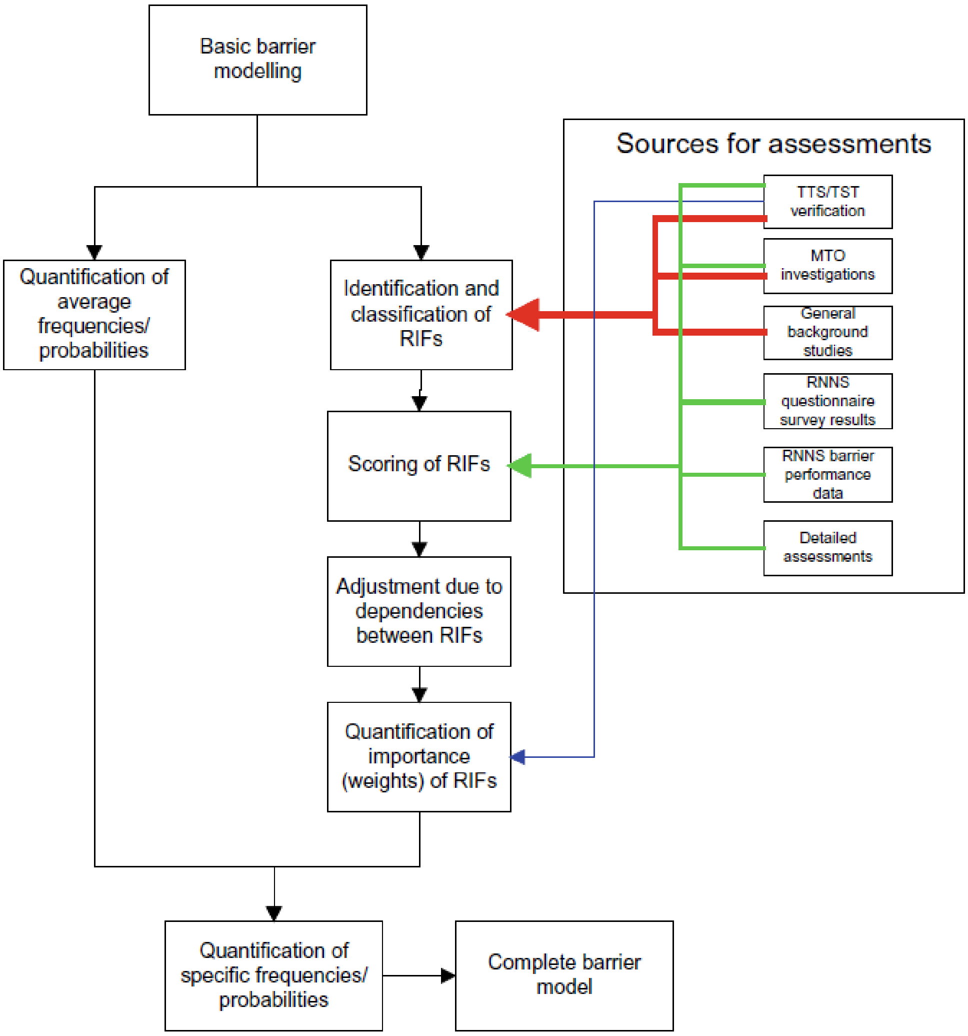


Figure 18. Framework and flowchart of BORA.

Bayesian Belief Network (BBN) is an increasingly popular method proposed by Jensen (Jensen, 2001) and Pearl (Kyburg & Pearl, 1991) because it takes Human and Organizational Factors (HOF) into account and provides precise quantitative and causal links between risks. The recently developed Hybrid Causal Logic (HCL) (Mosleh et al., 2004; Røed et al., 2009) method is used chiefly in dynamic risk assessment because it can exchange causal relationships and quantitative probability values with the nodes of FTA and ETA. Figure 19 shows a Bayesian network, for example, a leak caused by an improper flange or bolt installation during a pipeline inspection.

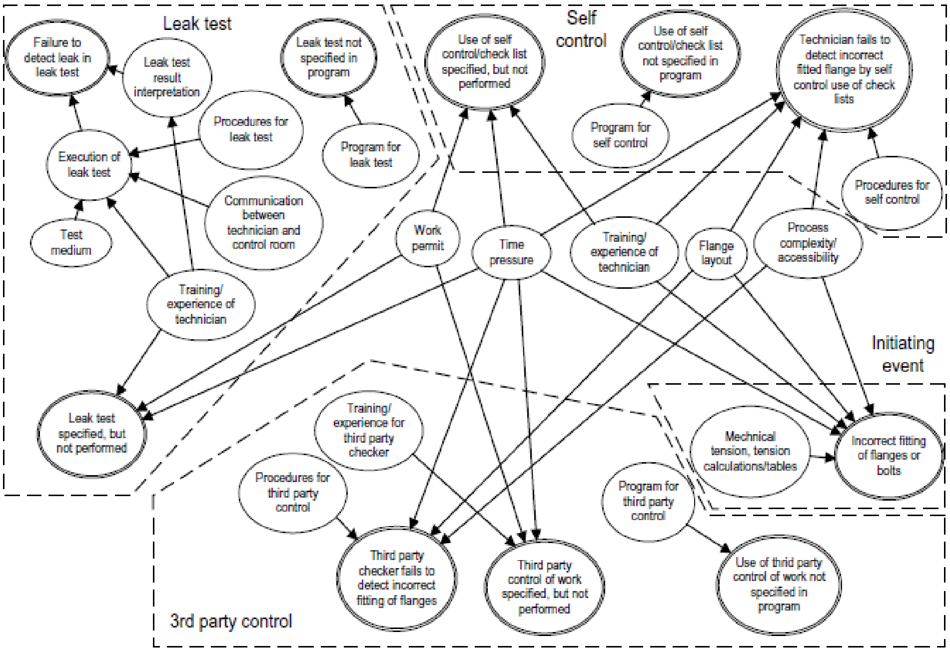


Figure 19. BBN case example for pipe leakage (Røed et al., 2009).

Risk Organizational, Human and Technology (OMT) Project is a proactive method for detecting the status of operational safety barriers for the risk of significant accidents in offshore and onshore oil and gas facilities. OTS-verification is a systematic and independent assessment of the status of safety barriers, making OTS suitable for developing risk reduction measures. To evaluate the performance of safety barriers, OTS provides seven performance criteria (Gran et al., 2012):

- Run practice.
- Competence.
- Procedures and Documentation.
- Communication.
- Workload and Physical Work Environment.
- Management.
- Change in management style.

Both these new and that standard contain a set of performance requirements and related checkpoints. The method typically uses questionnaires, interviews, document reviews, field observations, and data analysis for assessment and grading. Its operation process is more responsible and will be closely integrated with BORA and OTS. For details, please refer to the case use of RISK OMT by Gran et al. (Sklet et al., 2010).

2.4.5 Domino Effect Accidents Assessment Technologies

Domino Effect Accidents (DEAs) are like dominoes-the previous accidents are constantly triggering new accidents. The technical details of its QRA are not much different from the traditional QRA technology mentioned above. In the risk assessment of offshore facilities, researchers usually evaluate the two accidents of hydrocarbon leakage and fire together, which is the most common DEAs technique. Therefore, according to former researchers' studies (AIChE, 2000; Frank P. Lees, 1996; Cozzani et al., 2006), in a QRA system, the domino effect accidents have three basic properties:

- The causes must be clear and straightforward.
- The consequences are independent but may aggravate the overall consequences.
- May not happen if not triggered.

The second property is innovatively proposed in this paper and requires a particular explanation. The DEAs follow the definition of "accident", which means that the consequences may not increase the severity to the stakeholders but may alleviate or even eliminate the harmful consequences caused by the previous accidents—also known as the "happy accident". For example, the fire caused the water storage to leak and extinguish the fire. Regarding accident sequence, fire is primary, and the consequence that triggers the water storage leakage is secondary - or a domino effect event. However, the secondary accident's consequence is reducing the overall accident severity.

The development history of DEAs risk assessment technology is not long. Lee (Frank P. Lees, 1996) was the best known for assessing the DEAs. Later, a new approach was developed by Bagster et al. (Bagster & Pitblado, 1991), according to Lee's thought. Canvey (Executive, 1978, 1981) published the most comprehensive study of the DEAs for constructing more refineries. Afterwards, Khan et al. (Fdisal I Khan & Abbasi, 1998) established the Domino Effect Analysis model framework and developed a program (Faisal I. Khan & Abbasi, 1998; Khan & Abbasi, 2000; Ovidi et al., 2021). In recent years, Cozzani and his colleagues (Antonioni et al., 2007; Cozzani et al., 2005; Lan et al., 2022) have improved previous results with progressive ideas to establish an assessment system for DEAs in the onshore integrated industrial district. Researchers are still improving the DEAs assessment method according to these foundations (Ding et al., 2020; Misuri et al., 2021). In general, the DEAs assessment systems mentioned above are based on two premises:

(1) The domino effect increases the consequences of a given accident with a fixed failure frequency.
(2) The domino effect increases the frequency of failures for a given accident with a fixed consequence.

2.5 Impact Assessment

After introducing the cost assessment of the decommissioning of offshore facilities and the common methods of risk assessment, the impact assessment of offshore engineering will be introduced at the end. The negative impact of Brent Spar (Huxham & Sumner, 1999; Lyons et al., 2015), and the severe oil spill caused by the Deepwater Horizon (Beyer et al., 2016; Rung et al., 2017; Parks et al., 2020), have brought public attention to the environmental protection of offshore facilities. Public attention has also raised concerns among academics and industry that this concern may adversely affect the business. There are few related studies in this area, and the quantitative evaluation method required by this project is less, so it is very necessary to introduce this part of the content.

According to the official certification method for the decommissioning of offshore facilities in the UK - Comparative Assessment (CA) (Palandro & Aziz, 2018), generally speaking, the content of impact assessment includes two aspects, one is environmental risk assessment (MIRA-Miljørettet Risiko Analyse), and the other is social risk assessment:

- Environmental assessment not only refers to the impact of engineering accidents or wastes generated by normal activities on the marine environment and marine organisms, but also the impact of engineering activities on the normal behavior of marine organisms (such as marine organism migration, gathering for mating, etc.)
- Social risks also have two meanings, one is whether the decommissioning project itself will affect the interests of other users (such as fishermen) in this sea area; The censure and claim of the responsible individual results in damage to their financial or reputational interests.

2.5.1 Environmental Impact Models

The assessment of the environmental impact of offshore industry projects has received considerable attention from all parties. NORSOK Z-013 has made nine environmental-related requirements, which are briefly described as follows (Standard, 2001):

a) The analysis should include all scenarios identified in the HAZID that may affect the level of systemic risk.
b) For identified release scenarios, distributions of release rates and durations should be established to reflect changes in release rates and release durations.
c) The analysis should include modelling of the drift and dispersion of relevant hazardous substances on the sea surface, as well as the area of the polluted coastline.
d) The analysis should consider the impact of the relevant safety barriers.

e) Analyze modelling of exposure of sensitive environmental resources to contamination scenarios at least during the planned activities and for one month after that.
f) The analysis shall include the calculation of environmental consequences. Consequences should be a function of the relationship between the amount of hazardous material and environmental sensitivity.
g) Documenting the results of environmental impact calculations.
h) Comparing the environmental risk contributions of different facilities unambiguously, i.e., the calculation of environmental consequences must be comparable.
i) The analysis should also include emergency preparedness measures.

In order to meet the above requirements, the MIRA method developed in Norway is the most mature environmental assessment method. MIRA was developed in the mid-1990s. It is limited to specific facilities and does not start with ecological concerns (Vinnem, 1997; Sørgård et al., 1997; Vinnem & Røed, 2020).

MIRA has been used in nearly all new NCS drilling projects since the late 1990s. The basis for MIRA is usually derived from the distribution of QRA studies, giving the frequency, leak rate, and duration of possible leak situations. MIRA’s primary work is to simulate the possible behavior of hydrocarbon spills under the influence of weather, waves and currents. And the local impact of spill consequences on Valued Environmental Components (VECs) and drinking water.

MIRA can be performed based on the resources and time available for analysis and the level of prior knowledge under comparable conditions. The three levels are called:

- Source-based analysis: The simplest method, based on the duration and rate of release and the distance to shore.
- Exposure-based analysis: A broader approach based on the duration, rate and amount of release and simulation of oil drift at the sea surface.
- Damage-based analysis: The most extensive method to model pollution impact results based on release duration, rate and impact potential, and oil drift on the sea surface.

The source-based analysis is the most conservative and has been shown to overestimate frequencies by almost an order of magnitude using this approach. The damage-based analysis is the least conservative, but the method still has an apparent conservatism. Source-based calculations should be the first round for a quick estimate of environmental damage to determine if a more careful examination is needed.

The general process of MIRA is as follows:

- Identify environmentally hazardous spill scenarios.
- Analyze the effectiveness of safety barriers at facilities to prevent and mitigate spills.

- Build a leakage scenario.
- Simulate the drift and diffusion behavior of oil in different scenarios.
- Establish environmental response mechanisms, including the vulnerability or susceptibility of resources in an area to pollution.
- Calculate the overlap of drift time and exposure of environmental resources to pollutants.
- Assess (quantitative or qualitative) the short- and long-term impacts of pollution on these environmental resources.
- Assessment methods and data should be based on the latest scientific and biological resource testing results.
- The calculation method of environmental risk assessment results is the combination of the probability of environmental damage caused by an event and the severity of damage.

The evaluation results will be displayed in terms of recovery time and divided into four levels according to the amount of oil leakage: Minor means the recovery time is one month to one year; Moderate means the recovery time is one year to three years; Significant means the recovery time is 3 to 10 years; Serious means the recovery time is more than ten years, which is a catastrophic accident.

According to the basic information of MIRA, the environmental damage distribution mathematical expression can be obtained as follows:

$$\lambda_{damage,i} = \sum_T \sum_J \lambda_{end,j} \cdot P_{A,j}(t) \cdot P_{B,j}(t) \cdot P_{damage,i,j}(t) \tag{9}$$

Where, $\lambda_{damage,i}$ is the frequency of damage for damage category *i*; $\lambda_{end,j}$ is the frequency of end event; $P_{A,j}(t)$ is the probability of exposure of an area with component *j* present at time *t*; $P_{B,j}(t)$ is the probability of the presence of the valued component *j* at time *t*; $P_{damage,i,j}(t)$ is the probability of damage in category *i* and valued component *j* at time *t*; *T* is the total time over which damage frequencies are considered; *J* is the total number of valued components.

In addition to MIRA, in the mid-2000s, led by SINTEF and DNV GL, the Environmental Impact Factor (EIF) method developed by Statoil was presented at IMEMS in 2005 by Nilsen et al. The method introduces EIF to assess the environmental hazard risk of produced water, and the EIF Acute model for acute oil spill risk assessment is currently under development (Spikkerud et al., 2005; Vinnem & Røed, 2020).

In addition, there is the ERA Acute model, which is designed to replace the MIRA method. The model is more complex and is based on understanding and physical modelling mechanisms rather than historical data. The consequence assessment of this model is based on continuous functions rather than using discrete information like MIRA. A Resource Destruction Factor (RDF) is also included in ERA Acute as a combination of impact and recovery time (Stephansen et al., 2017, 2021).

The above is a method for environmental risk assessment. These methods comprehensively discuss the possibility and consequences of damage to marine organisms, the marine environment, and marine resources. The consequences of the evaluation are mostly the time for the restoration of the marine environment. It must be said that the focus is more on environmental protection issues. The public and other organizations demonstrate the seriousness of pollution incidents. The following mentions are aimed explicitly at oil spills, including the cost of cleaning up the oil spill, estimates of oil spill fines, and the economic losses caused by negative publicity to the responsible individuals.

2.5.2 Oil Spills Economic Models

One of the most severe and wide-ranging accidents in offshore engineering must be oil spills - including catastrophic blowouts, small oil spills, and oil spills caused by ship grounding. Industry and academia have poured considerable support into studying this type of accident. Since the late 1960s (Gaines, 2005), it has been committed to quantifying and accurately quantifying the economic effects of oil spill accidents.

This quantitative model is similar in method to the decommissioning cost assessment model. It mainly adopts one of the bottom-up or top-down methods, that is, it is mainly based on data regression, and economic losses are caused by existing oil spill accidents. To construct the functional relationship between the variables of the oil spill accident and the economic loss, or to first analyze the factors and period relationships that made the main contribution to the economic loss in the oil spill accident, and then substitute it into the market economic data.

Related research has been developed so far, and the main configuration has been determined, including the cleaning cost per unit oil volume, the amount of oil leaked multiplied by the leakage area, pollution situation, poisoning situation and other parameters (ARI, 1993). Later, based on related researches (Etkin, 2005, 2000, 2004), the modern quantitative oil spill economic loss model includes more information considerations, including oil spill location, oil type, oil spill scale, and oil spill treatment methods. Later, the universal oil spill model added more parameters such as onshore oil spill, social impact, animal habitat, drinking water source (Thi & Trang, 2013), etc.

The current oil spill clean-up cost assessment model has both the functions of quantitative environmental assessment and socioeconomic assessment. Combining the physical behavior of oil spills in water, water surface, and shallow water, as well as the toxic effects of oil spills on different marine resources and organisms, a relatively complete impact assessment model that the industry can use can be obtained. Although more related scholars in socioeconomics are still needed to contribute to quantitative research to improve the accuracy of assessment, it is currently sufficient for dealing with non-catastrophic accidents or non-major engineering events.

2.6 Literature Review Summary

This chapter is divided into five parts to summarize relevant:

- laws, regulations, conventions.
- various theoretical frameworks of multi-attribute assessment systems.
- cost assessment models for assessing the cost of decommissioning project.
- quantitative risk models for offshore and other industrial operation and decommissioning.
- comprehensive impact assessment tools of offshore facility decommissioning.

For multi-attribute decision-making assessment tools for the decommissioning of offshore facilities, the development focus of industry and academia is still in the cost assessment part. The relevant laws and regulations are only a little follow-up and need to be improved. For various reasons, some decommissioning options are prohibited in Europe. The government has ignored the academic community's scientific advice, especially when discussing European rig-to-reef projects. The overall framework of multi-attribute assessment tools, risk assessment, and comprehensive impact assessment methods are developed for the offshore facilities' operation phase and still need to be fully adapted to the decommissioning phase. The current situation further shows the innovation and importance of this topic.

Chapter 3. MADM-Q Framework and Inputs

3.1 The Framework of MADM-Q and Inputs Categories

At the beginning of this chapter, we will introduce the main framework of this research, the methodology of module construction, and the mathematical expression equations of each required calculation item in the module. This research is a multi-attribute quantitative engineering evaluation mathematical model called MADM-Q (Multiple Attribute Decision Making - Quantitative). The model takes the decommissioning process as the skeleton, six categories of data as the input, and three quantitative evaluation modules as the core. And there is also interaction between modules.

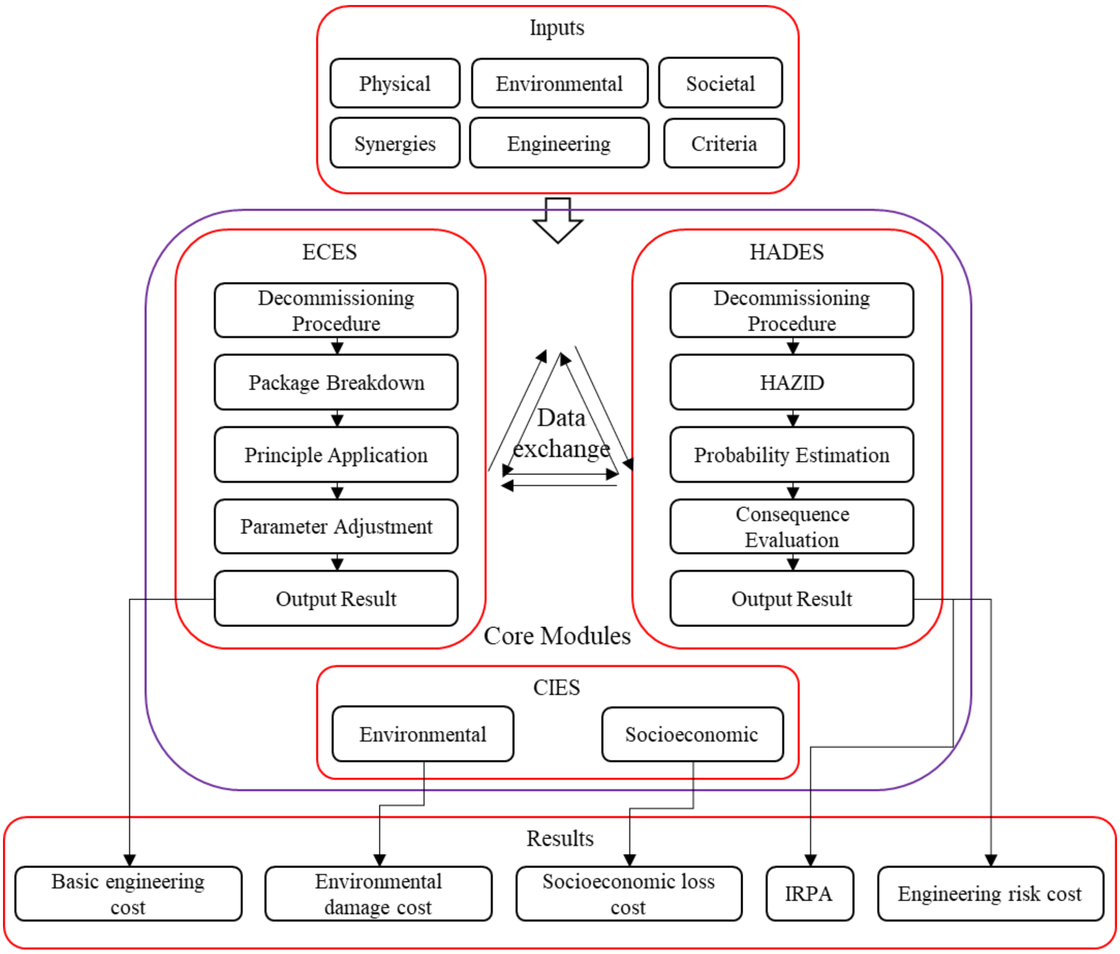


Figure 20. Offshore Decommissioning MADM-Q Framework.

As mentioned above, the framework of this system is shown in Figure 20. The decommissioning process is the skeleton of the entire system. The two main modules - Engineering Cost Evaluation System (ECES) and Hierarchical Analyst Domino Evaluation System (HADES) calculate results for different decommissioning options based on the six aspects input data of the Inputs module. The costs and risks of platform decommissioning project implementation.

Cost and risk results are entered as inputs, and some data from the Inputs module is entered into the Composite Impact Evaluation System (CIES). The result mainly consists of a monetary form and IRPA. And five parts, which are:

- Basic engineering cost
- Environmental damage cost
- Engineering risk cost
- Socioeconomic loss cost
- IRPA

3.2 Inputs and Outputs

The input module is firstly introduced. As shown in Figure 21, this module revolves around the three core modules of the system, and a total of six categories of data need to be input:

- The data in the standard part is mainly used as the constraints of decommissioning options and as the judgment basis in the HADES module.
- The physical part is mainly the data of the facility.
- The environmental part of the data is mainly the content of the sea state data and marine biological data where the platform is located.
- The Synergies part is mainly for engineering practice. It is not the case that only a single facility is decommissioned at a time, but multiple facilities. The cooperative use of high-cost resources (such as semi-submersible ships) can reduce the decommissioning cost of multiple users.
- The Engineering part mainly includes the construction time, equipment, vessels, and materials.
- The Social section contains information on the collection of fisheries near the facility, the shipping situation and the project's contribution, which created jobs for society.

The Input module is the cornerstone of the entire evaluation system, related to the optional range of decommissioning options and the smooth operation of HADES. Most of these data are displayed in quantitative form. The non-quantitative data does not need to be involved in the calculation process, so no expert participation is required in this module. The operator only needs to have these basic data before using the system without relevant professional industrial knowledge.

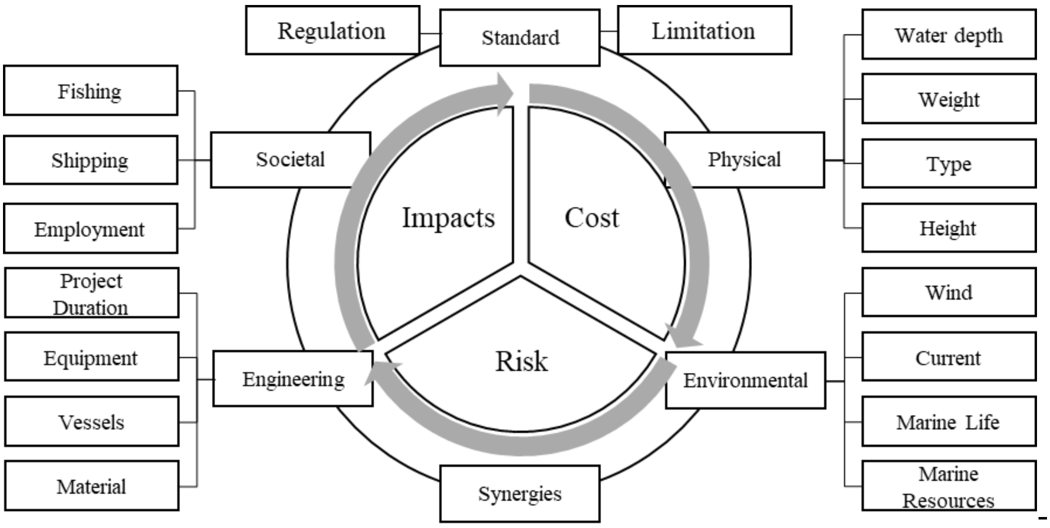


Figure 21. Input categories of MADM-Q.

Then, the output results of this system are introduced. The output results of each module and the overall module of this quantitative evaluation system will also be used as the input results of other modules, which makes the final output results only cost and IRPA, which will make it easily to be employed by engineers and decision-makers. However, the output results of each module are also considerable. Next, we will introduce each module separately:

ECES-The final output results are all currency values. However, due to calculation requests, results such as the time spent on engineering steps and the number of personnel and materials will also be output in the middle. At the same time, these results will also be input into HADES as input values to evaluate the IRPA.

HADES-The final output is mainly the economic loss caused by the accident and IRPA. However, there are many results in the middle process, including but not limited to the amount of oil leakage, the scope of the accident, heat flux, mechanical energy, temperature, pressure, torque, etc. The amount of oil spilt will be directly input into CIES for environmental and socio-economic assessment.

CIES-The final outputs only content the currency values. Since this is a module with relatively simple calculations, its fundamental input values come from the raw inputs and the previous two modules' outputs. So, this tool only outputs the currency value as its output result and adds it to the final cost to determine the exact cost floating range.

ECES, HADES and CIES are the three core modules of this multi-attribute evaluation system. The details of these three modules will be detailed in the three following chapters 4, 5 and 6. The characteristics of these three modules are that they use many physical equations, classical probability calculation equations and highly versatile empirical equations for calculation instead of dedicated industrial equations for a particular industry or situation. Such a design can ensure the reliability of the assessment results, generality to different sea areas worldwide, and ease of use.

Chapter 4. Cost Assessment Methodology

After the introduction of the literature review in the previous chapter, the concepts, approaches and flowchart required to construct the multi-attribute decision-making tools of this topic are generally complete. Therefore, this chapter begins with the methodology introduction of the cost assessment module. Therefore, in this study, a top-down model applicable to the UK North Sea was constructed using decommissioned facilities data in the North Sea based on the top-down method mentioned in the literature review. Then, the bottom-up model is constructed by combining the theory of bottom-up method with the data of the UK North Sea market. The evaluation results of the two models will be compared in later chapters to determine which model is more suitable for the current decommissioning cost assessment of UK offshore facilities in the North Sea.

4.1 Top-down Framework Model

After the two basic frameworks of decommissioning cost assessments for offshore facilities has mentioned in Chapter 2, the choice of framework is a big question. The models of decommissioning cost of offshore facilities previously studied by scholars are mainly based on the top-down framework. The cost assessment models are constructed using data from the United States (Proserv Offshore, 2010) and Malaysia (Amila Wan Abdullah Zawawi et al., 2015).

This study also considers adopting a similar method, using the data of decommissioned offshore facilities in the North Sea to construct a mathematical model of the top-down framework. The data used are shown in the appendix. And the analysis procedure is shown as Figure 22. According to the complete decommissioning process in Figure 3 and the simplified decommissioning process in Figure 20, study each decommissioning procedure independently, estimate the independent variables, and analyze the strength of the correlation between the independent variables and the results to exclude independent variables with weak relationships. The data is then preprocessed according to the distribution of the data to avoid being too concentrated for practical regression. Then comes the establishment of regression equations, possibly multiple equations in different equation forms. The evaluation performance of each equation is then compared to determine which regression equation is ultimately used for cost evaluation. Some of these costs cannot be applied to regression analysis due to a lack of data, and their costs will be directly estimated based on the proportion of costs of this part in most cases.

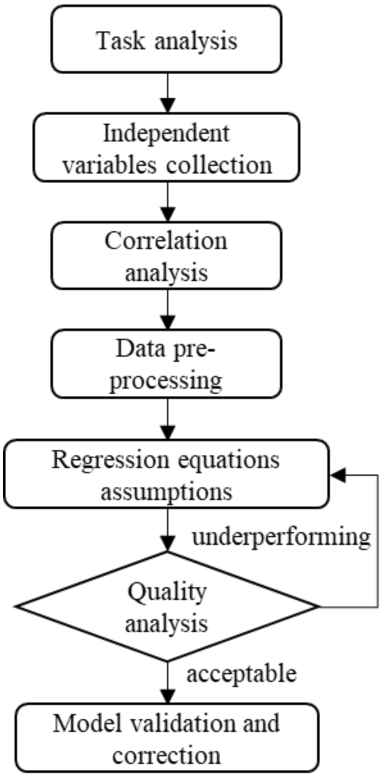


Figure 22. Top-down framework model regression analysis procedure.

According to the proportion of the cost of each activity of the decommissioning cost of offshore facilities obtained by Andrew (Bressler & Bernstein, 2015) and Proserv Offshore's papers (Proserv Offshore, 2010), if the top-down framework is to be used, some projects still need more data. According to their papers, 8% of the decommissioning engineering cost can be used as the management and planning costs; 15% of the project cost is used as a general work emergency; and the cost range caused by weather and accidents is set from 5% to 15% of the project cost according to the complexity of the platform structure and the weather in the sea area.

A mathematical model for top-down cost assessment for North Sea offshore facilities can be established based on the Andrew and Proserv's model which just mentioned above. Divide the decommissioning costs according to the following equations:

$$C_{Total} = 1.08C_{Eng.} \tag{10}$$

$$C_{Eng.} = C_{P\&A} + C_{Platform} + C_{Pipe} + C_{Sub} + C_{Others} \tag{11}$$

In these two equations, C_{Total} represents the total decommissioning cost, and C_{Eng} represents the cost of the engineering implementation stage. C_{Eng} consists of $C_{P\&A}$, $C_{Platform}$, C_{Pipe}, C_{Sub} and C_{Others} mentioned above.

Using the data from the North Sea in the United Kingdom lists in the Table 44 in the Section 7.1, the cost evaluation equations are constructed using univariate or multiple regression methods. However, it should be mentioned that since the data volume is not very large, it is necessary to preferentially pre-process some data set when using regression analysis for averaging the data distribution on the coordinate axis to prevent the regression results from being inconsistent. The following equations (12) to (26) can be obtained.

4.1.1 Well Plug and Abandonment

Through the study of the data relationship, the water depth has little effect on the well decommissioning cost, so the water depth is not considered as one of the characteristic variables in this sub-model. The model is expressed as follows:

$$C_{P\&A} = \sum_{i=1}^{2} f(N_i, T_i) = \sum_{i=1}^{2} f(N_i) \tag{12}$$

Where i=1 means platform wells, i=2 means subsea wells; N means the number of corresponding wells; and T means operational period. In this model, T is also analysed, and T is predicted using the number of wells N, so the final expression of the equation is as shown above.

Table 15 shows the correlation analysis among 5 variables that may be related to Well P&A cost according to the Correl equation(Angelini, 2018). The number of wells has a very large correlation with the decommissioning duration, reaching 0.83, the number of wells, the number of subsea wells, the length of well decommissioning and the cost of decommissioning very high and decisive. The impact of water depth on all other items is very low, not enough to achieve a decisive impact.

$$Corirel(X,Y) = {\sum(x-\bar{x})\,(y-\bar{y})}\Big/{\sqrt{\sum(x-\bar{x})^2\,(y-\bar{y})^2}} \tag{13}$$

Where x and y mean the samples' values, $\bar{x}$ and $\bar{y}$ mean the average values of samples.

Table 15. Correlation analysis.

	Water Depth	Operating Period Well P&A	Wells Number	Subsea Wells No.	Platform Wells No.	Well P&A Cost
Water Depth	1					
Well P&A Period	0.18	1				
Wells Number	0.14	0.83	1			
Subsea Wells No.	0.07	0.39	0.36	1		
Platform Wells No.	0.13	0.73	0.93	-0.02	1	
Well P&A Cost	0.09	0.87	0.92	0.95	-0.05	1

Then, according to the correlation between the well decommissioning duration and other characteristic variables, it can be determined that the well decommissioning duration has a linear relationship with the total number of wells. The total number of wells is composed of subsea wells and platform wells and the decommissioning duration of subsea wells is generally higher than that of platform wells. Therefore, the number of subsea wells and the number of platform wells are used as characteristic variables X_1 and X_2, and the duration for well decommissioning is $T_{P\&A}$. Then the empirical equation can be obtained, the R^2 is 0.79, and the relative error is 42.1%:

$$T_{P\&A} = 2.45X_1 + 1.82X_2 \tag{14}$$

In the process of studying the decommissioning cost of wells, since Proserv Offshore mentioned (Proserv Offshore, 2010) water depth as a characteristic variable, there were many tentative models in the modelling process. The details are shown in Table 16.

Table 16. List of tried models.

Variables	Equations	R^2	Relative error
T_{SW}, N_{SW}	$C_{P\&A\ SW} = 1.467T_{SW} + 2.66N_{SW}$	0.76	49.42%
D, N_{SW}	$C_{P\&A\ SW} = 0.003D + 16.76N_{SW}$	0.91	59.43%
$D^2, {N_{SW}}^2, D * N_{SW}$	$C_{P\&A\ SW} = 3.23 * 10^{-6}D^2 + 1.51{N_{SW}}^2 - 0.05D * N_{SW}$	0.97	82.17%

In the above table, T_{SW} means subsea wells decommissioning duration, N_{SW} means subsea wells number, and D means water depth. It can be clearly seen that although the performance of R^2 is very good, the performance of relative error is very poor, so it is not possible to only focus on the performance of R^2 in the modelling process.

Since the models established above are not perfect, the final well-decommissioning cost assessment model is determined as shown in table 17. The average accuracy is 32.43% for this model.

Table 17. Equations of well P&A cost.

Equations	Boundary Conditions	R^2
$C_1 = 3.5N_1$	$N_1 \in N$	0.99
$C_2 = 7.1311N_2$	$0 \le N_2 \le 10$	0.99
$C_2 = 45.16 \times \sqrt[2]{\frac{{N_2}^2}{2.364^2} - 1}$	$10 \le N_2$	0.98

4.1.2 Platform Removal

According to Kaiser's paper (Kaiser, 2006) and a logical analysis of the characteristic variables that may affect the decommissioning cost of the platform structure, it can be concluded that the decommissioning cost of the platform structure may mainly be caused by the depth of the water, the weight to be decommissioned, the complexity of the platform structure, the maximum module size and weight, and even determined by the transport distance. So, process correlation analyses and, following tables can be obtained.

Table 18. Correlation analysis.

	Water Depth	Decommissioning Total Weight	Operating Period	to the Coast	Topsides Weight	Jacket Weight	Preparation/Removal and Disposal Cost
Water Depth	1.00						
Decommissioning Total Weight	0.46	1.00					
Operating Period	0.64	0.56	1.00				
to the Coast	0.71	0.62	0.57	1.00			
Topsides Weight	0.68	0.89	0.85	0.72	1.00		
Jacket Weight	0.39	0.98	0.57	0.49	0.88	1.00	
Preparation/Removal and Disposal Cost	0.62	0.92	0.85	0.61	0.99	0.94	1.00

Table 18 shows the correlation coefficients between these characteristic variables and costs. The relationship between the structural weight of the platform and the cost of decommissioning is the most obvious in terms of water depth, operating period, and distance from the shore. In addition, the decommissioning duration of the platform structure and the weight of the platform, namely its composition-the correlation between the weight of the topside and the jacket is acceptable. Therefore, first analyse the decommissioning duration of the platform structure. The following results can be obtained:

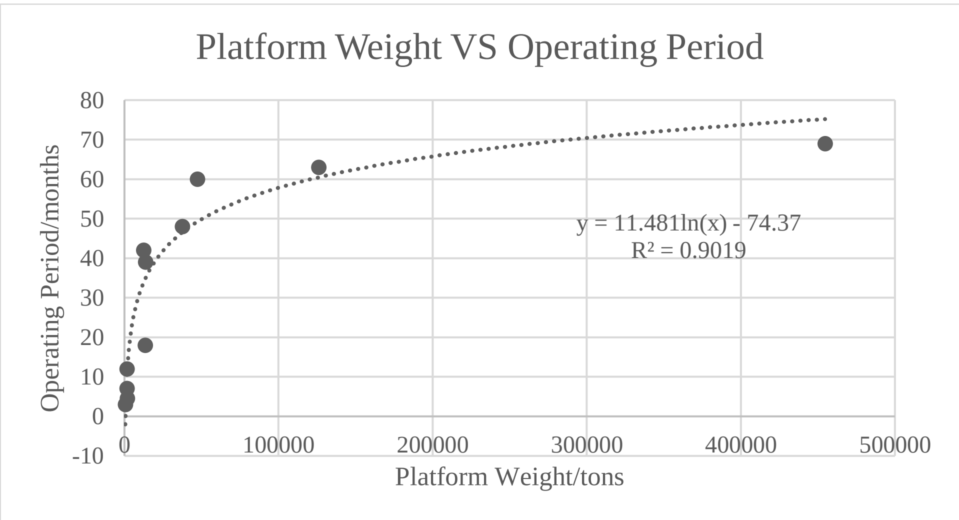


Figure 23. Platform weight VS operating period.

It can be obtained from Figure 23, the relationship between T_P and platform weight W is:

$$T_P = 11.48\ln(W) - 74.37 \quad (15)$$

The R^2 is 0.9 and the relative error is 50.07%.

After completing the study of platform structure removal duration, the next step is to study the cost of platform structure removal. According to Table 18, the total weight of the structure, the water depth, and the distance from the shore will all affect the cost of decommissioning. Therefore, the model obtained is shown in Table 19:

Table 19. List of models that have been verified to be eliminated.

Variables	Equations	R^2	Relative error
D, W, T_P, Dis	$C_P = 0.93D + 0.001W + 0.99T_P - 0.35Dis$	0.93	115.8%
D, W	$C_P = -8.75 + 1.27D + 0.001W$	0.86	101.53%
D, W, Dis	$C_P = 31.42 + 1.83D + 0.001W - 0.72Dis$	0.87	147.6%

Although the correlation is acceptable and R^2 performs well, the predictive capabilities of the above three models cannot meet the requirements. The estimated reason is that the weight data distribution is relatively concentrated, so in the determined model, take the natural logarithm of the platform structure weight and then perform the calculation, so that the weight data can be more evenly distributed on the X axis.

However, because the decommissioning reports provided by the OGA official website are produced by different companies, the types of data are too different. Therefore, through the mathematical analysis of the data correlation, in this sub-model, the water depth, the weight of the platform to be decommissioned will be used as characteristic variables. The model is expressed as follows:

$$C_{Platform} = g(W, D) = a_0 + \sum_{i=1}^{2} a_i X_i \quad (16)$$

$$Ln(C_{Platform}) = -1.23 + 0.01X_1 + 0.48X_2 \quad (17)$$

Where X_1 is water depth D; X_2 is the natural logarithm of the weight to be decommissioned Ln(W). The R^2 is 0.84, and the average relative error is 24.08%.

4.1.3 Subsea Structure and Pipelines

As mentioned above, subsea structure refers to large structures such as WHPS and manifolds located on the seabed. In some cases, such as the anchor chain system adapted to FPSO (HESS, 2014, 2013b), STL (Submerged Turret Loading System) (TAQA, 2017) and other structures floating in the sea will also be considered as subsea structures.

Pipelines decommissioning is currently the least studied one. The reason is that, as mentioned above, the world’s major international conventions related to the decommissioning of offshore oil and gas facilities, and regional regulations do not make detailed requirements for the decommissioning of pipelines. According to relevant literature (Kaiser & Liu, 2015) and logical reasoning, the characteristic variables that affect the decommissioning cost of pipelines may include: water depth, pipelines diameter, pipelines length, pipelines decommissioning methods and options, and even pipelines liquid transportation types may affect decommissioning costs. It is generally believed that ROV and the corresponding DSV are necessary during the pipelines decommissioning process, and sometimes trenching vessels are needed to bury the pipelines in situ.

Follow the steps above, conduct a correlation analysis between the items likely to affect the decommissioning cost and the decommissioning cost, and get Table 20.

Table 20. Correlation analysis for pipeline and subsea structure decommissioning cost.

	Water Depth (m)	to the Coast (km)	Pipe Length (km)	leave situ pipe length km	remove pipe length	Subsea Structure Number	Subsea structure Weight	Operating Period (months) Pipe and subsea	Pipelines Cost (£ million)	Subsea Installation Cost (£ million)	Subsea Installation and Pipeline Cost
Water Depth (m)	1.00										
to the Coast (km)	0.34	1.00									
Pipe Length (km)	0.16	-0.24	1.00								
leave situ pipe length km	0.10	-0.29	0.92	1.00							
remove pipe length	0.16	0.13	0.22	-0.19	1.00						
Subsea Structure Number	-0.11	0.07	0.54	0.36	0.45	1.00					
Subsea structure Weight	0.05	0.17	-0.05	-0.16	0.28	0.34	1.00				
Operating Period (months) Pipe and subsea	0.30	0.21	0.38	0.14	0.59	0.50	0.09	1.00			
Pipelines Cost (£ million)	0.87	-0.02	0.26	0.25	0.11	-0.30	-0.15	0.40	1.00		
Subsea Installation Cost (£ million)	-0.21	0.20	0.27	0.27	-0.13	0.62	0.29	-0.16	-0.49	1.00	
Subsea Installation and Pipeline Cost	0.89	0.04	0.26	0.25	0.13	-0.20	-0.08	0.42	0.99	-0.40	1.00

The analysis of pipeline decommissioning costs is the most complicated in the entire cost model. According to the results of the literature and correlation analysis, there are three types of pipeline decommissioning models. Excluding the sub-models mentioned in the text, four test models left, and they are listed in the Table 21.

Table 21. List of models that have been verified to be eliminated.

Variables	Equations	R^2	Relative error
D, V', P_l, P_r	$C_{Pipe} = -6.99 + 0.15D - 2 * 10^{-4}V' + 0.18P_l + 1.82P_r$	0.89	84.31%
$Ln(D), Ln(V'), P_l, P_r$	$Ln(C_{Pipe}) = -3.98 + 0.67Ln(D) + 0.4Ln(V') - 0.004P_l + 0.03P_r$	0.55	66.99%
D, V'	$C_{Pipe} = -2.32 + 0.17D + 6.91 * 10^{-5}V'$	0.86	104.29%
D, V', L	$C_{Pipe} = -4.09 + 0.16D - 0.0001V' + 0.1L$	0.87	80.87%

In the equations, D is the water depth, V' is the flushing volume, P_l is the pipe left in place, P_r is the removed pipe, and L is the total length of the pipe. The third row in the table uses the calculation method given by the U.S. MMS, which can be seen not applicable to the U.K. North Sea offshore oil and gas facilities decommissioning.

However, according to the ICF report (ICF International, 2015), cleaning pipelines is a necessary process for pipelines decommissioning and that may also lead significant cost. It is generally believed that at least 250% of the pipelines' capacity is required to complete the cleaning task. And gives the relevant industry equations:

$$v = \frac{\pi}{4} ID^2 * \frac{1ft^2}{144in^2} * \frac{7.48\,gal}{ft^2} = 0.0408\,\frac{gpf}{in^2} * ID^2 \quad (18)$$

$$V = v * L \quad (19)$$

Where v is the pipelines unit volume in gallons per foot (gpf); ID is the pipelines internal diameter in inches; V is the total volume in gallons. After applying 250% of V, the total flushing volume required for the decommissioned pipelines can be obtained. Therefore, the expression of this sub-model is as follows:

$$C_{Pipelines} = h(D, V', Pl, Pr) = a_0 + \sum_{i=1}^{4} a_i X_i \quad (20)$$

Where X_1 means water depth D; X_2 means 250% flushing water volume V'; X_3 is leave situ pipe length Pl; X_4 is removal pipe length Pr.

Or

$$C_{Pipelines} = h(D, V') = a_0 + \sum_{k=1}^{2} a_k X_k \tag{21}$$

Where X_1 means water depth D; X_2 means flushing water volume V'.
These two models' details show as the Table 22.

Table 22. Details of models.

Equation	(22)	(23)
Detail	$C_{Pipe} = -6.99 + 0.16X_1 - 0.0002X_2 + 0.18X_3 + 1.82X_4$	$C_{Pipe} = 5.712 - 10^{-3} \times (7X_1 - 0.1X_2 + 0.3{X_1}^2 + 0.004X_1X_2)$
R^2	0.89	0.90
Average related error	46.33%	46.81%

Although the fitting results of the above two equations are good, in fact, the water depth and flushing volume involved are relatively concentrated, which will cause a certain degree of deviation when performing data analysis. Therefore, after processing these two sets of data of the (23) model, a new model (24) is obtained, as follows:

$$C_{Pipeline} = -3.36 + 0.69X_1 + 0.3X_2 \tag{24}$$

Where X_1 represents the natural logarithm of water depth Ln(D); X_2 x1 represents the natural logarithm of flushing volume Ln (V'). The R^2 is 0.54 and the average related error is 27.72%. Although this result looks better, in fact, comparing the (23) models, their absolute errors are quite different. The absolute error of model (23) is 51.86%, and the absolute error of model (24) is 66.72%. Which model is more reasonable requires more data for verification.
And according to the Table 20's results, the subsea structure decommissioning cost equations are expressed as follows:

$$C_{Sub} = h(W, D) = a_0 + \sum_{i=1}^{2} a_i X_i \tag{25}$$

$$C_{Sub} = 0.000431X_1 + 0.76X_2 \tag{26}$$

Where X_1 is water depth D; X_2 is the natural logarithm of the weight to be decommissioned Ln(W). The R^2 is 0.903, and the average related error is 16.88%.

4.1.4 Other Aspects

The cost composition of this part is rather messy, and most companies put the costs of site clearance and verification, post-decommissioning, and drill cutting cleaning among them. However, the proportion of this part of the total cost is very low, about 2%. (OGUK, 2018)Based on the existing data and related literature, it is difficult to estimate the cost of this part in more detail. Therefore, in this model, this part is limited to 2% of the total cost, namely:

$$C_{Other} = 0.02C_{Eng} \tag{27}$$

4.1.5 Summary

The above cost assessment model is constructed according to the top-down framework with the data of the UK North Sea decommissioning platform. Compared with the models developed by others, this model uses a different data pre-processing method, so from the perspective of the variance and residuals of the regression equations, the results of this model are like the model constructed by Proserv Offshore.

It should be mentioned that in some parts of the top-down model constructed in this study, water depth was not taken as an important variable to construct the regression model, because the historical data used in this study were all in the North Sea region, with a small variation of water depth. The maximum water depth of the decommissioned facilities is 425m and floating, while the rest are 200m or less. We suspect that this distribution of data results in water depth not having a significant impact on facility decommissioning and suggest that other researchers use historical data containing a wider range of water depths to improve the top-down model presented here.

Furthermore, the data used in this model is not only the engineering cost but may include the incremental cost caused by some accidents. This means that the results of the risk assessment module and the composite impact assessment module cannot be fused in the cost assessment results when using the top-down architecture. Therefore, the results of the cost assessment model under the top-down framework are more suitable for government departments as the basis for policy adjustment. For enterprises, decision-makers need more granular results rather than rough results.

4.2 ECES-a Bottom-up Framework Model

Due to regression analysis by using historical data may contain accident cost, the top-down framework model introduced in the last section cannot theoretically achieve the final purpose of this study (Kaiser, 2006). So, this section will present a bottom-up framework model established for decommissioning offshore facilities in the North Sea. The Engineering Cost Evaluation System (ECES) flowchart is shown in Figure 24.

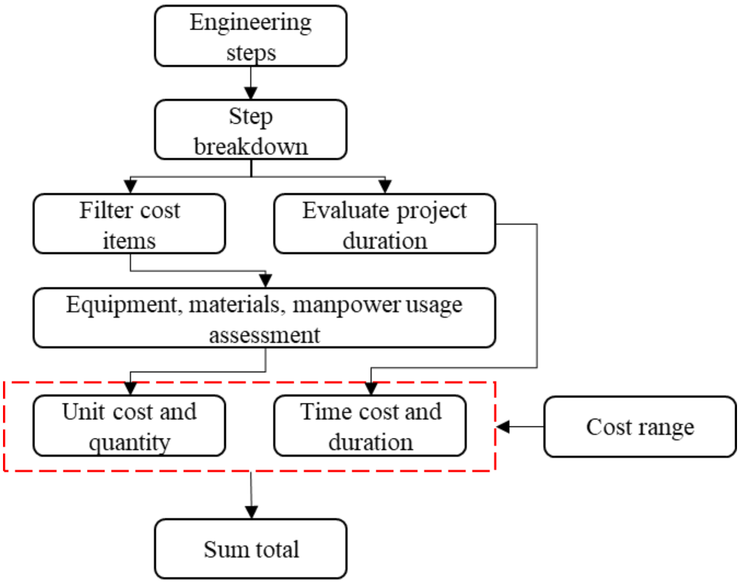


Figure 24. ECES Methodology.

The first step of ECES is to clarify the steps of the decommissioning project because some steps require special operations or equipment, and the evaluation method needs to be determined according to the actual situation. Then it is subdivided into the cost items involved in each step, including labor, equipment, materials, ships, and other costs. Some steps include all subdivision items, while others do not include one of them, which needs to be clarified by the user in advance. The purpose of the subdivision is to combine similar cost items to deal with the problem of insufficient detailed data. The segmentation results in the ability to assess the amount of people, equipment, ships, and materials used for each step. At the same time, the duration of each construction step must be evaluated, which is directly related to the calculation of labor costs, equipment, and vessel rental costs. The results are multiplied by the time unit cost and the quantity unit cost, respectively. The summation yields the final cost estimate value. The following content is implemented step by step according to each step in the flow chart. It mainly includes cost item breakdown, engineering duration, equipment, labor, material, vessel amount estimation, time and quantity unit price research and data collection.

The following content will introduce the whole process of ECES construction in detail according to the steps shown in Figure 24. Firstly, 4.2.1 describes how to break down cost packages so that similar cost items can be combined to determine the specific algorithm of ECES. Then estimate the duration of different engineering activities in 4.2.2 as one of the bases for calculating the cost of labor, rental equipment and engineering ships. 4.2.3 mainly introduces the material usage estimation method of the decommissioning project. 4.2.4 lists the decommissioning activities, materials, equipment, personnel unit price, daily rent, and salary.

4.2.1 Cost Packages Breakdown

Subdividing engineering steps into cost items is the first step in implementing ECES. The purpose of this step is first to determine all items that need to be costed. According to the engineering steps of decommissioning offshore facilities, analyze each step's cost items involved in engineering operations:

- Well P&A. As mentioned above, the plugging and decommissioning of wells involve very complex content. Combining platform wells - or dry wells, and subsea wells - or wet wells decommissioning unit price and decommissioning difficulty correction parameters, the total cost of well decommissioning can be obtained by times the number of wells with the same type.
- Conductor Removal. The conductor is the casing from the wellhead to the platform outside the production pipeline of the platform well, so it is only suitable for facilities with platform wells. Decommissioning this part of the structure requires cleaning the casing, followed by underwater cutting with ROV and worker hanging or cutting in sections from the casing using an internal cutter. Therefore, the cost of conductor removal consists of the sum of the equipment, materials, and labor used for decommissioning each conductor multiplied by the number of conductors.
- Platform Preparation. This stage contains the most labor and material costs, using small equipment, containers, cutting cylinders, and standby ships. It also usually takes longer.
- Pipeline Preparation. This phase usually runs concurrently with platform preparation, mainly the cutting and cleaning of the pipes. This stage primarily uses many cleaning agents, pipeline engineering ships or diving support ships. Salaries for crew and use of BYOD equipment are not included in the calculation. However, the rental fee of the boat does not include other special equipment, such as the use of ROVs.
- Topside Removal. The number of workers required at this stage is tiny, mainly using lifting engineering ships such as HLV or SSCV and transportation ships such as flat barges. The cost composition is relatively simple.
- Pipeline Decommissioning. The cost of pipeline decommissioning is generally greatly influenced by pipeline decommissioning options. If buried in place, only trenching will be needed. If it is to be transported away, SLV or DSV is required for construction. So, the cost components ddivided into these two categories.

- Substructure Removal. This stage is similar to topside removal, which removes the facility's underwater part according to the decommissioning option decision. The main cost components are the use of lifting and transporting vessels and the use of underwater cutting equipment (including divers or ROVs).
- Sub-sea Structure Removal. It is similar to the previous stage, except that the target subject has become an independent underwater facility, such as WHPS, manifolds, etc. The cost structure is the same as the previous stage.
- Onshore Dismantle. This stage is outsourced to the ship recycling yard for construction, so the quotation is provided by Party B. Generally, the quote is per ton according to the structural weight and complexity of the facility.

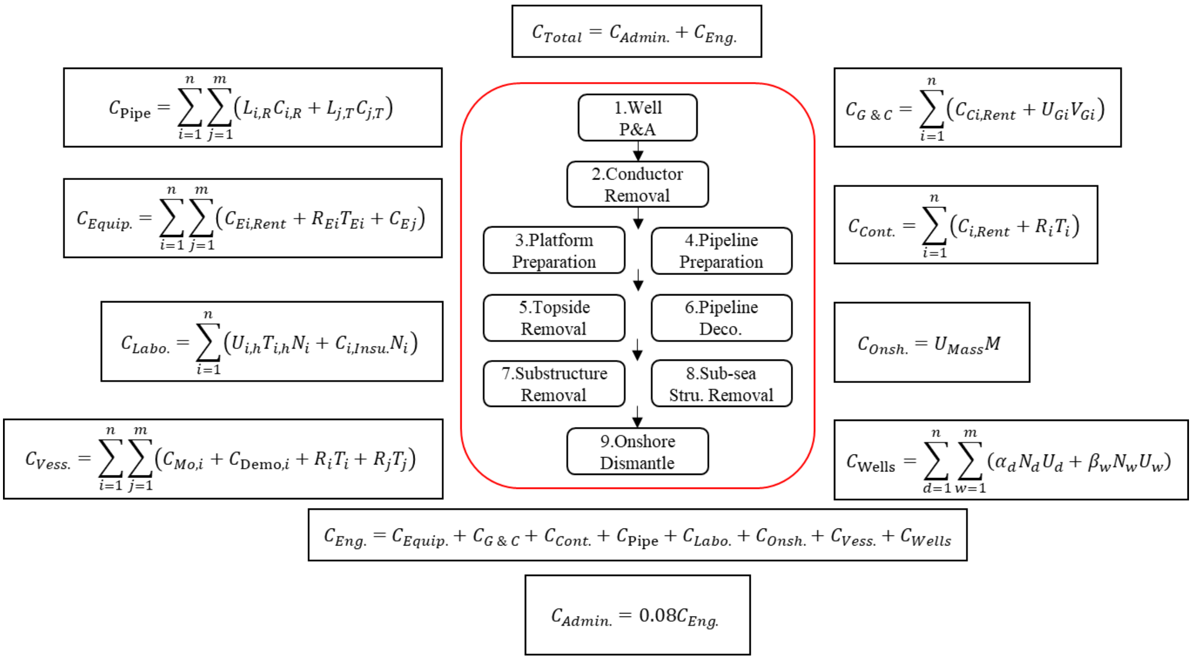


Figure 25. Algorithm of ECES.

After breakdown the work packages of offshore facilities' decommissioning engineering, the cost evaluation equations for each package can be obtained as equations (28) to (38):

$$C_{Total} = C_{Admin.} + C_{Eng.} \tag{28}$$

$$C_{Eng.} = C_{Equip.} + C_{G\,\&\,C} + C_{Cont.} + C_{Labo.} + C_{Onsh.} + C_{Vess.} + C_{Wells} \tag{29}$$

$$C_{Admin.} = 0.08 C_{Eng.} \tag{30}$$

$$C_{Wells} = \sum_{d=1}^{n} \sum_{w=1}^{m} (\alpha_d N_d U_d + \beta_w N_w U_w) \tag{31}$$

$$C_{Equip.} = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(C_{Ei,Rent} + R_{Ei} T_{Ei} + C_{Ej} \right) \tag{32}$$

$$C_{Pipe} = \sum_{i=1}^{n} \sum_{j=1}^{m} \left(L_{i,R} C_{i,R} + L_{j,T} C_{j,T} \right) \tag{33}$$

$$C_{G\,\&\,C} = \sum_{i=1}^{n}\left(C_{Ci,Rent} + U_{Gi}V_{Gi}\right) \tag{34}$$

$$C_{Cont.} = \sum_{i=1}^{n}\left(C_{i,Rent} + R_iT_i\right) \tag{35}$$

$$C_{Labo.} = \sum_{i=1}^{n}\left(U_{i,h}T_{i,h}N_i + C_{i,Insu.}N_i\right) \tag{36}$$

$$C_{Vess.} = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(C_{Mo,i} + C_{Demo,i} + R_iT_i + R_jT_j\right) \tag{37}$$

$$C_{Onsh.} = U_{Mass}M \tag{38}$$

Where C_{Total}, $C_{Admin.}$ $C_{Eng.}$ and C_{Wells} are same meaning with top-down framework method; $C_{Equip.}$ is the cost of equipment; C_{Pipe} is the pipe decommissioning cost; $C_{G\,\&\,C}$ is the cost of gas and cylinders; $C_{Cont.}$ means the cost on containers; $C_{Labo.}$ means the cost on workers' salary; $C_{Onsh.}$ means the cost for onshore dismantle; $C_{Vess.}$ means the cost on all vessels; α_d and β_w means decommissioning difficulty factor of dry and wet wells; U_d and U_w means the unit decommissioning price of dry and wet wells; $C_{Ei,Rent}$ means equipment *i* renting initial price; R_{Ei} means equipment i renting day rate; T_{Ei} means the duration of equipment *i* renting; C_{Ej} means the cost for buying equipment *j*; $C_{Ci,Rent}$ means the cost for renting cylinders type *i*; U_{Gi} means the unit price of gas type *i*; V_{Gi} means the volume of gas type *i*; $L_{i,R}$ and $L_{j,T}$ means the pipe length need to be removed and trenched with diameter *i* and *j*; $C_{i,R}$ and $C_{j,T}$ is the unit cost for removing and trenching pipe with diameter *i* and *j*; $C_{i,Rent}$ means the renting cost for container type *i*; R_i means the day rate for renting container type *i*; T_i means the duration for renting container type *i*; $U_{i,h}$ means the hourly salary for labour type *i*; $T_{i,h}$ means the duration of labour type *i*; $C_{i,Insu.}$ means the insurance cost for labour type *i*; N_i is the labour number of type *i*; $C_{Mo,i}$ and $C_{Demo,i}$ is the mobilization and demobilization cost of vessel type *i*; R_i and R_j is the day rate of vessel type *i* and *j*; T_i and T_j means the duration of vessel type *i* and *j* (some types of vessels do not asking for mobilization and demobilization); U_{Mass} is the unit price of onshore dismantling per tonnage; M is the dismantling mass.

According to the Figure 25, the total cost is obtained by summing up the management and engineering costs, and the management cost is still calculated at 8% of the engineering cost. The project cost is obtained by summing the eight sub-items, which are:

- Equipment cost. It consists of equipment acquisition, lease, daily rate, and impairment costs. The equipment includes welding torches, hoses, lighting, detection, and other small equipment used for thermal cutting. These are generally already available, need to be purchased, and cannot be leased. Large equipment, such as remotely operated underwater vehicles (ROVs), are usually not bought but leased.

- Gas and cylinders cost. Both are necessary consumables for thermal cutting, gas needs to be purchased, but cylinders are generally leased and refilled with gas.
- Material costs. Including the used scaffolding, diamond wire saw, cleaning agent, neutralizer and other materials. Since most of these materials are consumable, the total price can only be calculated by multiplying the unit price by the quantity.
- Container cost. Containers will only be leased as freight packaging or waste collection containers in the project.
- Labor wages. Salaries for workers, technicians, field specialists, etc.
- Onshore dismantling costs. Generally, the ship recycling yard will estimate the unit price per ton of dismantling according to the facility parameters.
- Engineering vessels costs. Expenses for decommissioning all engineering, living, and supporting vessels used. Usually consists of mobilization, demobilization and day rate. Some ships calculate the day rate.
- Well decommissioning costs. Oil well decommissioning is complicated, and the professional equipment, technology and materials used are difficult to estimate. A more straightforward method is to evaluate the decommissioning unit price of each well platform well and subsea well, multiply its decommissioning difficulty coefficient by the unit price correction and multiply it by the number of wells.
- Pipeline decommissioning costs.

4.2.2 Engineering Duration Estimation

It is generally believed that the setting of the project duration is positively correlated with the facility's scale or a linear regression relationship, which is different when decommissioning offshore facilities. The timeframe for decommissioning an offshore facility is constrained by several factors, including weather, marine animal migration, congregation activities, and the waiting period for critical equipment to be in place. Usually, the actual waiting period for a step may be several times or even dozens of times longer than the engineering duration. Therefore, estimating project duration is a vital part of this model.

However, the timing of each engineering step in decommissioning an offshore facility is complicated to estimate in terms of segmented costs. Because, as mentioned above, the offshore climate is changeable, the window period for construction is usually very long, and the climate laws in different regions are also other. This knowledge is beyond the scope of the author's research, and it is more appropriate to hand it over to relevant researchers and experienced experts. In this study, regression analysis obtained the engineering duration estimation. The first is to determine the components of engineering duration.

According to the decommissioning steps in Figure 25, the total project duration is obtained by summing the duration of each step. Which also means that if the duration of most steps and the total project duration is known, one particular step's duration, which may be difficult to use regression analysis, can be obtained by subtracting the sum of other step durations from the total project duration. In addition, for UK decommissioning, conductor removal is sometimes integrated into the well p&a step, and the same treatment was done in this study. The following empirical equations can be obtained using the same sets of data used in top-down framework models.

Total Engineering Duration.

To conduct regression analysis of total engineering duration, the correlation analysis must first be performed to determine which variables are used for regression, show in Table 23.

Table 23. Correlation analysis.

	Topsides weight	Jacket weight	Wells number	Subsea wells no.	Platform wells no.	Operating Period
Topsides weight	1.00					
Jacket weight	0.67	1.00				
Wells number	0.63	0.54	1.00			
Subsea wells no.	-0.14	0.09	0.15	1.00		
Platform wells no.	0.66	0.53	0.99	-0.01	1.00	
Operating Period	0.66	0.62	0.53	-0.12	0.56	1.00

Through the correlation analysis of all variables and the total decommissioning duration, in this study, the variables that are strongly correlated with the total engineering duration of decommissioning fixed offshore facilities are:

- The topside decommissioning weight.
- The jacket decommissioning weight.
- The number of wells and the number of platform wells.

The number of platform wells is included in the total number of wells, so it is not considered. Performing multiple regression analysis on the above three items and the total duration, the following regression analysis results can be obtained, the R square is 0.76:

$$D_{Total} = 0.001W_{Top} + 0.002W_{Sub-stru.} + 1.485N_{well} \quad (39)$$

Where D_{Total} is the total engineering duration in months; W_{Top} is the weight of topside; $W_{Sub-stru.}$ is the weight of facility jacket or substructure; N_{well} is the number of well.

Well P&A Duration

The same as the method used above, the correlation between each variable and the well decommissioning duration is first studied, and the appropriate variable is selected for regression. The results of the correlation analysis are shown in Table 24.

Table 24. Correlation analysis.

	P&A	Wells Number	Subsea Wells No.	Platform Wells No.	Water Depth
P&A	1.00				
Wells Number	0.69	1.00			
Subsea Wells No.	0.36	0.15	1.00		
Platform Wells No.	0.55	0.93	-0.16	1.00	
Water Depth	0.16	0.17	-0.02	0.17	1.00

It can be seen from the correlation analysis results that although the number of wells has the highest correlation with the well decommissioning time, the correlation between the number of subsea wells and platform wells and the well decommissioning time is relatively high. To obtain more detailed regression analysis results, using platform wells and submerged wells as independent variables, the regression equation is as follows, and the R square is 0.71:

$$D_{Well} = 2.75N_{Sub} + 1.13N_P \tag{40}$$

Where D_{Well} is the duration of well p&a in months; N_{Sub} is the sub-sea well number; N_P is the platform well number.

Platform Preparation Duration

The tasks in the platform preparation stage are complicated, and the duration of the construction period is logically only related to the scale of the superstructure without using special techniques (such as the overall float-over method). The obtained regression equation is as follows and the R square is 0.71:

$$D_{pl.p} = 0.0008W_{Top} \tag{41}$$

Where $D_{pl.p}$ is the duration of platform preparation in months; W_{Top} is the weight of topside.

Topside Removal Duration

Similar to the above research method, the author believes that the variables related to topside removal duration are the distance from the facility to the coast and the weight of the superstructure. The correlation analysis of these quantities is in Table 25.

Table 25. Correlation analysis.

	Coast distance	Topside weight	Topside deco. duration
Coast distance	1.00		
Topside weight	0.40	1.00	
Topside deco. duration	0.30	0.27	1.00

The correlation analysis results show that although the correlation between the topside weight, the distance from the facility to the shore, and the topside removal duration is not high, other data are logically irrelevant. Therefore, the correlation analysis of these three sets of data can get the following regression equation, and its R square is 0.47:

$$D_{Top,R} = 0.064Dis_{Shore} + 0.0001W_{Top} \quad (42)$$

Where $D_{Top,R}$ is the duration of topside removal in months; Dis_{Shore} is the distance from facility to the shore; W_{Top} is the topside weight.

Sub-structure Removal Duration

Similar to the topside removal duration evaluation method, using the weight of the sub-structure and the distance from the facility to the shore as variables and performing correlation analysis, Table 26 can be obtained.

Table 26. Correlation analysis.

	Sub-stru. deco. duration	Coast distance	Sub-stru. weight
Sub-stru. deco. duration	1.00		
Coast distance	0.07	1.00	
Sub-stru. weight	0.58	0.26	1.00

It can be seen from the analysis results that the correlation between distance from shore and sub-structure removal duration needs to be higher, so it is not suitable for regression analysis.

Therefore, only jacket weight is selected for regression analysis, and the results are as follows, R square is 0.52:

$$D_{Sub-stru.,R} = 0.0004W_{Sub-stru.} \tag{43}$$

Where $D_{Sub-stru.,R}$ is the duration of sub-structure removal in months; $W_{Sub-stru.}$ is the weight of sub-structure.

Pipeline Subsea Facilities Preparation & Removal Duration

Preparation and removal times for pipelines and subsea installations are difficult to estimate. Using pipeline length, underwater facility weight, water depth, etc., to conduct correlation analysis with preparation and removal duration, Tables 27 (a) and (b) are obtained. It can be seen from the data in the table that the above three independent variables have a very low correlation with the preparation and removal duration, and regression analysis cannot be performed. Therefore, the decommissioning duration of the total project should be subtracted from other engineering durations with better regression effects to obtain the estimated results of this part, and the following equation can be obtained:

Table 27. Correlation analysis

(a)

	Water depth	Pipe length	Pipeline preparation
Water depth	1.00		
Pipe length	-0.22	1.00	
Pipeline preparation	-0.22	0.21	1.00

(b)

	Water depth	Pipe length	Subsea structure weight	Pipeline & sub-facilities deco.
Water depth	1.00			
Pipe length	-0.22	1.00		
Subsea structure weight	-0.23	0.72	1.00	
Pipeline & sub-facilities deco.	0.06	0.08	-0.19	1.00

$$D_{pipe\ \&\ subsea} = 0.0015W_{Sub-stru.} + 0.355N_{well} - 0.0001W_{Total} - 0.064Dis_{Shore} - 1.62N_{Sub} \tag{44}$$

In case the value of above equaiton is nagative, the second regression equation for $D_{pipe\,\&\,subsea}$ is:

$$D_{pipe\,\&\,subsea} = 0.11L_{Pipe} \tag{45}$$

Where $D_{pipe\,\&\,subsea}$ is the duration of pipe and subsea facilities preparation and removal duration in months; $W_{Sub-stru.}$ is the weight of sub-structure; N_{Well} is the number of well; N_{Sub} is the number of subsea well, Dis_{Shore} is the distance from facility to the nearest shore; W_{Total} is the total weight of structure need to be decommissioned; L_{Pipe} is the length of pipeline need to be decommissioned.

Onshore Dismantle Duration

The onshore dismantling duration is no longer affected by the ocean climate, etc. It is usually estimated by the shipbreaking yard in terms of days/tons and is not used to calculate the salary the energy company needs to pay. Still, it needs to be used to calculate pipeline decommissioning and subsea facilities' duration costs. Correlation analysis is no longer necessary. It is only required to perform regression analysis on the weight of the structure to be decommissioned and the dismantling duration to obtain:

$$D_{Dis} = 0.0002W_{Total} \tag{46}$$

Where D_{Dis} is the duration of structure dismantle in months; W_{Total} is the total weight need to be decommissioned.

So far, the basis for building a cost assessment model based on the bottom-up framework is in place. According to calculation and comparation with actual engineering duration, the Table 28 can be obtained. The performance of regression analysis for engineering duration is not good to use, but there is no other method for now. The next step is to collect data related to unit price costs, which will be described in the next section.

Table 28. Related Error of engineering duration prediction model.

	P&A	Platform preparation	Pipeline deco.	Topside removal	Sub-stru. removal	Onshore disposal	Operating Period
RE	0.34	0.23	0.69	0.52	0.53	0.08	0.04
	0.00	11.64	0.00	2.69	0.00	0.78	0.11
	0.59	0.47	0.00	2.43	0.53	0.00	0.41
	2.48	0.61	0.00	2.70	0.00	0.00	1.93
	0.87	0.03	0.00	2.93	0.00	0.00	0.47
	0.88	0.47	0.91	0.68	0.60	0.44	0.51
	0.62	1.00	0.50	0.39	0.00	0.99	0.91
	0.30	0.75	0.96	0.77	0.86	0.94	0.75
	0.00	0.96	0.00	2.30	0.77	0.95	0.93
	2.77	1.00	3.44	0.00	0.00	1.13	0.19
	0.34	0.09	0.97	0.47	1.48	0.71	0.00
	1.36	0.33	0.81	1.58	1.12	0.86	0.06
	0.27	0.60	1.61	0.50	0.79	0.00	0.59
	0.04	0.93	0.42	0.22	0.97	0.97	0.82
	7.25	0.00	4.47	21.79	0.04	0.88	0.86
	0.00	0.72	0.00	0.37	0.00	0.93	0.86
Average	1.13	1.24	0.92	2.52	0.48	0.60	0.59

Decommissioning Activity Duration Statistics

From the above results, the accuracy of the results obtained by regression analysis can be called a disaster, but this is currently unavoidable because the metadata is too scarce. However, Accenture (Accenture, 2018) provides additional statistics to show that the decommissioning time of various seas in the UK territorial waters may be a good choice. Tables 29 to 33 show that the number of days required to decommission different structures is provided, but these tables do not include waiting times.

Table 29. Decommissioning activity duration statistic.

Decommissioning activity	Number	demand days	No. or ton/day
Platform well p&a	804	29400	0.03
Subsea well p&a	462	17700	0.03
Subsea infrastructure removal<400te	88	1320	0.07
Subsea infrastructure removal>400te	10	210	0.05
Topside removal	115	579	0.20
Sub-structures removal	109	1015	0.11
Onshore dismantling tonnes	801660	15241	52.60

Table 30. Topside removal vessel days (per tonnage range) by region.

Topside tonnage	0-1600	1601-4000	4001-8000	8001-16000	>16000
CNS, NNS	1.25	3.75	6.25	12.5	27.5
IS (including EIS), SNS	1.25	3.75	5	-	-

Table 31. Substructure removal vessel days (per tonnage range) by region.

substructure tonnage	0-1600	1601-4000	4001-8000	8001-16000	16000+
CNS	7	7	7	27	40
NNS	-	-	7	27	40
IS, EIS	7	7	7	27	-
SNS	7	7	7	-	-

Table 32. Subsea infrastructure removal vessel days by weight (Te).

Subsea tonnage	0-500	501-1000	1001-2000	>2000
Removal days	15	20	30	40

Table 33. Onshore decommissioning duration by infrastructure type and weight (Te).

Activity	Te ranges	Days
subsea infrastructures	2000	14
substructures	1000-1500	28
topsides	2000-3000	28

Moreover, it only provides statistical results of topside, substructure, subsea infrastructure, and onshore dismantling. It only has other vital data such as well decommissioning, pipeline decommissioning and platform preparation time. However, the regression results of well decommissioning and platform preparation time perform better, so the author believes combining official statistical results and regression results may be the best solution. Therefore, Table 34 is the evaluation method finally established by the author to evaluate the duration of offshore facilities' decommissioning activities. The model performance shall be show in chapter 7.4.2, the model performed slightly better than the pure regression model.

Table 34. Engineering duration estimation for offshore decommissioning.

Activities	Duration (days)
Well p&a	$D_{Well} = 82.5N_{Sub} + 34N_P$
Platform preparation	$D_{pl.p} = 0.024W_{Top}$
Topside removal	$D_{Top,R} = 0.064Dis_{Shore} + 0.0001W_{Top}$
Substructure removal	$D_{Sub-stru.,R} = 0.0004W_{Sub-stru.}$
Pipeline decommissioning	$D_{pipe\ \&\ subsea} = 3.3L_{Pipe}$
Onshore dismantling	See Table 33
Topside removal vessel days	See Table 30
Substructure removal vessel days	See Table 31
Subsea infrastructure removal vessel days	See Table 32

4.2.3 Equipment, Labor, Material Usage Estimation

As shown in the flow chart in the first part of this section, not only the project duration is a vital cost evaluation basis, but also the use of equipment, materials, and labor quantities in the project are also necessary data. These data are greatly affected by the technology used in the project, and even the evaluation results of energy companies have a large gap with the results of their actual projects.

In most cases, it is just a summary of the project's progress without a special list of statistics, which dramatically complicates this study. Therefore, in the end, the author decided to use the North West Hutton platform as a reference standard and use the comparative evaluation method to evaluate the relevant values of other platforms. For applying the comparative evaluation method, you can refer to the description of the method in the literature review section, and the source of relevant data will not be explained below.

4.2.4 Unit Price

This part begins to sort out all the unit price cost data sources involved in ECES. According to the content of the bottom-up framework, this part of the cost mainly comes from market data rather than historical data regression. According to the description in Section 4.2.1, these basic costs include:

- Well decommissioning unit price and decommissioning difficulty correction parameters for platform wells and subsea wells
- Equipment rental daily rate, equipment unit price, the single rental fee
- Gas consumption unit price, cylinders rental fee
- Consumable material unit price and material consumption
- Container rental fees and day rates

- Salaries of construction personnel at all levels, insurance premiums borne by the company
- Engineering ship mobilization/demobilization fee and ship charter day rate
- Onshore structure demolition unit price

For confidence of this research, all of data above will be collected from government statistic or companies reports or historical projects like what OECD did in nuclear plant decommissioning (OECD & NEA, 2010).

The first is the unit cost of well p&a. The cost of decommissioning a well is affected by many variables, including but not limited to water depth, weather, reservoir type, age, condition, and operational complexity. Therefore, it can only be selected according to the market average of single well decommissioning combined with the decommissioning difficulty coefficient of the well, or the decommissioning cost range of a single well is equally divided according to the difficulty of well decommissioning and then judged by the user. In this study, the author tends to use the second method for the time being because the first method requires the user to have an in-depth analysis of the well to determine the selection or calculation method of the difficulty coefficient of well decommissioning. Table 35 shows the unit cost of well decommissioning in various sea areas in the UK in 2017.

Table 35. Well decommissioning cost in UKCS in 2017 (Scottish Enterprise, 2018).

Location	Well Type	2017 average cost (per well)	2017 cost range (per well)
Central and Northern North Sea and West of Shetland	Platform wells	£ 4.9M	£ 0.6~£14.8M
	Subsea wells	£ 10.1M	£ 2.9~£24.9M
Southern North Sea and Irish Sea	Platform wells	£ 2.8M	£ 1.3~£7.6M
	Subsea Wells	£ 7.8M	£ 3.3~£11.4M

Similar as well decommissioning, the pipeline decommissioning unit price show in the Table 36.

Table 36 Cost data for pipeline (Scandpower Risk Management Inc, 2004).

P/L diameter	Water depth (m)	Cost min (£/km)	Cost max (£/km)	Vessel working rate min £/day	Vessel working rate max £/day	Min Cost £/day for retrieval	Max Cost £/day for retrieval	Trenching £/km	Pipe disposal cost £/ km
<4”	0-60	105904	162929	46500	80000	113500	166000	25000	26400
	60-150	169000	175000	53000	89000	123500	172500	25000	26400
	150+	187500		94000		175500		25000	26400
4”-12”	0-60	129000	197000	53000	91000	137000	170500	25000	39600
	60-150	160000	216500	80000	100000	166000	178000	25000	39600
	150+	187500		94000		175500		25000	39600
12”-16”	0-60	131000	211000	66000	91000	145000	152500	25000	42000
	60-150	190000	245000	85000	100000	183000	174500	25000	42000
	150+	206000		96000		165000		25000	42000
16”-24”	0-60	185500	229500	85500	93000	15400	157500	25000	47500
	60-150	206500	254500	91500	102500	156000	156500	25000	47500
	150+	228000		101000		154000		25000	47500
24”-30”	0-60	206000	278000	87000	94000	144000	150000	25000	52800
	60-150	229500	310000	93000	103500	152500	158500	25000	52800
	150+	254500		102500		157500		25000	52800
30”-36”	0-60	247000	319500	87000	95500	134500	138000	25000	58100
	60-150	278000	358500	94000	10500	144000	147000	25000	58100
	150+	310000		103500		152500		25000	58100

There are many primary data sources for the unit price and daily rate of other items mentioned above, including government statistics, quotations from various companies, authorities from mediators, etc. See Table 37 for details. These prices generally fluctuate with the market and change quickly. Users should decide which data to use according to the market conditions at the time of use.

Table 37. Day rate and unit price for decommissioning (Twachtman Snyder & Byrd Lnc., 2000; PCCI, 2014; UK Government, 2022; Special Container, n.d.; Container, n.d.; Arish Engineers, 2022; ADAMS, 2022).

£	Annual salary			Vessel cost			Unit price	Fulfil price
	normal	expert	manager	mobilization	demobilization	rent day rate		
Labour	40000	41000	55000					
Barge						8800		
DCV						210000		
SSCV						421000		
Semi-submarine Rig						230000		
Rigless Light Well Intervention						193000		
Light Construction Vessel						168000		
DSV				300000	200000	80000		
Trenching				300000	100000	70000		
Support Vessel				50000	50000	25000		
HLV				100000	100000	180000		
Cargo barges						230		
Tug						4370		
Tank or pipe cleaning						1700		
Onshore dismantle/ton							300	
Containers10/20/40 ft						12/17/25		
Gas cylinder quad 32 – Oxygen 50L							1350	82
Gas cylinder quad 32 – Acetylene 50L							1350	140
Cutting equipment							130	
Rack							110	

Having the above data is necessary for the bottom-up framework cost evaluation system and is the main content of each cost item. The final cost can be calculated by combining the project duration of each part in the decommissioning of the facility, the amount of labor used, the amount of equipment and materials used, etc. The more detailed the evaluation sub-items are, the more accurate the evaluation results will be. This method is very suitable for enterprise use and operation. Still, due to the problem of access to detailed data, it may need to be more conducive to using non-industry personnel.

4.2.5 ECES Summary

Obviously, the ECES method based on the bottom-up framework is very complicated, and the exact data required is much more than the cost assessment method of the top-down framework. However, the theoretical accuracy of this method is higher than that of the top-down method with insufficient original data, especially when the risk assessment and impact assessment are carried out separately.

In addition, it can be seen from the above research history that the difficulty of building a bottom-up framework cost evaluation model is not in the framework construction stage but in the following three sections:

- Engineering duration estimation part. Especially for the construction duration of offshore facilities, weather, technology, and equipment scheduling will significantly affect the construction progress. However, this kind of interference cannot be well predicted by scientific methods for the time being, and relevant researchers need to establish a reliable duration evaluation model.
- Estimates of manpower, equipment, and material usage. For the author, this part cannot be evaluated temporarily because there is no relevant data. This study is looking forward to follow-up by practitioners or relevant statistical institutions.
- Data collection and update section. The mixed-use of a large amount of market data and government statistics may affect the accuracy of the assessment results. Market data differs from region to region, and its changing nature over time requires users to update the data frequently.

Although there is still no bottom-up framework cost assessment model applied to the decommissioning of offshore facilities, the theory for constructing the model is fully available, and the main difficulty in model construction lies in the acquisition of reliable data. Section 4.2 shows the detailed steps of building a cost assessment model under the bottom-up framework and the specific algorithm and will use case analysis later to show which model under the two frameworks is more suitable for the North Sea.

Chapter 5. Risk Assessment Methodology

The risk assessment method is the core content of this project research. The model constructed in this chapter would output not only the QRA results caused by potential accidents but also the results of the incremental range of total costs caused by accidents as the correction data of engineering costs. This study is unique from the general offshore facility QRA model in the following six points:

- The necessary and sufficient conditions for the triggering mechanism of domino accidents are proposed for the first time. The proposal of necessary and sufficient conditions has dramatically clarified the conditions for domino accidents.
- The first hierarchical domino accident assessment method. The quantitative analysis of domino accidents is more organized and using a causality matrix makes the system highly exploitable.
- The establishment of a targets criteria database. Establishing a domino accident triggering targets criteria database based on physical rules can be used not only in the dynamic scene construction process but also in the severity assessment of accident consequences.
- Quasi-dynamic accident scenarios. It is no longer up to the user to plan accident scenarios based on logical reasoning and historical accident data but to determine all possible accident scenarios through step-by-step calculations.
- The domino accident assessment mechanism with multiple risk interactions has been added. It is more than just considering the risk value caused by each accident without considering the mutual trigger relationship between them.
- Set the willingness parameter for the first time. The accident itself has two sides. When the triggered accident may reduce the overall accident intensity, it should be given a positive evaluation, and the evaluation is based on the will and judgment of the user.

Next, this chapter will introduce the overall configuration, algorithm, accident probability and consequence calculation method of the Hierarchical Analyst Domino Evaluation System (HADES), as well as the construction method and content of the target standard database.

5.1 Hierarchical Analyst Domino Evaluation System (HADES)

HADES is a novel evaluation system of DEAs constructed further and innovatively based on Cozzani's research (Cozzani et al., 2006). Combining the three characteristics mentioned in Chapter 2.4.5 with the demonstration in Figure 26, the necessary and sufficient conditions for DEAs triggering can be obtained as follows:

- The impact of the previous accident must cover the target object where DEAs may occur.
- The consequences of the previous accident must be severe enough to cause an accident on the target.

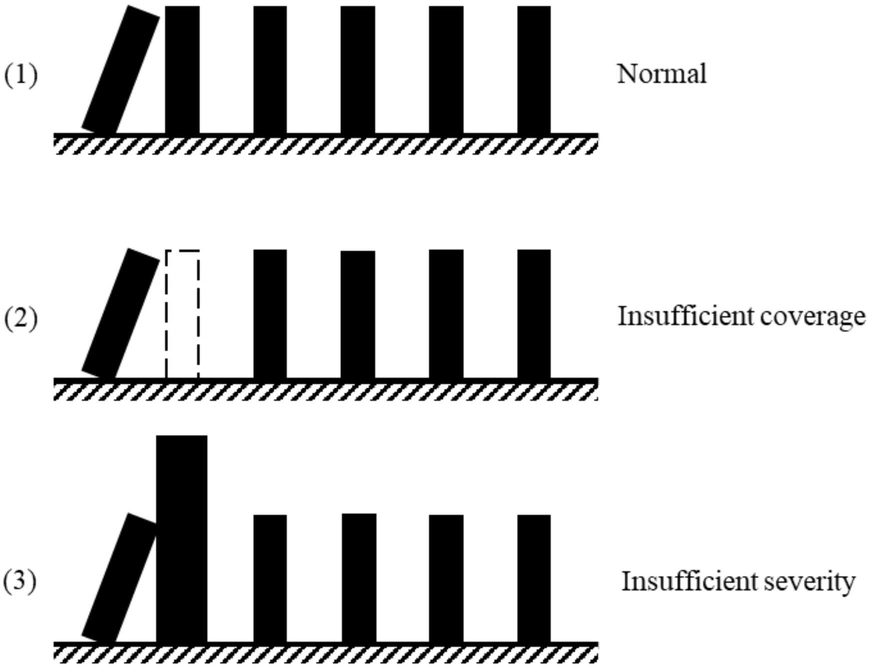


Figure 26. DEAs triggering mechanism schematic diagram.

Based on the necessary and sufficient conditions for DEAs to trigger, combined with industrial engineering procedures, the system integrates AHP (Bernasconi et al., 2010) into traditional QRA to clarify the causation between the initial accident and DEAs. The innovative causality matrix can quickly and easily express the causality between accidents in matrixes. The addition of the willingness module makes the QRA results more accurate and correspond with industrial reality. The frequency and consequences of DEAs are based on the two DEAs trigging mechanisms, placed in matrixes for intuitive and fast calculation. Following contents show a series of excellent QRA results evaluated by HADES.

5.1.1 HADES Introduction

As described above, HADES is a quasi-dynamic quantitative DEAs risk assessment system established by integrating AHP thought into QRA. The characteristic of this system is different from the traditional DEAs risk assessment system. The most significant feature is that establishing accident scenarios no longer depends on the user’s prior planning but is dynamically generated by the HADES. The occurrence of DEAs no longer depends on assumptions. However, after comparing the actual physical data with the target standard database and verifying that the comparison results meet the two necessary and sufficient conditions for DEAs triggering mentioned above, it will be determined that DEAs have occurred. HADES is an advanced QRA evaluation system. Its supporting algorithm mainly uses matrix operations, which can be very well adapted to popular artificial intelligence technology. The data selection can be upgraded using the Monte Carlo algorithm, and the calculation process can be adapted to the Bayesian belief network. With suitable sensor peripheral hardware, real-time risk monitoring and dynamic assessment can be performed on any construction site.

The HADES framework shown in Figure 27 consists of five parts:

- The hazards module. Hazards are identified, categorized, and stratified. This is the first step of the HADES system, and it is the most intuitive embodiment of integrating AHP thought into QRA. In this module, the introduction of causality matrix can directly stratify hazards and reflect the causal relationship between them.
- The primary layer. This is the initial accident evaluation module, meaning that all accidents considered to be self-inflicted rather than triggered will be evaluated at this level. The content of the assessment includes traditional accident frequency and physical effect consequences.
- Target criteria database. The core module of HADES is responsible for comparing and calculating whether the intensity of the physical consequences of the upper-level accident can trigger other accidents. The existence of this module makes HADES a quasi-dynamic evaluation system capable of dynamic accident scene rendering.
- Domino layers. The calculation of this module can only be triggered after the calculation of the target criteria database is passed. The evaluation content is similar to that of the primary layer, focusing on calculating data such as the frequency of triggered accidents, the scope of accident impact, and the intensity of the physical effects of consequences.
- Willingness module. This module embodies the dialectical characteristics of the accident itself. It provides a calculation method for scenarios where the occurrence of some accidents may reduce the negative impact of the disaster overall. The function of this module is similar to safety barrier, the parameters are set between -1 and 1, which the operator selects according to their wishes.

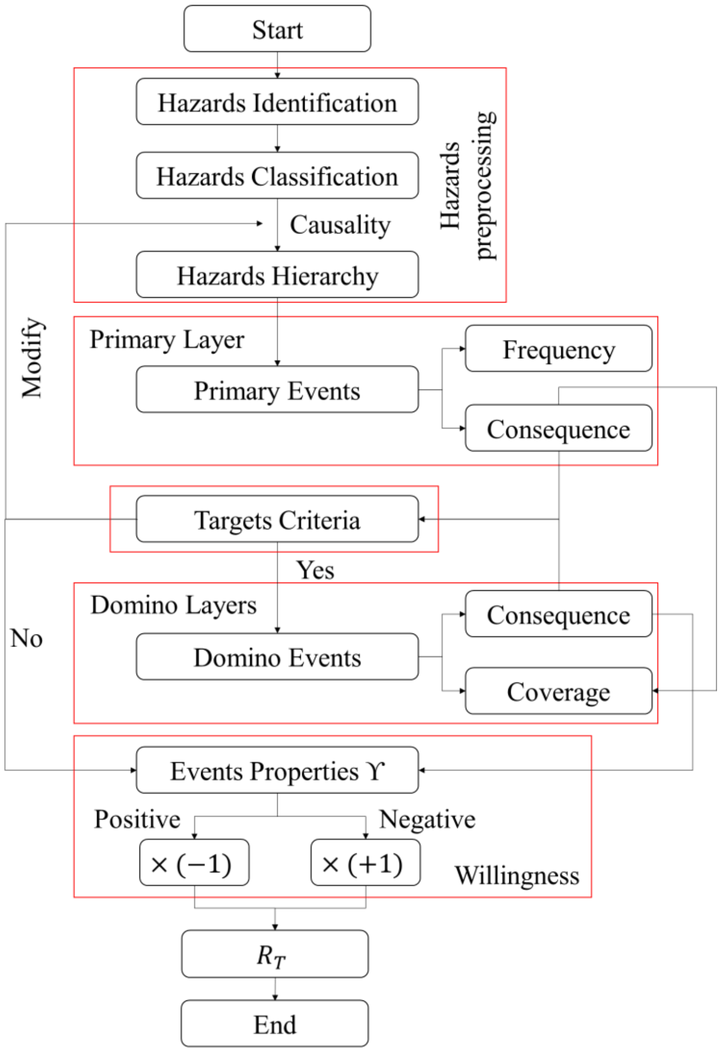


Figure 27. The flowchart of HADES.

After understanding the architecture of HADES, it is necessary to explain in detail the innovative concepts mentioned above.

The first is the specific role of the causality matrix in the Hazards preprocessing part. After the hazard identification is completed, the traditional DEAs evaluation system will build several hazards into an accident chain based on historical data and logical judgment as the DEAs accident scenario and perform quantitative evaluation chain by chain. This approach would be fragile in practical assessments, as the consequences of a single primary accident often led to the triggering of multiple DEAs. The purpose of introducing the causality matrix is to:

- Group spontaneously occurring incidents and triggered incidents to prevent confusion about causation.
- Construct accident layers layer-by-layer and use causality factors to establish a causal network between elements in each layer.

The advantage of this newly proposed method is that DEAs can be evaluated globally, systematically, and visually. Meanwhile, the Spatio-temporal sequence of DEAs scenarios can also be more easily constructed after classification and stratification.

Next, the Targets Criteria Database (TCD) is the core of HADES and is also the key to this system's quasi-dynamic scene construction and risk assessment. The logic of this method is not complicated. Compare the accident consequence's physical effects with the target's corresponding physical value to determine whether the target is damaged and whether the internal pressure is too high, broken, slipped, ignited, etc. These values include but are not limited to mechanical energy, heat flux, temperature, pressure, and force. Each time, by comparing the consequences of the upper-level accident with the target database of the affected target, it can be judged whether DEAs will occur on the target. Feedback on the trigger results to causality matrix to modify the parameters of the matrix to gradually build dynamic DEAs accident sequences and scenarios.

Finally, an explanation of the safety barriers and willingness modules. The above description does not mention the assessment of the security barrier. HADES divides the security barrier into two parts and integrates it into the assessment. First, the types of security barriers need to be explained. There are three main types of safety barriers according to their functions:

- Passive guards as protective equipment. Essentially the same as equipment that loses its safety barrier effect if it fails – such as a fire door.
- As active mitigation of accident consequences, restraint devices are usually also viewed as equipment. Its failure means it cannot slow down or reduce the intensity of the disaster. However, its failure will not lead to the aggravation of accident consequences – such as an active fire protection system.
- As a passive mitigation of accident consequences, restraint devices' purpose is to quickly damage the critical time or location when an accident occurs to contain or alleviate the progress or intensity of the global accident.

According to the characteristics of the above three safety barriers, it can be known that:

- The first type of barrier is similar to normal equipment, and its failure means that traditional accidents will occur. Therefore, it can be directly regarded as general equipment, and its physical tolerance Limits are put into TCD for comparison and judgment with consequent physical effects.
- The second type of barrier focuses on actively delaying the accident after it occurs, limiting the scale of the accident and reducing the intensity of the accident. In this study, it can be regarded as general equipment, and it is not necessary to consider the possible

domino accident itself, but only the possibility of its failure. However, even if this system fails, it will not make the original accident. The consequences worsened.

- The third type of barrier is memorable. It can be called the “happy accident”, which usually relies on the designer’s ingenious design in the early stage of structure construction or accidents in the event of an accident. Accidents at such barriers may be intentional or unintentional coincidences. However, the actual effects limit accidents’ scale, and/or slow down the development of the accident, and/or mitigate the consequences of the accident. The probability and physical consequence assessment methods of such situations are the same as those of general accidents. However, the operators must determine the specific results according to their wishes.

The above features show the originality and superiority of HADES. Next, the algorithm corresponding to the HADES framework, the use of causality matrix, and the complex dynamic risk calculation matrix in the algorithm are the core content of the mathematical expression of HADES.

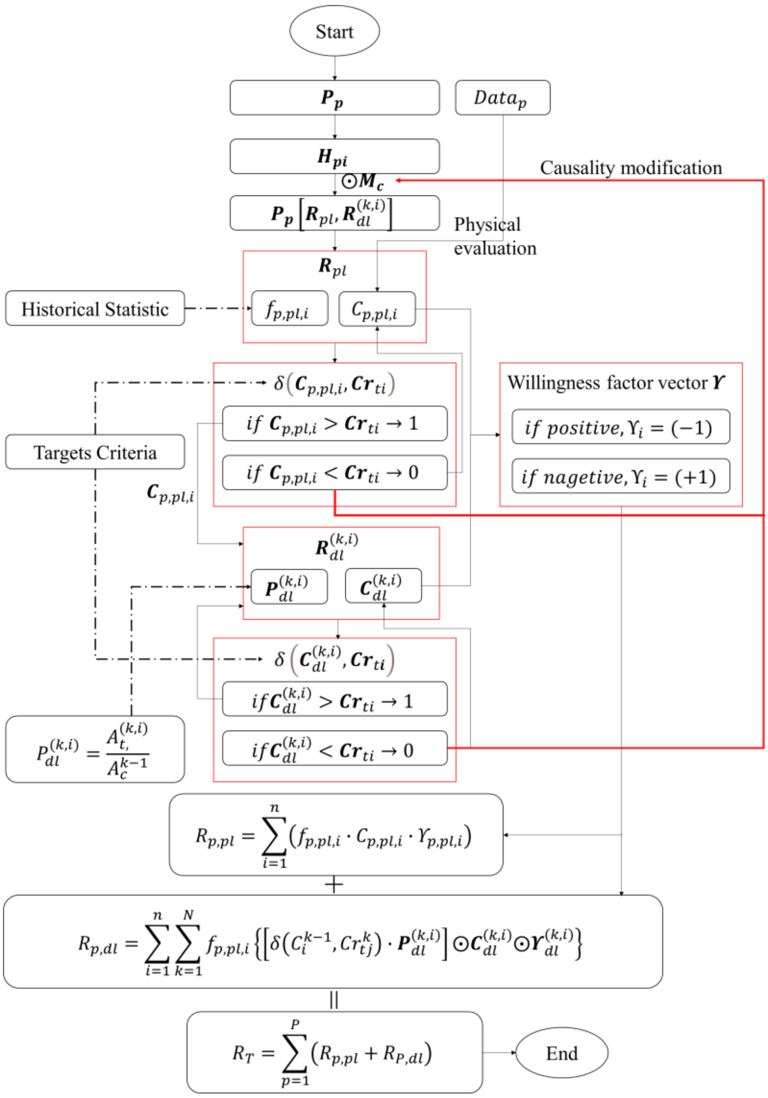


Figure 28. The algorithm of HADES.

As mentioned above, the algorithm flowchart of HADES is shown in Figure 28. Clarifying the main processes of the industrial activity $\boldsymbol{P_P}$ firstly, hazard identification follows to obtain $\boldsymbol{H_{pi}}$ for each process $\boldsymbol{P}$. Then Figure 29 introduces the causality matrix $\boldsymbol{M_c}$. $\boldsymbol{M_c}$ is a binary matrix for now with a scale of $(n \times N)^2$. The accidents' causation between two neighbouring layers represents by each $n \times n$ size group element. The value $H_i^{k-1}H_j^k$ is 1 or 0 means there is causation or not between any two accidents of neighbouring layers. Then process to the second module-primary layer module. The HADES recommends industrial historical statistics data for primary layer accidents' frequency $f_{p,pl,i}$ due to unclear causation of some accidents, and $C_{p,pl,i}$ means the physical results obtained through the corresponding physical algorithm. These physical results are compared with the criteria database $\boldsymbol{Cr_t}$ to judge the fulfilment of the severity requirements of DEAs. Meanwhile, evaluating the coincidence of the target objects and the accident range $A_t^{(k,i)} \Big/ A_c^{k-1}$ for judging the coverage requirement. Otherwise, the physical results will be used for getting IRPA value, economic loss, and environmental loss, and modify the causality matrix $\boldsymbol{M_c}$. For the domino layers, consequence evaluation and criteria comparison steps are similar to primary layers until the loop terminates by the users or $\boldsymbol{M_c}$. The willingness module will consider all evaluation results to make corrections according to users' preferences about accidents and output.

Equation (47) to (52) show the mathematical expression of HADES algorithm:

$$R_T = \sum_{p=1}^{P}[R_P(pl) + R_P(dl)] \quad (47)$$

$$R_{p,pl} = \sum_{i=1}^{n}\left(f_{p,pl,i} \cdot C_{p,pl,i} \cdot \Upsilon_{p,pl,i}\right) \quad (48)$$

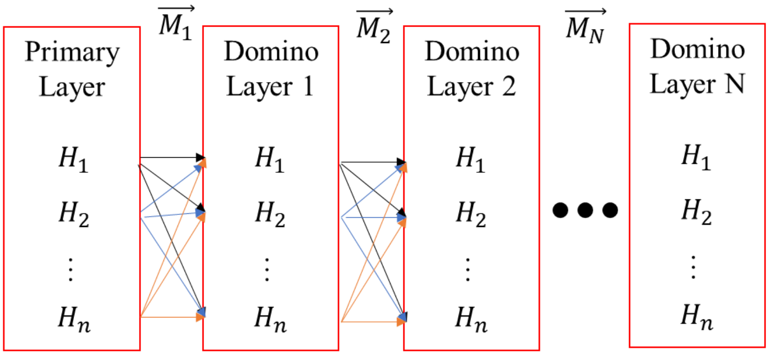
$$R_{p,dl} = \sum_{i=1}^{n}\sum_{k=1}^{N} f_{p,pl,i}\left\{\left[\delta\left(C_i^{k-1}, Cr_{tj}^{k}\right) \cdot \boldsymbol{P}_{dl}^{(k,i)}\right] \odot \boldsymbol{C}_{dl}^{(k,i)} \odot \boldsymbol{\Upsilon}_{dl}^{(k,i)}\right\} \quad (49)$$

$$\delta\left(C_{p,pl,i}\ or\ C_{dl}^{(k,i)}, Cr_{ti}\right) = \begin{cases} 1, & C_{p,pl,i}\ or\ C_{dl}^{(k,i)} \in Cr_{ti} \\ 0, & C_{p,pl,i}\ or\ C_{dl}^{(k,i)} \notin Cr_{ti} \end{cases} \quad (50)$$

$$\boldsymbol{P}_{dl}^{(k,i)} = \left[\overrightarrow{P_{dl}^{1}} \quad \overrightarrow{P_{dl}^{1}} \otimes \overrightarrow{P_{dl}^{2}} \quad \cdots \quad \bigvee_{k=1}^{N} \overrightarrow{P_{dl}^{k}}\right] \ (1 \le k \le N, 1 \le i \le n) \quad (51)$$

$$P_{dl}^{(k,i)} = A_t^{(k,i)} \Big/ A_c^{k-1} \quad (52)$$

Where R_T is the total risk value of the project; $R_P(pl)$ is the risk value of primary layer's accidents; $R_P(dl)$ is the risk value of domino layers' accidents; P means procedure; $f_{p,pl,i}$, $C_{p,pl,i}$ means the frequency and consequence of *i*-th accident; C_i^{k-1} means *k-1* layer's *i*-th accident consequence; Cr_{tj}^{k} means target *j*'s physical criteria for *k* layer, *i* may or may not equal to *j*; $\delta\left(C_i^{k-1}, Cr_{tj}^{k}\right)$ represents consequence severity judgement process; $A_t^{(k,i)} \Big/ A_c^{k-1}$ means the ratio of the area of the layer *k*'s *i*-th target object in the area of accident coverage the layer *k-1*'s accident may occur area; $\boldsymbol{P}_{dl}^{(k,i)}$, $\boldsymbol{C}_{dl}^{(k,i)}$ and $\boldsymbol{\Upsilon}_{dl}^{(k,i)}$ are size $(n \times N) \times (n^N - 1) \Big/ (n-1)$ matrix with $(n \times N)$ rows and $(n^N - 1) \Big/ (n-1)$ columns where the elements of $\boldsymbol{P}_{dl}^{(k,i)}$ represent the Kronecker product of DEAs' uncertainty layer by layer (if the accident cannot occur, take the probability as 0 to take the position), $\bigvee_{k=1}^{N} \overrightarrow{P_{dl}^{k}}$ means the accumulation of Kronecker products from domino layer *1* to *N*. The $\boldsymbol{C}_{dl}^{(k,i)}$ and $\boldsymbol{\Upsilon}_{dl}^{(k,i)}$ combine with $\boldsymbol{P}_{dl}^{(k,i)}$ using the Hadamard product, the number 0 would take empty positions in the matrix, as shown in Figure 30.

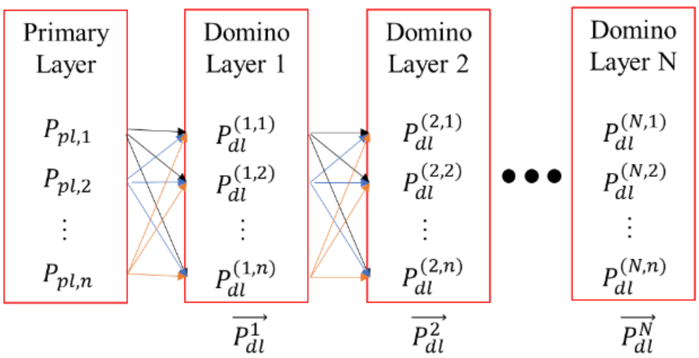


$$\overrightarrow{M_1} = \begin{bmatrix} H_1^P H_1^{d1} & H_1^P H_2^{d1} & \cdots & H_1^P H_n^{d1} \\ H_2^P H_1^{d1} & H_2^P H_2^{d1} & \cdots & H_2^P H_n^{d1} \\ H_i^P H_1^{d1} & H_i^P H_2^{d1} & \ddots & H_i^P H_n^{d1} \\ H_n^P H_1^{d1} & H_n^P H_2^{d1} & \cdots & H_n^P H_n^{d1} \end{bmatrix}$$

$$\overrightarrow{M_c} = \begin{bmatrix} \overrightarrow{M_1} & 0 & & 0 \\ 0 & \overrightarrow{M_2} & & \\ & & \ddots & 0 \\ & 0 & 0 & \overrightarrow{M_N} \end{bmatrix}$$

$$H_i^{k-1} H_j^k = \begin{cases} 1 & \textit{has}\ \text{causality} \\ 0 & \textit{no}\ \text{causality} \end{cases}$$

Figure 29. The using of causality matrix.



$$\boldsymbol{P}_{dl}^{(k,i)} = \begin{bmatrix} \overbrace{\overrightarrow{P_{dl}^1}}^{n^0 \times n} & \overbrace{0}^{n^1 \times n} & & 0 \\ 0 & \overrightarrow{P_{dl}^1} \otimes \overrightarrow{P_{dl}^2} & & \\ & & \ddots & 0 \\ & 0 & 0 & \bigvee_{k=1}^{N} \overrightarrow{P_{dl}^k} \end{bmatrix} \} \, n^{N-1} \times n$$

$$\boldsymbol{\Upsilon}_{dl}^{(k,i)} = \begin{bmatrix} \overbrace{\overrightarrow{\Upsilon_{dl}^1}}^{n^0 \times n} & \overbrace{0}^{n^1 \times n} & & 0 \\ 0 & \overrightarrow{\Upsilon_{dl}^2} & & \\ & & \ddots & 0 \\ & 0 & 0 & \underbrace{\overrightarrow{\Upsilon_{dl}^N}}_{n^{N-1} \times n} \end{bmatrix} \quad \boldsymbol{C}_{dl}^{(k,i)} = \begin{bmatrix} \overbrace{\overrightarrow{C_{dl}^1}}^{n^0 \times n} & \overbrace{0}^{n^1 \times n} & & 0 \\ 0 & \overrightarrow{C_{dl}^2} & & \\ & & \ddots & 0 \\ & 0 & 0 & \underbrace{\overrightarrow{C_{dl}^N}}_{n^{N-1} \times n} \end{bmatrix}$$

Figure 30. Probability, consequence and willingness matrix of HADES.

Overall, HADES is a modular assessment system. The evaluation methods of different accidents are independent modules in HADES, which can be replaced by other methods at any time according to the needs of users. Such as the CFD method that can simulate flame and smoke propagation or the FEM that can predict the structural failure more accurately. These modules are causally linked by the causality matrix of HADES to form a causal network. The consequences of all evaluation modules will be compared with the relevant data in the TCD to determine whether the severity of the accidents can trigger a domino event and modify the causality matrix. Meanwhile, these results will also be put into the willingness factor module to give subjective parameters to correct the severity of the accidents' consequences.

5.2 Probability Estimate Methods

Whether the primary layer or the domino layers module, its core content is probability estimation and consequence estimation. The difference is that all the accident probability data of the primary layer come from industrial statistics or related information. The accident probability of domino layers is the product of the geometric calculation result and the primary accident probability. It is essential to clarify the relationship between the two and explain the importance of what follows.

This chapter will show the calculation methods of the occurrence frequency of the four major hazards. These hazards result from selection based on the eight major hazards mentioned in Section 1.1.3. they are, respectively:

- Hydrocarbon Release - blowout
- Fire and explosion
- Ship collision
- Dropped objects

It should be clear that these hazards only need to calculate their occurrence frequency in the primary layer. As a domino event, it is only necessary to examine the coverage of the previous accident instead of calculating the probability of the accident itself.

5.2.1 Hydrocarbon Release-Blowout

The main manifestations of hydrocarbon leakage hazards are different in different layers. In the primary layer, only the probability of a blowout accident needs to be evaluated without considering the hydrocarbon leakage of equipment caused by equipment aging. The blowout accident is severe no matter whether it is natural gas or crude oil. It will cause significant environmental pollution and potential extreme hidden dangers. This part mainly introduces the probability calculation method for blowout.

So, first, the process of decommissioning and sealing wells would be introduced, which is the most crucial step in decommissioning. Each plug has 30 meters or 100 meters of cement (refer to the requirements of various countries for cement plugs) (Buchmiller et al., 2016). Figure 31 shows the comparison of the general well before and after plugging. The specific operation process is as follows (Joe & Dwight K., 1976). More details can be found in NORSOK-D10 and DNVGL-RP-E103 (NORSOK Standard D-010, 2004; Buchmiller et al., 2016):

1) Pull out the production pipe.
2) Clean the well with cleaning fluid.
3) Place the mechanical bridge plug at the junction of the reservoir and the rock layer and fix it (the fixture is used according to the situation, but it is not necessary)
4) A special scraper catheter is placed over the bridge plug to punch through the casing wall.
5) Pulled out the scraper and placed the catheter.
6) Cement (or other settable substance) is poured to fill the annulus, forming the barrier.
7) Take out the excess cement and wait for the cement to solidify.
8) Test the strength of the plug.
9) Pour in mud or other filler.
10) Place the next barrier and repeat the former steps.
11) Cut and remove casing below seabed about 10-15m, fill cement for forming the environmental plug and cover with seabed sediment.

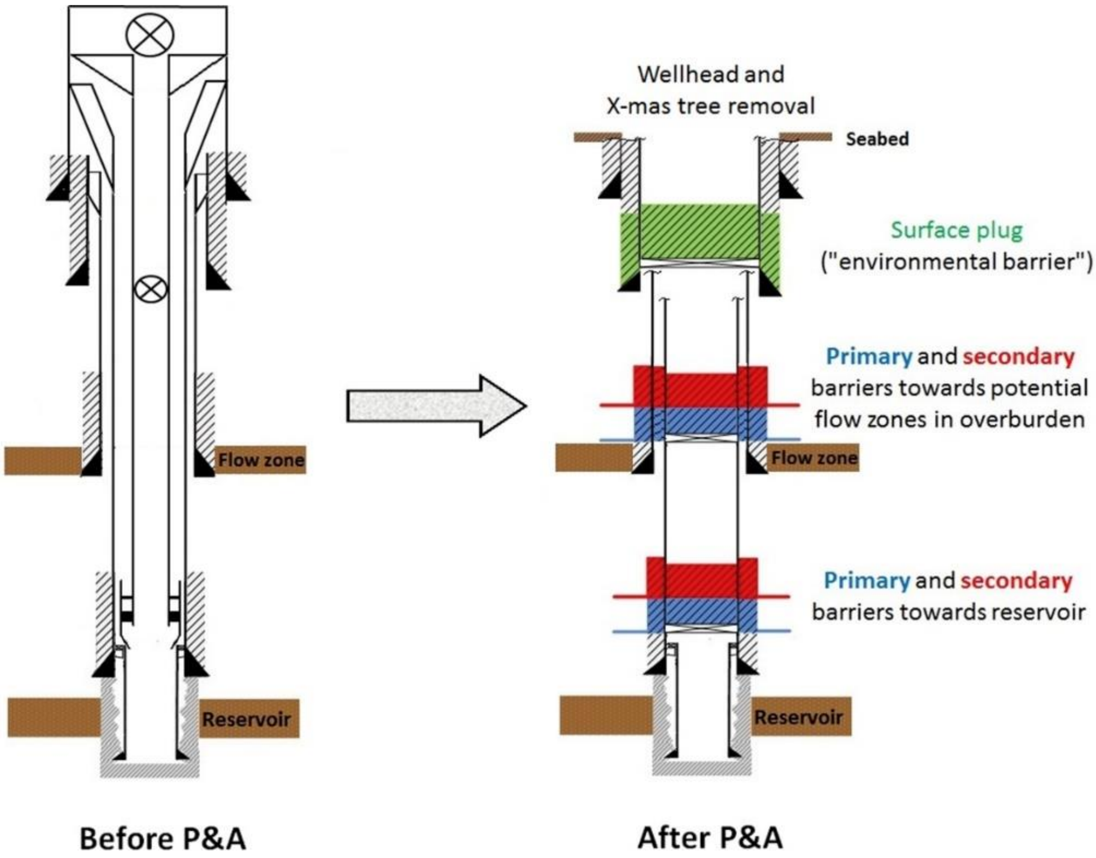


Figure 31. Well P&A (NORSOK Standard D-010, 2004).

According to plugging steps, if a blowout occurs, it must be that the cement plug fails when the lowest layer of the cement plug is arranged, and the blowout preventer (BOP) fails simultaneously. Because if the cement plug in the lowest layer is appropriately placed, no matter how poor the quality of the cement plugs in other layers is and whether the blowout preventer is proper or not, a blowout will not occur. So, one well blowout probability can be calculated as equation (53).

$$P_{bo} = P_{fc1} \cdot P_{fBOP} \tag{53}$$

The assessment method is different from some researchers' who research according to DNV published technique report. The reason is that even three or more cement plugs will be set in a complete well closure process, but if the cement plugs in the reservoir are set in good condition, the leakage rate is meagre do not need to consider a severe accident. These results can be obtained from multiple papers (Babaleye et al., 2019b, 2019a), so it is not practical to assume that numerous cement plugs fail simultaneously to cause blowouts. The occurrence of a blowout only needs to consider the blowout caused by the oil and gas channeling up because the cement plug in the reservoir is not solidified, and the BOP cannot stabilize the pressure. Therefore, it is only necessary to obtain the failure probability of a single cement plug and the failure probability of the BOP. According to Strand et al.'s paper (Strand & Corina, 2019), the failure probability for a cement plug of 30 m is selected as 1.6E-04/cement. According to the paper by Montgomery et al. (Montgomery et al., 2013), the failure probability of BOP can be considered 0.01. After a simple calculation, the probability of a single well blowout during the plugging period is 1.6E-06.

When studying blowouts, however, blowout should not be measured against worst-case scenarios. According to the reported by Thomas et al. (Nilsen et al., 2014), the daily rate of the blowout and the probability of its occurrence are subject to the normal distribution. The possibility of the worst blowout is tiny, but the blowout rate in the median value will be higher, and the blowout duration is 20 to 30 days. Therefore, in the actual calculation, the best method is to use the Monte Carlo method to take multiple sets of values from the distribution results estimated according to well conditions and put them into physical equations for calculation and evaluation.

5.2.2 Fire and Explosion

Generally speaking, the study of whether hydrocarbons can be ignited needs to be judged based on the Upper/Lower Flammable Limit (U/LFL) (J.Hurley, 2015) of the combustibles themselves and the ambient temperature, humidity, etc., as shown in equations (54) and (55) about flammability limits:

$$LFL = {}^{100}\Big/_{\sum_{i=1}^{n} {}^{C_i}/_{L_i}} \tag{54}$$

$$UFL = {}^{100}\Big/_{\sum_{i=1}^{n} {}^{C_i}/_{U_i}} \tag{55}$$

Where C_i is volume percent of fuel gas i in the fuel gas mixture; L_i is the volume percent of fuel gas i at its lower flammability limit in air alone; U_i is the volume percent of fuel gas at its upper flammability limit in air alone.

However, neither the user nor the researcher can better understand the data on-site. Since fires and explosions are caused only by hydrocarbon leaks, it is more efficient to give a statistically derived probability of ignition. According to relevant researches (Rew et al., 1997; Holand, 1997; Dahl et al., 1985), the ignition probability chooses 0.3 for gas and 0.08 for oil. Due to the structural and environmental characteristics of offshore facilities, Fire and explosion accidents can be classified according to the type of hydrocarbons, the location of the leak, the duration of the leak and the ignition event, shown in Figure 32 and Table 38.

Table 38. Fire & explosion category.

Ignition time	$X_iY_iZ_i$	$X_1Y_1Z_1$	$X_1Y_1Z_2$	$X_1Y_2Z_1$	$X_1Y_2Z_2$	$X_2Y_1Z_1$	$X_2Y_1Z_2$	$X_2Y_2Z_1$	$X_2Y_2Z_2$
Immediately ignition	Fire type	Flash	Jet	Pool	Jet Pool	No	No	Pool	Pool
Delay ignition		Flash	Flash Jet	Pool Fire ball	Jet VCE Pool	No	No	Pool	Pool

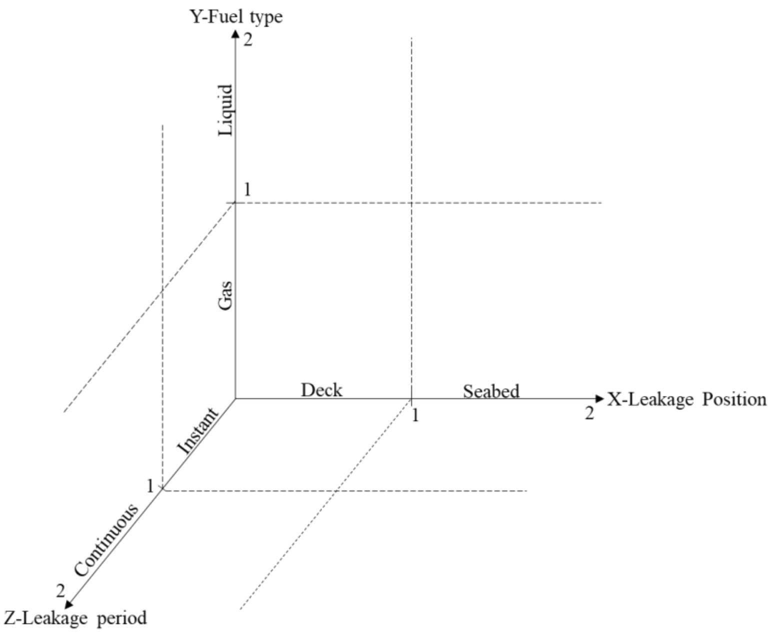


Figure 32. Fire Categories.

Some explanation for the Figure 32 and Table 38:

- Flash fire is a short time (usually less than 1s) that burns rapidly when the combustible gas cloud drifts to the fire source and does not produce an explosive overpressure wave. Only the personnel immersed in the flame need to be considered injured, and there is no need to worry about damage to the structure and not consider thermal radiation damage.
- Jet fire is a form of fire when a flammable liquid or gas leaking from a pipe, flange, valve or tank is ignited. The flames are long and fast and can cause severe damage to the target.

- Pool fires are fires caused by flammable liquids that collect on a flat surface or water surface and ignite. Usually, the flame height is two times the diameter of the liquid pool, and the wind will tilt to form a flame drag.
- Boiling Liquid Expanding Vapor Explosion (BLEVE) refers to the rupture of a pressure vessel resulting in rapid decompression and boiling of a liquid, often accompanied by a fireball. In the case of BLEVE, a large amount of flammable vapour is discharged into the atmosphere, and after being ignited, the vapor burns rapidly and becomes a burning ball floating in the air. The heat radiation intensity of the flaming ball is high, causing damage to the surrounding facilities and personnel.
- Vapor Cloud Explosion (VCE) is an outdoor vapor cloud explosion with strong pressure waves. Usually caused by liquid fuel vapor ignited.

Although fire and explosion have different forms, there is a consistent approach to assessing the heat flux of a fire to a target. HADES adopts the point source model method, and the heat flux evaluation formula of fire is shown in equations (56) to (61) (J.Hurley, 2015):

$$\dot{Q}_R = \chi_r \cdot \dot{m}' \cdot \Delta H_C \tag{56}$$

$$\dot{q}_r'' = \dot{Q}_R / 4\pi r^2 \tag{57}$$

$$\dot{q}_c'' = \chi_c (T_f - T_a) \tag{58}$$

$$Q_{ob} = \varepsilon \cdot \dot{q}'' \cdot A \cdot t \tag{59}$$

$$c = Q_{ob} / m(\Delta T) \tag{60}$$

$$PV = nR(\Delta T) \tag{61}$$

Where $\dot{Q}_R$ is the total heat generated for radiative; χ_r is the radiative fraction of combustion energy; $\dot{m}'$ is the mass burning rate of fuel; ΔH_C is the heat of combustion of fuel; $\dot{q}_r''$ is the heat flux to target; r is the distance from point source; $\dot{q}_c''$ is the convective fraction of combustion energy; T_f is the flame temperature of fire; T_a is the ambient temperature of ambient; Q_{ob} is the energy absorbed by target; ε is the emissivity of environment; $\dot{q}''$ is the heat flux, decided by target location; A is the target exposed area; t is the exposure time; c is the specific heat capacity of target; m is the mass of the target; P is the pressure of gas; V is the volume of tank; n is the amount of substance of gas; R is the universal gas constant showed before; ΔT is the temperature change.

5.2.3 Ship Collision

Ship and platform collisions are a type of accident unique to the offshore industry. Such accidents cannot be avoided entirely at any stage of the platform's life. However, the methods for assessing such accidents will not change too much at any stage.

The ship collision accident of offshore decommissioning is divided into two or three cases by different scholars (Zhang et al., 2019; Čorić et al., 2021):

- Direct collision in navigation state
- Avoid Collision in Navigation State
- Collision while drifting

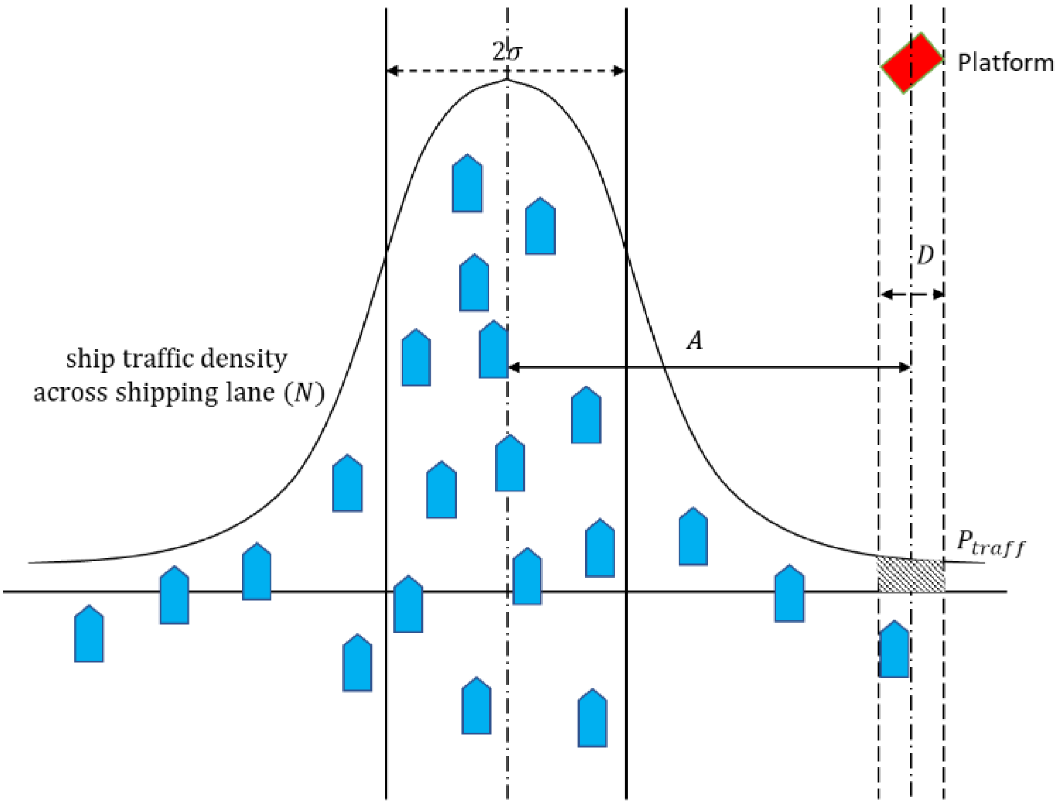


Figure 33. Lateral distribution of ship traffic across a shipping lane.

Mujeeb Ahmed (Mujeeb-Ahmed et al., 2018) provides an excellent method to combine the first two types of collisions into the collision in the navigation state. Based on this, this section offers a new idea for evaluating the collision probability in the drift state. The ship under navigation usually does not follow the lane strictly but parallelly, as shown in Figure 33 (Hughes & McNatt, 1993). The geometric diagram of the calculation is shown in Figure 34. Equations (62) to (68) show how to calculate the collision frequency between the navigation ship and the platform, and Table 39 shows the relationship between orientation angle and P_{dev}.

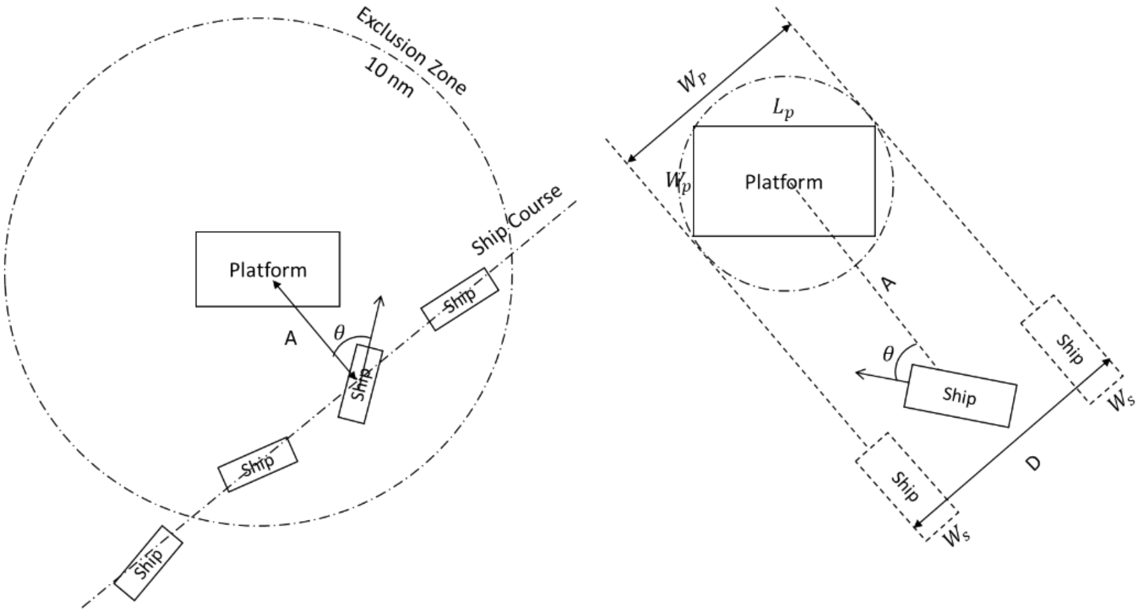


Figure 34. Collision geometry diagram.

$$F_{CCP} = N \times F_d \times P_1 \times P_2 \times P_3 \times P_4 \times M_1 \times M_2 \quad (62)$$

$$D = W_P + W_s \quad (63)$$

$$W_P = {}^{2}\!/_{\pi} \, (L_p + W_p) \quad (64)$$

$$F_d = P_{traff} \cdot P_{dev} \quad (65)$$

$$P_{traff} = D \times f(A) \quad (66)$$

$$f(A) = {}^{exp\left(-k^2/2\right)}\!\Big/_{\sqrt{2\pi}\sigma} \quad (67)$$

$$k = {}^{A}\!/_{\sigma} \quad (68)$$

Table 39. The value of P_{dev}.

Orientation angle θ	-30	-20	-10	0	10	20	30
P_{dev}	0.05	0. 1	0. 2	0.3	0.2	0.1	0.05

Where F_{CCP} is the frequency of the navigational vessel collision with the platform; N is the number of passing vessels; F_d is the probability of a ship being in collision mode; P_1 is the probability of failure of pre-voyage planning; P_2 is the probability of failure of vessel-initiated recovery; P_3 is the probability of failure of platform-initiated recovery; P_4 is the probability of failure to fix navigational error; M_1 is the enhanced collision alarming technologies failure rate=0.13; M_2 is the platform rotate device failure rate=0.28; D is the diameter of collision; W_P is the equivalent width of the platform; W_s is the width of the ship; L_p is the length of the platform; W_p is the width of the platform; F_d is the probability of a ship being in collision mode;

P_{traff} is the proportion of the vessels that are in the shipping lane directed towards the platform; P_{dev} is the probability of course deviation; $f(A)$ means the probability density at the centre of the platform; A is the distance between the centre of lane and platform; Table 39 illustrates the value of P_{dev} with different orientation angle of ship.

There are two types of drifting with and without mooring for the drifting collision. The first category refers to the ship's drift within the mooring system. The second category refers to the free movement of the vessels without mooring. Equations (69) to (78) explain calculating the collision frequency of drifting ships and platforms.

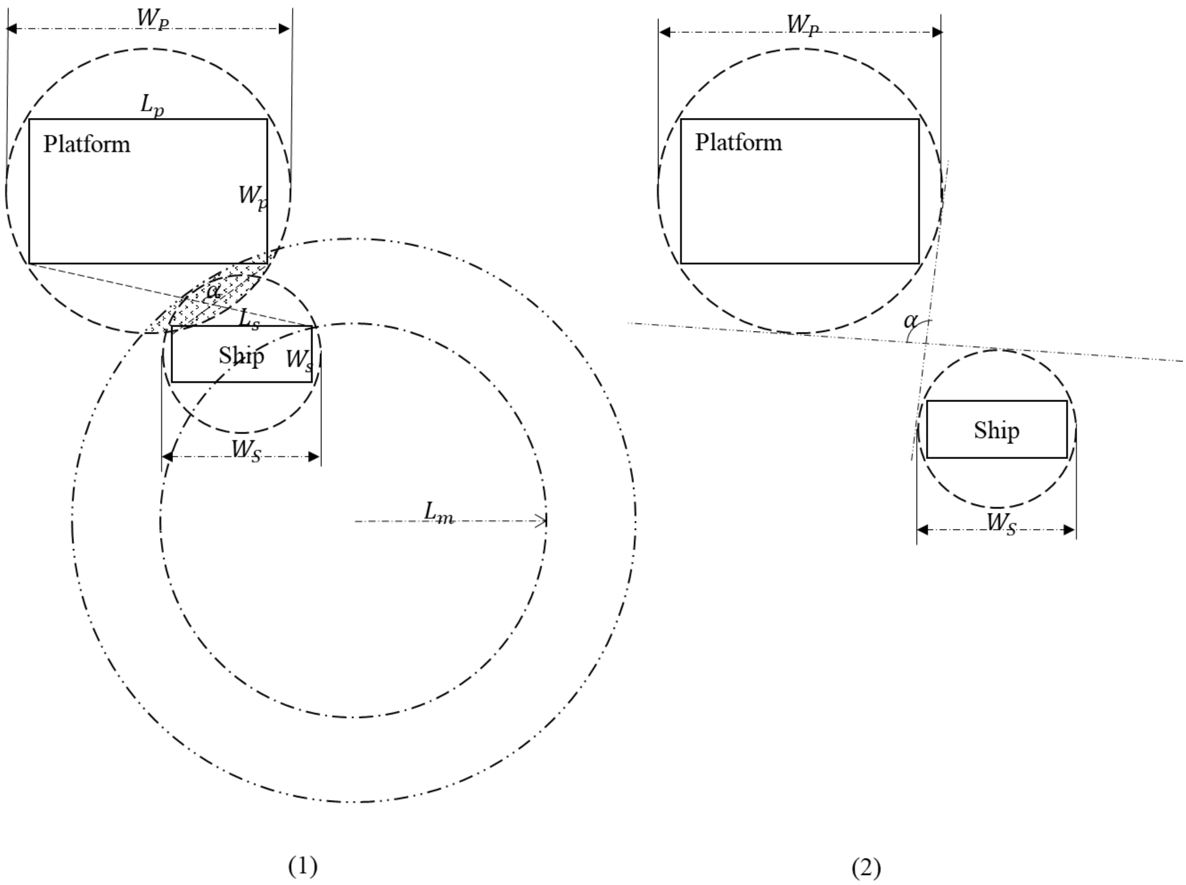


Figure 35. Ship and Platform Collision Geometry Schematic.

$$F_{CPD} = N_s P_\alpha \int_{\theta'=0}^{360} P_{w\&c}(\theta') \cdot [\, P_{tech\,erro} P_{drift} + (1 - P_{mf}) P_{cm} + P_{mf}] \tag{69}$$

$$P_{drift} = EXP\left(-\sqrt{A/0.605 v_{drift}}\right) \tag{70}$$

$$P_{cm} = (A + B - C) \Big/ \pi (L_m + W_S/2)^2 \tag{71}$$

$$A' = \left(W_P/2\right)^2 arccos\left(\frac{A^2 + \left(W_P/2\right)^2 - (L_m + W_S/2)^2}{A W_P}\right) \tag{72}$$

$$B' = (L_m + {}^{W_S}/_2)^2 arccos\left(\frac{A^2 - ({}^{W_P}/_2)^2 + (L_m + {}^{W_S}/_2)^2}{2AL_m}\right) \tag{73}$$

$$C' = \sqrt{[A + R_1 - (L_m + R_2)][A - R_1 + (L_m + R_2)][-A + R_1 + (L_m + R_2)]\,[A + R_1 + (L_m + R_2)]}\Big/_2 \tag{74}$$

$$R_1 = {}^{W_P}/_2 \tag{75}$$

$$R_2 = {}^{W_S}/_2 \tag{76}$$

$$P_\alpha = {}^{arctan\left(W_P + {}^{W_S}/_{2A}\right)}\Big/_{180^\circ} \tag{77}$$

$$P_{tech\,erro} = 1 - \exp\,(-P_f\,{}^{A}/_{v_0}) \tag{78}$$

Where F_{CPD} is the floating vessel collision frequency; N_s is the standby ship number; $P_{w\&c}(\theta')$ is the probability of the direction of action of wind and current on the resultant force on the ship; $P_{tech\,erro}$ is the probability of navigational ship loss navigating function; P_{drift} is the probability of ship recovery failed; P_{mf} is the probability of mooring failure; P_{cm} is the shadow area ratio in Figure 35 (1), the movable range area of the ship in the moored state, and is the probability of collision between the vessel and the platform; P_α is the geometric angle between the ship and the platform in the first case; v_{drift} is the speed of ship drift, normally $v_{drift} = 0.5m/s$; L_m is the length of the mooring system; W_S is the equivalent width of the ship, $W_S = {}^{2(L_s + W_s)}/_{\pi}$; L_s is the length of the ship; W_s is the width of the ship; P_f is the probability of simultaneous failure of the power system and rudder, ordinarily equal to 1.5×10^{-5}; $v_0 = 2m/s$ is the service speed of the ship.

5.2.4 Dropped Objects

Object falling accidents are one of the industry’s most common accidents, and their accident research methods are relatively mature(Ali & Sachin, 2020; Colwill & Ahilan, 1992). For the decommissioning project of offshore facilities, the scenarios of object falling accidents are mainly divided into two categories:

- The suspended object falls. It mainly considers the failure of the crane and hoisting rigging to cause the object to fall during the hoisting process or in the hoisting state.

- The object in the placed state slides. Objects on the facility are subject to external forces in a fixed or non-fixed state and break free to slide and collide with other personnel, structures or equipment.

However, regardless of the scenario, the probability and frequency calculation method of falling or loose objects colliding with equipment, personnel, and structures are the same. The difference lies in the failure probability of the limiting mechanism. The frequency at which the falling object hits the target can be calculated by equations (79) to (81):

$$F_{drop-j} = P_{lfj} * N_{lift-j} \tag{79}$$

$$F_{hit-i} = \sum P_{hit-ij} F_{drop-j} \tag{80}$$

$$P_{hit-ij} = {}^{N_i}/_{A_{deck}} \cdot A_j \tag{81}$$

Where F_{drop-j} is the object j drop frequency; P_{lfj} is the probability of item j lifting failure; N_{lift-j} is the number of item j lifting times; F_{hit-i} is the frequency of fallen objects hit target i; P_{hit-ij} is the probability of target i been hit by j; N_i is the number of target item; A_{deck} is the total area of the deck; A_j is the projection area of target objects.

For the hoisting scenario, the probability P of sling failure is suitable to use statistics. Detailed calculations of its failure mechanisms and failure scenarios can follow any reliable industrial or academic method. However, the difference is that the sliding of fixed or unfixed objects (without considering the failure of the fixed structure due to overage or corrosion) must rely on external forces, so it can only be regarded as a domino event. Therefore, the probability of the impact needs to be calculated according to the target's location, the force magnitude, the friction, the distance and the number of objects in the direction of the force, etc. However, whether such an event will occur, it is necessary to compare the non-vertical external force received by the facility with the static friction force of the object and the shear strength of the fixing device to determine whether sliding and damage to the fixing device will occur.

5.3 Consequence Estimation Methods

Following the content of the Section 5.2, this chapter will show the calculation methods of the physical consequences of the four major hazards. These evaluation methods can be partially used but selectively according to the accident scenario. The physical effects of accidents in HADES are used to evaluate the damage to equipment, structures and personnel and to compare the physical endurance limits of related targets in TCD to judge whether DEAs will happen.

This section will show how to apply physics effects to blowouts, cylinder and hose leaks, fires and explosions, ship collisions, and falling objects.

5.3.1 Blowout

After knowing the probability of a blowout, evaluating the blowout volume is the next focus. According to the Bernoulli's equation, liquid and gas leakage equations can be roughly evaluated according to equations (82) and (83), which include both blowout and storage device leakage:

$$\dot{m}_l = C_D A \rho_l \sqrt{2P_0 - {}^{P_a}/_{\rho_l}} \text{ for oil spill} \tag{82}$$

$$\dot{m}_g = C_D A P_0 \sqrt{M\gamma \left({}^{2}/_{\gamma + 1}\right)^{{}^{\gamma+1}/_{\gamma-1}} \Big/ RT_0} \text{ for gas leakage} \tag{83}$$

Where $\dot{m}_l$ and $\dot{m}_g$ means the leakage rate of liquid and gas in kg/s; C_D is the discharge coefficient equal to 0.62; A is the leakage area; P_0 is the initial pressure in the reservoir or tank; P_a is the ambient pressure; ρ_l is the density of liquid; M is the molecular weight of gas; γ is the ratio of specific heats; R is the universal gas constant equal to $8.314 kJ/mol \cdot K$; T_0 is the initial temperature of gas in Kelvins. The above two equations apply to reservoirs, gas cylinders, or hose leakage.

When a blowout occurs, different oil leakage areas will cause other pollution areas and hidden dangers. Suppose the oil leakage area is on the platform. In that case, it is considered that the oil will not spread to a large extent due to the limitation of the platform structure (although it may overflow due to excessive oil leakage). The maximum oil leakage area at this moment is the main deck area of the platform. If the oil spill occurs on the seabed, equation (84) (Fannelop & Sjoen, 1980; Loes & Fannelop, 1989) can estimate the maximum oil pollution area formed by crude oil on the sea surface. Where D is the diameter of oil on the water surface; z is the water depth.

$$D = 0.22z \tag{84}$$

5.3.2 Cylinder and Hose Leakage

Unlike well-blowout accidents, hydrocarbon leakage from gas cylinders and hoses is only considered a type of DEAs in this system, so there is a need to build a criteria database for the cylinder rack, gas cylinder and hose. The cylinders are not lifted or placed singly in decommissioning process; instead, they are always stored and set as a group in a rack as a gas supply station for safety and efficiency, so the limitation criteria for the frame are essential. The targets criteria database for rack, cylinder and hose is shown in Table 40, which includes the pressure limit, temperature limit, mechanical energy limit, and physical value of the gas pressure limit (combine the same physical categories by choosing smaller values). This database is intended to be compared with the physical consequences of other accidents, such as fire heat, explosion overpressure, explosion fragments' mechanical energy, and falling objects, to determine whether the accident's severity can lead to cylinders or hose rupture.

Table 40. TCD for the rack, cylinder and hose (SUPAGAS 2018; "SPECIFICATION FOR STEEL CYLINDERS," n.d.; ALFAGOMMA Group, n.d.).

	Pressure (MPa)	Force (MN)	Energy (kJ)	Temperature (°C)
Rack	\	\	4240	500
Cylinder	136	0.0235	6970	100
Hose	6	\	6970	100

Compare the consequences of other accidents with the targets' limits in Table 40. If they meet the severity requirement, it is considered that hydrocarbon release can occur. The accident occurrence probability is determined by the proportion of the target object and the previous layer's accident area. The consequences of the cylinder and the hose are different as follows:

- For accident consequences, the hose is considered wholly damaged in the accident. The leak size is the hose's cross-sectional area.
- When gas cylinders suffer heat, the internal gas's overpressure leads to the tank's rupture, which will be much earlier than the failure of the material of the tank, and the leakage size is based on the maximum leakage size.
- When a falling object hits cylinders, the rack will protect the cylinders and impact with falling objects firstly. The cylinder will be beaten until the rack fails. Moreover, because falling objects' sizes are generally large, it is difficult to estimate the angle and shape at the time of the collision, so the leakage size is based on the maximum leakage size.
- However, suppose the explosive fragments beat the cylinders or hose and the kinetic energy of fragments over the targets' limits. In that case, the leakage size is regarded as the same as the average size of the fragments.

The maximum leak size of the cylinders is calculated using equation (85) (Vinnem, 2014):

$$A_{lmax} = 0.24Dt \quad (85)$$

Where A_{lmax} is the maximal leakage area; D is the diameter of the cylinder; t is the wall thickness of the cylinder.

5.3.3 Flash Fire

A flash fire is created by a cloud of flammable gas or vapour due to delayed ignition. A rapid combustion reaction characterizes it, and the wind may blow the gas or vapor group to the leak source for a certain distance before igniting. The instantaneous temperature can reach 1500 °C, but due to the short time (less than 1s), it cannot cause damage to the structure of the facility, and do not need to consider heat radiative to distance objects, but it may burn people in the air mass due to high flame temperature.

The damage caused by a flash fire mainly depends on its burning duration. Equations (86) to (93) are given by Eisenberg (Norman A. Eisenberg et al., 1975) can be used to calculate the effective duration of the flash fire in seconds:

$$t_{eff} = 3t_{1/2} \quad (86)$$

$$t_{1/2} = \frac{1}{25T_a^3}\left[tan^{-1}\left(\frac{\beta+1}{2}\right) - tan^{-1}\beta - \frac{1}{2}ln\left(\frac{\beta+1}{\beta+3}\right)\right] \quad (87)$$

$$\beta = {T_{gi}}/{T_a} \quad (88)$$

$$k = {A_r\sigma}/{\rho V_r} \quad (89)$$

$$V_r = \frac{2\pi}{3}\sigma_x\sigma_y\sigma_z(r_l^3 - r_u^3) \quad (90)$$

$$A_r = \frac{2\pi}{3}\left(\sigma_x^2 + \sigma_y^2 + \sigma_z^2\right)(r_l^2 + r_u^2) \quad (91)$$

$$r_l = \left[2ln\left(\frac{2m}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z k_l}\right)\right]^{1/2} \quad (92)$$

$$r_u = \left[2ln\left(\frac{2m}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z k_u}\right)\right]^{1/2} \quad (93)$$

Where t_{eff} is the effective duration of flash fire; $t_{1/2}$ is the half-life time of flash fire; T_{gi} is the initial temperature of the hot gases; T_a is the ambient temperature; A_r is the flame surface area; V_r is the flame volume; $\sigma = 5.67 \times 10^{-12}\ kW/m^2K^4$ is the Stefan Bolzmann's constant; $\sigma_x, \sigma_y, \sigma_z$ are dispersion coefficient in the downwind, crosswind and vertical direction, respectively; r_l and r_u are parameters of gas cloud at lower and upper explosion limit; m is the total mass of gas or vapour released; k_l and k_u are the concentration at lower and upper explosion limit.

5.3.4 Jet Fire

The properties of jet fire and the calculation methods of its heat radiation and heat conduction have been given above, so this section introduces the details of the evaluation of the geometric parameters of jet fire flame. In windy conditions, using the Kalghatgi method (Kalghatgi, 1983), the flame set graph is shown in Figure 36. Equations (94) to (102) show how to obtain these flame size values:

$$\alpha_B = 94 - {}^{1.6u_e}/_{u_w} - {}^{35u_w}/_{u_e} \tag{94}$$

$$\alpha = 94 - {}^{1.1u_e}/_{u_w} - {}^{30u_w}/_{u_e} \tag{95}$$

$$D_s = D_e\sqrt{P_a M_f \left({}^{P_v}/_{P_a}\right)^{\gamma-1/\gamma} \Big/ \rho_0 R T_v} \tag{96}$$

$${}^{W_1}/_{D_s} = 49 - {}^{0.22u_e}/_{u_w} - {}^{380u_w}/_{u_e} + 950\left({}^{u_w}/_{u_e}\right)^2 \tag{97}$$

$${}^{W_2}/_{D_s} = 80 - {}^{0.57u_e}/_{u_w} - {}^{570u_w}/_{u_e} + 1470 \tag{98}$$

$${}^{L_{BV}}/_{D_s} = 6 + {}^{2.35u_e}/_{u_w} + {}^{20u_w}/_{u_e} \tag{99}$$

$$L = {}^{L_{BV} sin\alpha_B}/_{sin(90-\alpha_B)sin(180-\alpha)} \tag{100}$$

$$s^2 = L^2 + L_B^2 - 2LL_B cos(\alpha - \alpha_B) \tag{101}$$

$$L_B = {}^{L_{BV}}/_{sin(90-\alpha_B)} \tag{102}$$

Where u_e is the exit velocity; u_w is the wind velocity; D_e is the exit diameter; P_a is the ambient pressure; M_f is the molecular weight of gas; T_v is the upstream temperature of gas; ρ_0 is the gas density; L_{BV} is the vertical flame length; s is the lift-off distance.

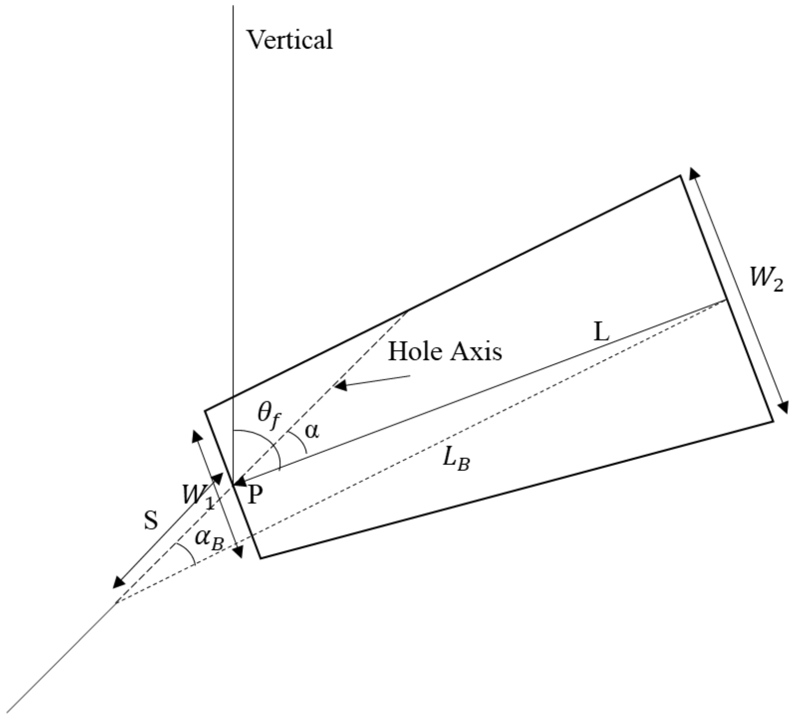


Figure 36. Sketch a jet fire's flame geometry (Chamberlain, 1987).

Through the geometric data of the jet fire calculated above, it can be determined whether the flame engulfs the target object according to the position of the fire to decide which method to use to calculate the heat flux received by the target.

5.3.5 Pool Fire

Pool fires, like jet fires, are common types that can have serious consequences. To calculate the geometric data of the pool fire, divide pool fire accidents into three categories: open air, sea surface, and enclosed area, according to the location of the pool fire. In the case of open air, it is also necessary to consider whether there is a geometrical constraint on the liquid at the leak location, thereby limiting the area of the liquid pool. At the same time, it is also necessary to consider the evaporation rate of the fuel after forming the liquid pool to calculate the volume and concentration of the combustible vapor cloud. However, this paper only gives the evaluation method of leakage on the deck plane. For more details, please refer to the literature (SINTEF, 2003). The following equations (103) to (115) can be used for assessing pool fire geometry and combustion energy (Mudan, 1984).

For instantaneous release:

$$D_t = D_m \left\{ \sqrt{3}t \big/ 2t_m \left[1 + 0.155 \left(t/t_m \right)^2 \right] \right\}^{1/2} \qquad (103)$$

$$D_m = 2\left(\frac{V_L^3 g}{v_f^2}\right)^{1/8} \tag{104}$$

$$t_m = 0.6743\left(\frac{V_L}{g v_f^2}\right)^{1/4} \tag{105}$$

$$D_a \approx 0.683 D_m \tag{106}$$

For continuous release:

$$D_{eq} = 2\left(\frac{v_L}{\pi v_f}\right)^{1/2} \tag{107}$$

$$t_{eq} = \frac{0.564 D_{eq}}{\left(g v_f D_{eq}\right)^{1/3}} \tag{108}$$

$$v_f = \frac{0.076 \Delta H_c [1 - exp(-0.67D)]}{\Delta H_v + c_p(T_b - T_a)} \tag{109}$$

$$m_f^{''} = \rho_l v_f \tag{110}$$

$$Q = \eta m_f^{''} A_p \Delta H_c \tag{111}$$

$$L = 42D\left(\frac{m_f^{''}}{\rho_a \sqrt{gD}}\right)^{0.61} \tag{112}$$

$$u^* = \frac{u_w}{\left(\frac{g m_f^{''} D}{\rho_v}\right)^{1/3}} \tag{113}$$

$$\rho_v \approx 12.18\, \frac{M_w}{T_b} \tag{114}$$

$$cos\alpha \begin{cases} 1 & for\ u^* \le 1 \\ 1/\sqrt{u^*} & for\ u^* \ge 1 \end{cases} \tag{115}$$

Where D_t is the pool diameter at time *t*; D_m is the maximum diameter; t_m is the time to reach the maximum diameter; V_L is the total volume of spilled liquid; g is the gravity acceleration; v_f is the fuel burning rate; D_{eq} is the equilibrium diameter; t_{eq} is the time to reach the equilibrium diameter; v_L is the leak rate of the liquid fuel; ΔH_c is the heat of combustion; ΔH_v is the heat of vaporization; c_p is the specific heat; T_b is the boiling temperature; T_a is the initial temperature of liquid; $m_f^{''}$ is the burning rate per unit pool area; ρ_l is the fuel density; Q is the heat release rate of pool fire; η is the combustion efficiency; A_p is the pool area; L is the flame height; ρ_a is the ambient air density; $D = D_{eq}\ or\ D_a$; ρ_v is the fuel vapor density at normal boiling point; M_w is the fuel's molecular weight.

According to the above formula, the pool fire in the open air and sea environment can be calculated, and the influence of the pool fire on the target can be evaluated by combining equations (55) to (60).

5.3.6 VCE, BLEVE and Fire Ball

VCE and BLEVE represent the explosion of fuel in an open environment and the explosion of overpressure of an encapsulated pressurized liquid (not necessarily flammable) due to elevated temperature. The Fireball occurs after the leakage of flammable fuel and with a high probability. Equations (116) to (120) introduce the TNT equivalent method for calculating the VCE and BLEVE blast pressure. Furthermore, equations (121) to (123) present the calculation method of the Fireball's geometric value and peak heat flux for the objects with a distance R from the center of the ball (Van Den Berg et al., 1993; Rashid et al., 2018):

$$E_{b-f} = \alpha \Delta H_C m_{fv} \tag{116}$$

$$E_{b-nf} = m_v(u_r - u_a) = {(P_t - P_a)V_t} \big/ {[E_{m-TNT}(\gamma - 1)]} \tag{117}$$

$$M_{eq-TNT} = {E_b} \big/ {E_{m-TNT}} \tag{118}$$

$$R' = {R} \big/ {\sqrt[3]{M_{eq-TNT}}} \tag{119}$$

$$P_o = {1616 P_a \left[1 + \left({R'}/{4.5}\right)^2\right]} \Bigg/ {\sqrt{1 + \left({R'}/{0.048}\right)^2} \sqrt{1 + \left({R'}/{0.32}\right)^2} \sqrt{1 + \left({R'}/{1.35}\right)^2}} \tag{120}$$

$$D_{max} = 5.25 m_{fv}^{1/3} \tag{121}$$

$$Z_p = 12.73 V_v^{1/3} \tag{122}$$

$$\dot{q}''_{max} = {828 m_{fv}^{0.771}} \big/ {R^2} \tag{123}$$

Where E_{b-f} means the blast energy of fuel; $\alpha = 0.5$ is the fraction of available combustion; m_{fv} is the mass of flammable vapor; E_{b-nf} is the blast wave energy of un-flammable liquid; m_v is the mass of liquid in tank; u_r is the internal energy of liquid at rupture; u_a is the internal energy of vapor after expansion; V_t is the volume of tank; $E_{m-TNT} = 4200 kJ/kg$ means TNT energy per kilogram; P_o is the blast peak pressure; D_{max} is the maximum of fire ball; m_{fv} is the mass of fuel vapour; Z_p is the rise of center of Fireball above tank; V_v is the fuel vapor volume; $\dot{q}''_{max}$ is the peak thermal radiation from Fireball; R is the distance of center to target.

5.3.7 Ship Collision

There are several ways to assess the consequences of a collision between a vessel and a platform. The method provided by DNV (Amdahl & Yu, 2021) is straightforward for a fast evaluation and Zhang's method (Zhang et al., 2015) would be suitable for obtaining detailed results. The ship collision consequences studied by this system not only need to judge whether the platform is damaged but also need to calculate the impact force on the platform to judge whether the fixing device on the platform will break or whether the unfixed objects will slide, and whether the collision moment on the platform will cause the platform capsized. So, following content will demonstrate two methodologies mentioned above.

Zhang's collision assessment method will be briefly introduced next. And the collision scenario is shown as the Figure 37.

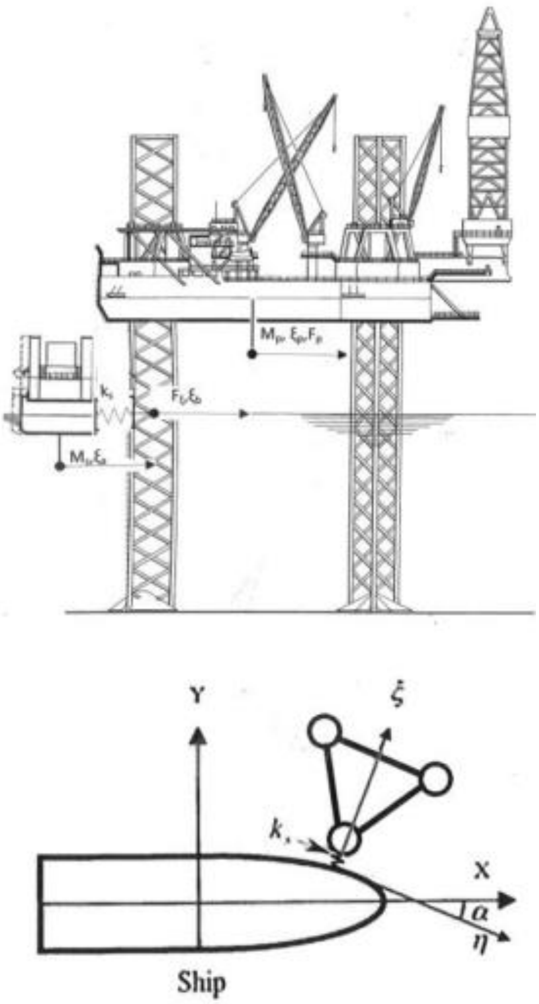


Figure 37. Vessel collision with platform.

$$F_{\xi} = k_{11}\xi_b + k_{12}\xi_p \tag{124}$$

$$F_p = k_{21}\xi_b + k_{22}\xi_p = -M_p\ddot{\xi}_p \tag{125}$$

$$F_\xi = \begin{cases} k_s(\xi_a - \xi_b) & for\ \dot{\xi}_a - \dot{\xi}_b \geq 0 \\ 0 & for\ \dot{\xi}_a - \dot{\xi}_b < 0 \end{cases} \tag{126}$$

Where F_ξ is the collision force between the vessel and the platform; F_p is the transmitted force acting on the generalized topside mass M_p of the jack-up; ξ_b is the displacement of the collision point on a leg; ξ_p is the displacement of the topside; $k_{11}, k_{12}, k_{21}, k_{22}, k_s$ are stiffness coefficients; ξ_a is the displacement of the vessel at the collision point. At the end of collision, $\dot{\xi}_a = \dot{\xi}_b$, assume ξ_p is small, then get equation (127):

$$F_p = {}^{k_{21}}/_{k_{11}} F_\xi \tag{127}$$

The impact impulse between vessel and the platform can be expressed as:

$$I_\xi = {}^{M_a}/_{D_{a\xi}} [\dot{\xi}(0) - \dot{\xi}_a] \tag{128}$$

$$D_{a\xi} = {}^{sin^2\alpha}/_{1 + m_{ax}} + {}^{cos^2\alpha}/_{1 + m_{ay}} + {}^{[y_c sin\alpha - (x_c - x_a)cos\alpha]^2}/_{(1 + j_a){R_a}^2} \tag{129}$$

Where M_a is the mass of the vessel; R_a is the radius of the ship mass inertia around the COG; the coordinate of the COG is $(x_a, 0)$; the coordinate of the impact point is (x_c, y_c); the added mass coefficient m_{ax} is taken as 0.05 for surge motion and 0.5 for sway motion; j_a is the added mass coefficient of moment for rotation around the COG is 0.25.

The impact impulse on the platform is:

$$I_p = -M_p\dot{\xi}_p = {}^{k_{21}}/_{k_{11}} I_\xi \tag{130}$$

At the end of crushing, the velocity of vessel and platform is equal at the collision point:

$$\dot{\xi}_a = -{}^{k_{12}}/_{k_{11}} \dot{\xi}_p \tag{131}$$

The velocity of the topside is:

$$\dot{\xi}_p = {}^{\dot{\xi}(0)}/_{{}^{k_{12}}/_{k_{11}} + {}^{k_{11}}/_{k_{21}} {}^{M_p D_{a\xi}}/_{M_a}} \tag{132}$$

The energy to be absorbed by the vessel and deformation of platform is:

$$E_c = E_0 - E_s - E_p \tag{133}$$

$$E_0 = {}^{M_a\left[(1+m_{ax})sin^2\alpha + (1+m_{ay})cos^2\alpha\right]\dot{\xi}(0)^2}\big/_{2} \tag{134}$$

$$E_p = {}^{M_p\dot{\xi}(0)^2}\Big/_{2\left({}^{k_{12}}/_{k_{11}} + {}^{k_{11}}/_{k_{21}}\ {}^{M_pD_{a\xi}}/_{M_a}\right)^2} \tag{135}$$

$$E_s = E_0 + {}^{M_p\dot{\xi}(0)^2}/_{2}\left[{}^{1}\Big/_{D_{a\xi}\left(1+{}^{k_{12}k_{21}M_a}/_{k_{11}{}^2M_pD_{a\xi}}\right)^2} - {}^{2}\Big/_{D_{a\xi}\left(1+{}^{k_{12}k_{21}M_a}/_{k_{11}{}^2M_pD_{a\xi}}\right)}\right] \tag{136}$$

$$E_{crush} = {}^{k_{11}E_c}/_{k_{11}+k_s} \tag{137}$$

$$E_{platform} = {}^{k_sE_c}/_{k_{11}+k_s} \tag{138}$$

Where E_0 is the initial kinetic energy of vessel; E_s is the kinetic energy of vessel at the end of the collision; E_p is the kinetic energy of the platform topside at the end of the collision; E_c is the energy to be absorbed by the crushing of vessel and deformation of platform; E_{crush} is the energy to be dissipated by the ship and platform structure; $E_{platform}$ is the energy stored in the deformation of the platform.

After obtaining the platform kinetic energy, topside velocity, and impulse after the collision, as long as the vibration frequency of the platform is calculated, the maximum instantaneous acceleration of the object on the platform can be obtained to obtain the inertial force on the object on the platform, as shown below:

$$t_{slow} = {}^{1}/_{4f_{p,n}} = {}^{\sqrt{{}^{k_p}/_{m}}}\Big/_{8\pi} \tag{139}$$

$$k_p = {}^{l_pb_pE_{platform}}/_{h_p} \tag{140}$$

Where t_{slow} is the time taken for the platform to decelerate the speed to 0 after collision; $f_{p,n}$ is the natural frequency of platform; k_p is the platform stiffness; l_p, b_p, h_p is the length, width, and height of platform; $E_{platform}$ is the Young's module of platform. But for a simpler assessment, 2 to 3 seconds can be taken as the shaking duration of topside.

After calculating the time for the topside reach to the highest displacement, it is also necessary to calculate the angular velocity and angular acceleration of the platform after the collision to obtain the moment of inertia of the object on the platform.

$$\omega = \sqrt{{24E_p}/{M_p\left(l_p^2 + b_p^2\right)}} \tag{141}$$

The last thing to calculate is the moment caused by the collision and the resisting moment of the platform itself.

$$M_R = M_{R,seabed} + M_{R,gravity} \tag{142}$$

$$M_{R,seabed} = {\gamma DH^3}/{6} \tag{143}$$

$$M_{R,gravity} = {M_p g A_p}/{2} \tag{144}$$

Where M_R is the resistance torque of platform; $M_{R,seabed}$ is the resistance torque of seabed; $M_{R,gravity}$ is the resistance torque of gravity; γ is the soil bulk density taken $1500\ kg/m^3$; D is the pile diameter; H is the pile penetration depth below seabed; A_p is the footing area diameter of platform. Usually, the collision event between the ship and the platform is set to 0.5s (Consultancy, 2004), so it can be concluded that the force after the platform collided is:

$$M_{collision} = {4E_p H_P}/{\dot{\xi}_p} \tag{145}$$

Zhang's method is complex but detail. However, the value of $k_{11}, k_{12}, k_{21}, k_{22}, k_s$ is essential when using his method. This would be a problem when dealing with an actual case. So, DNV's method maybe more suitable for using when dealing with little raw data.

According to DNV PR C204 (Amdahl & Yu, 2021), the navigating vessel collision speed can be set as 2m/s and drifting speed can be set as 0.5m/s. Still, in NORSOK-003 (Moan et al., 2019), 50MJ would replace the former standard 11MJ and 14MJ, but new standard just for new facilities which is unbuilt yet, so 11MJ AND 14MJ can be set as the standard design collision energy. The kinetic energy of ship is:

$$E_k = {(1 + m_a)M_a {v_0}^2}/{2} \tag{146}$$

Where m_a is the added mass and taken 0.4 for sideways and 0.1 for bow and stern collision; M_a is the mass of vessel; v_0 is the collision speed of vessel taken 2m/s.

So, if the E_k of vessel is lower than 11MJ for stern and bow collision, 14MJ for sideways collision, the facility can be considered as safe. With 0.5s collision duration with navigating state and 1s for drifting collision, and 2s vibration duration, the highest liner and rotate acceleration after collision can be calculated easily.

The above two methods have their characteristics, and the user needs to make a suitable choice according to the data situation. The author believes the evaluation method used in the planning stage need not be too detailed. Regardless of the system's collision risk assessment results, relevant companies and third parties will inevitably conduct more detailed structural safety assessments. Therefore, if it is only used to provide quantitative support for decision-making results in the planning stage, DNV's method is more suitable for the needs.

5.3.8 Objects Impact

Regardless of whether it is a falling object or a sliding object, in the event of an impact accident, the calculation method of the physical effect of the object on the target is similar.

For a falling object, since the falling height is not high and the size of the object is not large, the influence of air resistance on the falling speed of the object can be ignored when the object falls in the air. There are three ways to judge whether the falling objects will break the targets' structure.

- The energy conservation formula of gravitational potential and kinetic energy can be directly used to calculate the object's maximum velocity to calculate the object's momentum before impact. Then set impact duration as 0.5s (Consultancy, 2004) to get the impact force to compare yield strength of target shell or structure.
- Compares the modulus of toughness of targets with the impact energy of the object. In this research, take yield strength as the limit strength of targets. First, estimate the energy conversion after the collision, and judge how much energy acts on the structural deformation of both sides of the collision. It is usually assumed that both colliding parties stop entirely after a collision, and their speed is zero. Then there is equation (147) to judge. Then, using the linear equivalent of stress-strain of nonlinear material can estimate the calculation method of fracture energy. However, if it can be sure that the object will cross the target, equation (148) and (149) would be used to make sure of the energy transformation state in the impact accident.

$$G_c = {m_o gh}/_A \approx \left({\sigma_y + \sigma_u}/_2\right)(1 + eL)t - {\left({\sigma_y + \sigma_u}/_2\right)^2}/_{2E} \tag{147}$$

$$e = 3.1(\sigma_y)^{\frac{5}{8}}\left(1 - {\mu^2}/_E\right)^{\frac{1}{2}}\left({1}/_{\nu}\right)^{\frac{1}{2}}\left({1}/_{\rho}\right)^{\frac{1}{8}} \tag{148}$$

$$E_{defor.} = m_0 gh(1 - e) \tag{149}$$

Where G_c is the crash energy density of target's shell; m_o is the mass of fallen object; g is the acceleration of gravity; h is the initial height of the object; A is the impact area; σ_y is the yield strength of the target material; σ_u is the ultimate strength of the target material; eL is the elongation percentage of the material; t is the thickness of the target's shell; E is the Young's Module of the target's material; e is the coefficient of restitution; μ is the Poisson's ratio; ν is the impact speed; ρ is the density of the target; $E_{defor.}$ is the deformation energy of the target shell.

Due to the difficulty in obtaining detailed data, Consultancy method is temporarily adopted in this study to estimate the possible damage caused by falling objects.

In addition, it is essential to investigate whether fastening devices on the installation fail. According to industry experience, under normal circumstances, the shear stress intensity of bolts can be roughly calculated as 0.6 times the tensile strength of bolts, refer to equation (150):

$$[\tau] = 0.6\sigma_y A_s \tag{150}$$

Where $[\tau]$ is the limit shear strength; σ_y is the yield strength of the bolt's material; A_s is the cross-section area of the bolt. Assume bolts fixed targets to deck directly, when facing accident force like explosion pressure or collision or inertial force, the Figure 38 can be used for demonstrating the scenario. Assume the screw hole wall is rigid and will not being crushed, the equation (150) can be used to estimate the limit force that bolts could take.

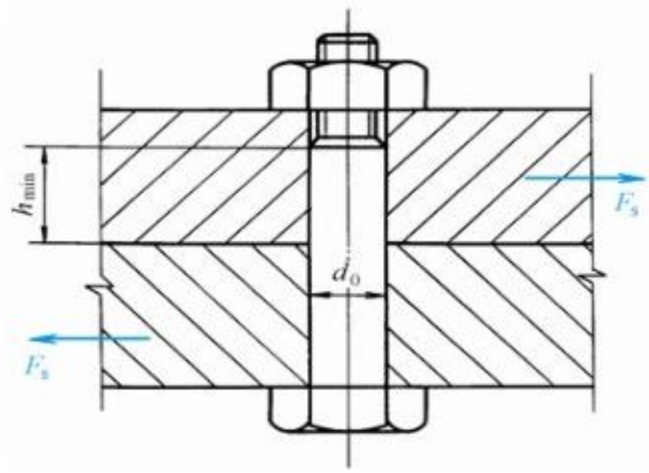


Figure 38. Bolts being shear during accident.

$$[\tau] = {}^{4F_S}\!/_{i\pi {d_0}^2} \quad (151)$$

Where F_S is the shearing force; i is the surface number of bolt being shearing; d_0 is the diameter of bolt. By using the equations above, it would be easy to judge the safety of fixing bolts.

5.4 Targets' Criteria Database (TCD)

The Targets' Criteria Database (TCD) is the core of HADES to realize the dynamic construction of accident scenarios. The content of this part is the limit of each physical quantity that the target of DEAs that may occur on all platforms can bear. The function of this part is to compare the physical effect of the accident to judge whether the severity of the previous level accident is enough to trigger DEAs.

On offshore facilities, the targets that trigger the major hazards mentioned above can be divided into the following categories:

- Jacket. When hit by a ship, whether the jacket structure fails will be directly related to whether the facility capsizes. In addition, when hit by a ship, whether the resistance moment of the facility itself is sufficient to prevent the entire facility from falling. Finally, if the oil slick on the sea surface is ignited, the jacket will not fail due to heat within a certain period. Therefore, it is necessary to set the safe temperature, mechanical energy and resistance moment of the jacket.
- Deck. Falling objects and further damage to the lower equipment layer may penetrate it. It may also rupture due to fire or explosion. Therefore, it is necessary to set the safe temperature of deck energy, mechanical energy, and yield limit.

- Rack. As a protection device for cylinders, it can resist a certain degree of impact but cannot prevent fire and explosion. Therefore, only the possibility of failure after being hit needs to be considered, that is, the limit of mechanical energy and strength.
- Cylinder. It is the target that needs the most attention in the decommissioning project of offshore facilities. It may explode due to excessive pressure due to temperature, or the contents may leak due to impact, resulting in a more severe accident. Therefore, the cylinder not only needs to consider the withstand temperature and mechanical energy of its shell, ultimate strength and so on. It is also necessary to consider whether the cylinder shell will rupture when the internal gas expands under pressure.
- Hose. The hose must be used when performing thermal cutting. Although the exposed area is small, the length is longer, the number is larger, and it is more fragile than other targets. It can be broken by external force and melted by heat, causing the contents to leak.
- Bolts. As a fixed primary device on the facility, the ultimate strength of its shear stress is mainly considered.

The above content is the composition of TCD data in this study. These physical parameters determine whether the object will be damaged in the event of an accident, thus triggering a domino accident. The user can determine the settings of these values to be set entirely following the relevant standards or being more strictly limited. The TCD established in the case study used in this paper is presented in Section 7.3.

Chapter 6. Impact Assessment Methodology

In Chapter 2.5, it has been mentioned how to conduct the engineering impact assessment for the decommissioning of offshore facilities. The primary sources of these effects are twofold:

- Environmental pollution caused by normal engineering process
- Adverse effects caused by engineering accidents, personal injury, and environmental pollution.

A small amount of pollution caused by the normal engineering process is unavoidable and will not affect other users of the sea area, nor will it cause a negative public impact, so it will not be considered in this study. Therefore, this study will mainly evaluate how to conduct an impact assessment if an accident occurs.

To study the impact of an accident and output it in monetary terms, it is necessary first to clarify what negative impacts will occur with the accident:

- Mitigation and/or restoration costs of environmental damage. It is mainly aimed at the cost of cleaning up accident residues when oil spills or other environmental pollutants leak.
- Compensation for other users due to damage to area resources. Oil spill accidents or other pollutant leakages will cause damage to the interests of other area users; for example, it will cause significant damage to fishermen, tourism, etc., and they need to be compensated.
- Social losses are caused by damage to regional resources or environmental pollution. Including but not limited to suffering public boycotts that limit the sales of other products, being fined by the government, falling stock prices, damage to reputation, etc. may be non-economic long-term losses.
- Compensation for accident casualties. If an accident occurs that causes casualties, the company will inevitably compensate the victims, but usually, the compensation is paid by the insurance company.
- Loss of reputation and credibility due to the accident. Major accidents will undoubtedly lead to public distrust of business or government.

Among the above, the direct economic loss is easy to estimate quantitatively. However, the impact on reputation and credibility is complicated to quantify and can only be estimated based on case statistics.

However, whether it is the quantitative assessment of environmental or socioeconomic impact, it is necessary to consider the basic parameters used in the quantitative assessment. According to the views of many scholars, these parameters mainly include (Etkin, 2000, 2004, 2005; Thi & Trang, 2013):

- Volume of pollutants. Mainly refers to the spill amount. Small and large amounts of pollutants are not purely positively correlated with cleanup costs and negative impacts. When the volume of pollutants rises, society's adverse reaction to accident will increase dramatically.
- Type of pollutants. It involves the cleaning method, difficulty and cost, and the degree of social repercussions. Like the volume of pollutants, certain pollutants that are difficult to eliminate harmful effects will cause more serious negative social repercussions.
- Accident location. The location of the accident, whether there is an animal habitat or critical natural resources in the area or adjacent areas, and whether it will affect the coastline and offshore water quality are all great public concern. Therefore, different accident locations need to be treated differently.
- Pollutant cleanup methods. Different cleaning techniques will inevitably lead to different cleaning costs. The public also rejects the by-products of some technologies. For example, flame ignition can clean up large spills, but toxic and harmful combustion products will be released into the atmosphere, causing secondary pollution.

According to the explanation of the critical parameters above, combined with previous related research, the framework of the impact assessment model should be as shown in Figure 39.

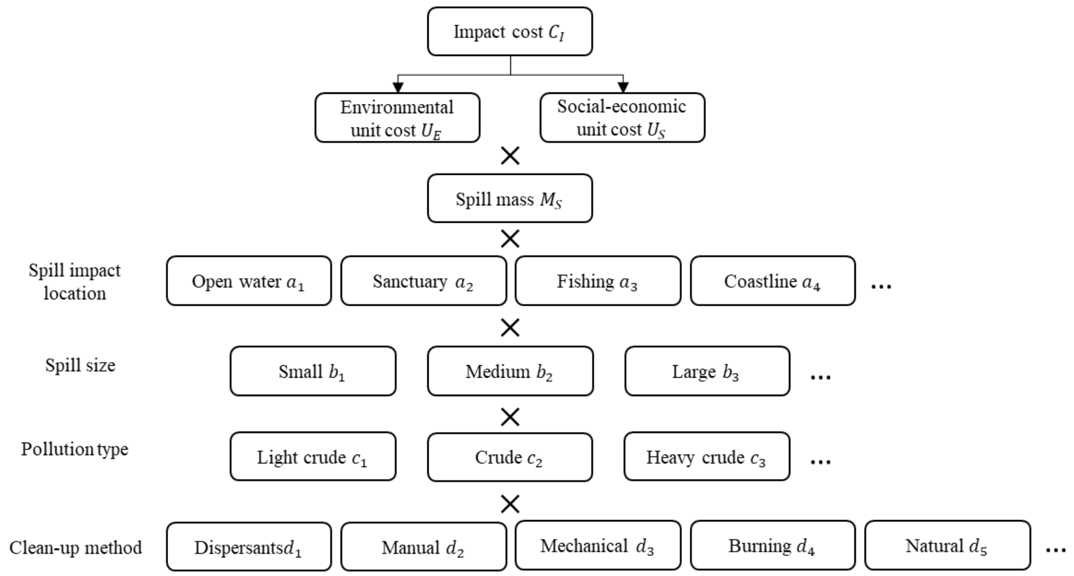


Figure 39. The framework of impact assessment model.

It can be seen from this framework that six types of parameters need to be determined. Namely, the environmental and socioeconomic unit price for unit pollutants, the correction parameters of spill location, spill size, pollutant types and cleaning methods. These parameters are available are shown in Tables 41 to 43 (Etkin, 2000, 2005, 2004). Although the information displayed by these parameters is not based on U.K. data, it is still of a considerable reference value. These parameters need to be revised in future studies using the historical case of the United Kingdom.

Table 41. Environmental and socioeconomic unit cost with spill volume and type.

Spill type	Volume (m^3)	Base cost (£/m^3)	
		Socioeconomic	Environmental
Volatile distillates	<1.89	13855.26	10231.68
	1.89-3.79	56487.4	9592.2
	3.79-37.85	85264	7460.6
	37.85-378.54	38368.8	6394.8
	378.54-3785.41	19184.4	3197.4
	>3785.41	14921.2	2131.6
Light crude	<1.89	17052.8	18118.6
	1.89-3.79	70342.8	17052.8
	3.79-37.85	106580	14921.2
	37.85-378.54	42632	13855.26
	378.54-3785.41	21316	6394.8
	>3785.41	19184.4	5329
Crude	<1.89	10658	19184.4
	1.89-3.79	42632	18544.92
	3.79-37.85	63948	17052.8
	37.85-378.54	29842.4	15560.68
	378.54-3785.41	14921.2	7460.6
	>3785.41	12789.6	6394.8
Heavy crude	<1.89	31974	20250.2
	1.89-3.79	127896	19184.4
	3.79-37.85	191844	18118.6
	37.85-378.54	106580	15987
	378.54-3785.41	42632	8526.4
	>3785.41	37303	7460.6

Table 42. Spill location parameter.

Location	Length (km)	Parameter
Nearshore	\	1.46
Sanctuary		1.7
Fishing		2.2
Open water		0.9
Shoreline	0-1	0.47
	2-15	0.54
	20-90	0.61
	100	1.06
	500	1.53

Table 43. Spill size, clean-up methods parameter.

Spill size (t)	Parameters	Methods	Parameters
<34	2.00	Dispersants	0.46
34-340	0.65	Burning	0.25
340-1700	0.27	Mechanical	0.92
1700-3400	0.15	Manual	1.89
3400-34000	0.005	Natural	0.10
>14000	0.01		

According to the model framework and the data above, the mathematical equations that affects the quantitative evaluation is as follows:

$$C_I = C_E + C_S \tag{152}$$

$$C_E = U_{E,T,V} \cdot V_{Spill} \cdot P_{size} \cdot P_{Location} \cdot P_{Method} \tag{153}$$

$$C_S = U_{S,T,V} \cdot V_{Spill} \cdot P_{size} \cdot P_{Location} \cdot P_{Method} \tag{154}$$

Where C_I is the whole impact cost; C_E is the environmental impact cost; C_S is the socioeconomic impact cost; $U_{E,T,V}$ is the environmental impact unit price with spill type and volume; $U_{S,T,V}$ is the socioeconomic impact unit price with spill type and volume; V_{Spill} is the spill volume; P_{size} is the spill size parameters; $P_{Location}$ is the spill location parameters; P_{Method} is the spill clean method parameters.

The quantitative evaluation system's evaluation method for the environment and socioeconomics has been demonstrated in this study. This method can be considered the best existing method, but the specific parameters still need to be revised according to the British market conditions.

Chapter 7. Cases Study

After the detailed introduction of the methodology above, the next step is to use the above method, combined with the historical data of the offshore decommissioning facilities in the UK North Sea, to conduct case analysis and model verification. The case of study analysis will mainly use the representative North West Hutton oil platform as a specific case, assume three decommissioning options of the platform, and obtain the evaluation results corresponding to each option to verify the function of the decision support system.

This chapter includes the following:

- Introducing specific cases,
- Target Criteria Database settings,
- Presentation of MADM-Q framework and the category of input data,
- The results and comparison of the two framework of cost assessment model,
- The risk assessment results and summaries of each layer of HADES,
- Impact assessment results using input data and risk assessment data,
- Integrate the results obtained and discuss the results,
- Results of the evaluation of three decommissioning options for NWH decommissioning projects are presented.

7.1 Historical Data and Specific Cases Introduction

7.1.1 Decommissioned Programme in the North Sea

A total of 26 engineering reports and data from 34 projects (among them several joint projects) were used in this case-of-study. Each item has about 48 data types. However, due to the discrepancies in the data contained in the reports produced by different decommissioning engineering execution companies, some data are temporarily vacant. For details, see Appendix A.

This data is used for several purposes, including:

- Used to build a top-down framework cost assessment model,
- Put into linear analysis to obtain the engineering duration estimation for ECES,
- Reasonably modify and integrate part of the data to obtain evaluation results under different options.

The following table lists the reports of raw data.

Table 44. Facilities name and data source.

Platform Name	Source
Brent Field	(Shell U.K., 2017; Shell U.K, 2017; Shell U.K. Limited, 2018; Shell U.K., 2015b, 2015a)
Frigg	(Total E&P Norge AS, 2003; Climate and Pollution Agency, 2011; Total E&P Norge AS, 2011)
Horne and Wren	(Tullow Oil SK LTD, 2015a)
Indefatigable	(Shell, 2014; Shell U.K. Limited, 2007)
Leman BH	(Shell U.K. Limited, 2019a, 2019b)
Maureen	(Phillips Petroleum Company UK Limited et al., 2001)
Miller	(Beyond Petroleum, 2011b)
North West Hutton	(Farrow et al., 2009; Kirby et al., 2005; British Petroleum, 2005)
Thames	(Perenco, 2015c; Cooper et al., 2013)
Wellland	(Perenco, 2010)
Camelot CA	(Energy Resource Technology Ltd, 2012)
MCP-01	(Total E&P UK, 2007, 2013)
Schiehallion	(Beyond Petroleum, 2013, 2018)
Shelley	(PremierOil, 2010, 2015)
FFFA	(HESS, 2014)
IVRR	(HESS, 2013a, 2013b)
Orwell	(Tullow Oil SK LTD, 2015b)
Rose wellhead	(Centrica Energy, 2015a; Spirit Energy, 2018a)
Stamford	(Centrica Energy, 2015b; Spirit Energy, 2018b)
Tristan NW	(SilverStone Energy Limited, 2010; Silverstone Energy Limited, 2010)
Wissey	(Tullow Oil SK LTD, 2015c)
Don	(Beyond Petroleum, 2011a)
Kittiwake	(Centrica Energy, 2012)
Linnhe	(Mobil North Sea LLC, 2008; Apache Corporation, 2013)
Arthur	(Perenco, 2015a)
Gawain	(Perenco, 2015b)

7.1.2 North West Hutton Platform

The reason for using North West Hutton as a specific research project is that the decommissioning of this facility is very typical. NWH is a large-scale composite purpose jacket platform, including oil and gas exploration, refining, and personnel living functions. The entire decommissioning project includes superstructure, substructure, subsea wells and platform wells, pipelines, and subsea control units, etc. Various stages of decommissioning can be used for research. In addition, the project report content and additional research reports of this project are detailed, which can be used not only as a reference for engineering evaluation but also as a reference for environmental and social impact assessment.

NWH is a jacket oil platform belonging to Beyond Petroleum located in the UKCS Block 211/27a area. The platform was built in 1983, production ceased in 2002-2003, and was moved entirely ashore for disassembly in 2009. The total weight of the platform is about 37,630 tons, and the topside has 23 modules weighing 20,160 tons. The jacket weighs 17,470 tons, 154m high, has 20 piles with a diameter of 60 “, and penetrates 55-62m into the seabed. Figure 40-42 shows the platform’s overall structure, layout, module, and jacket.

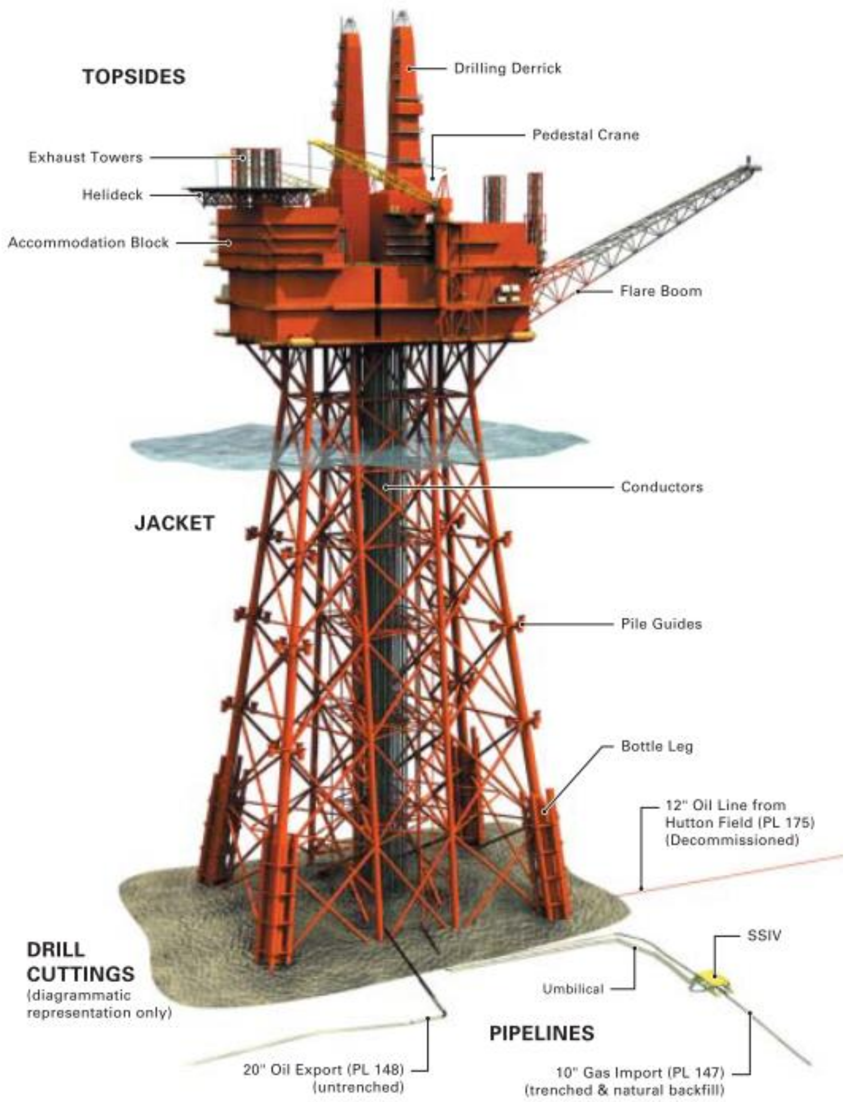


Figure 40. The layout of the North West Hutton platform.

Table 45. North West Hutton modules dimensions and wight.

Module description	Dimensions (meters-lxbxh)	Weight
Power generation module	60*26*9	2660
Utilities module	45*26*9	2000
Wellheads module	45*15*20	1830
Production modules (two)	61*14*20	2540/2780
Mud and drilling utilities modules (two)	25*21*10	1420/1350
Accommodation and recreation module	45*20*16	1860
Helideck	35*30*4	300
Derrick sub-structures (two)	19*22*26	990/1000
Flare boom	85*6*5	*
Drilling derricks (two)	9*8*39	*
Exhaust tower for main compressor turbines	8*4*35	*
Exhaust tower for sales gas compressor turbines	4*2*24	*
Exhaust tower for main generator turbines	14*5*33	17
Bulk storage units (two)	16*5*15	*
Pedestal cranes (two)	8*4*50	*
Intake ducts for main compressor turbines	16*4*5	*
Module support frame	78*22*15	1430

*The weight of this component with associated module shown in the Figure 41

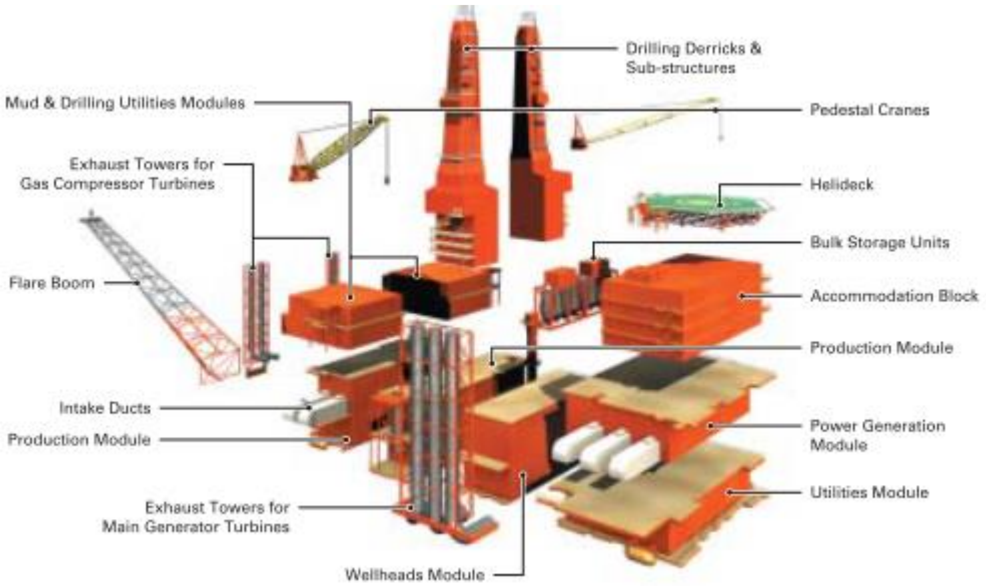


Figure 41. Topside modules of the North West Hutton platform.

The water depth of the facility is 144.3 meters, and the seabed rock and soil state is sand, silt, and very stiff to tough clay. The highest tide is 2.3m, and the nearest land is the Shetland Islands, 130km. The ocean data of other facilities are shown in Table 46.

Table 46. NWH sea state data.

Aspect	Information	
Location	64°06'23.950" N, 01°18'32.974" E	
Seabed surface soil type	Sand, silt, and very stiff to very hard clay	
Water depth	144.3 m LAT	
Maximum tidal range	2.3 m	
Nearest land	The Shetland Islands, 130 km	
Distance to median line	25 km	
Waves	1 year	50 years
Significant wave height	11.6 m	16.1 m
Maximum wave height	21.6 m	29.9 m
Winds (maximum)	1 year	50 years
1 hour mean	25.9 m/s	36.5 m/s
1 minute mean wind speed	NA	42.5 m/s
3 second gust of wind	NA	50.0 m/s
Currents	1 year	50 years
Maximum surface speed	0.73 m/s	0.82 m/s
Maximum seabed speed	0.47 m/s	0.53 m/s
Temperatures	1 year	50 years
Air	-6 °C	+27 °C
Sea surface	0 °C	+18 °C

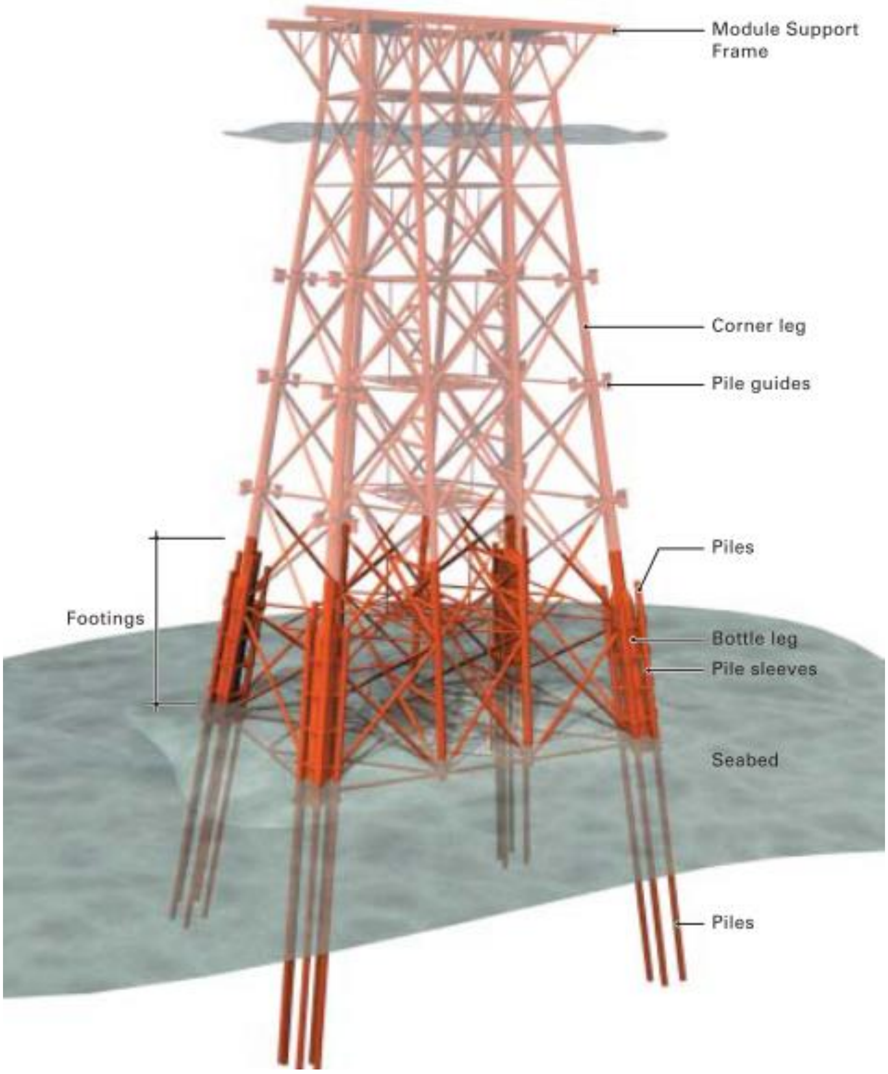


Figure 42. Jacket of the North West Hutton platform.

7.1.3 Inputs for Three Modules

According to the introduction of data sources and exceptional cases mentioned above, it is also necessary to explain the type and purpose of the input data used to verify the model's reliability.

7.1.3.1 Inputs for Cost Assessment

The inputs used for cost assessment are mainly determined according to the cost model used by the system. As mentioned in the methodology, there are two options for this system: the first is the top-down framework, and the other is bottom-up framework. Different models mean different input parameters, need to be discussed separately according to these two frameworks. For the top-down framework methodology, since the framework's core is the regression equation, the independent variables used to construct the regression equation are the parameters that need input. According to the corresponding part of the methodology, this includes:

- For calculating the cost of well p&a, the number of subsea wells and platform wells is required.
- For calculating the cost of removing the facility, the weight of the facility to be removed and the depth of water in which the facility is located.
- Used to calculate the cost of pipeline decommissioning, the depth of water at which the pipeline needs to be removed, and the diameter of the pipeline.
- For calculating the cost of subsea decommissioning, the weight of the subsea needs to be decommissioned.

The above independent variables can all be obtained from the reports of the companies to which the facilities belong and do not involve confidential and difficult-to-measure data.

The model of the bottom-up framework is much more complicated than that of the top-down framework, so the types of independent variables input also increase. According to the relevant content mentioned in the methodology, the bottom-up framework first needs the following inputs to estimate the duration of each construction procedure:

- The number of platform wells and subsea wells is needed to evaluate the duration required for well p&a.
- The weight of the topside is required to evaluate the platform preparation duration.
- The distance from the shore, the position and the weight of the topside are needed to evaluate the topside removal duration and the length of use of the engineering vessel.
- The position and weight of the sub-structure are needed to assess the duration of the sub-structure removal and the duration of the related engineering vessel.
- The weight of the subsea unit is required to estimate the length of time the subsea unit will need to be decommissioned using the engineering vessel.
- Pipeline length is required to estimate the duration.
- The mass of each part of the facility is required to estimate the time needed for onshore dismantling.

Then, it is also necessary to roughly evaluate the number of workers, equipment, engineering ships, and materials used in the project based on the overall scale of the decommissioning project. And the unit price of each piece of equipment, engineering vessel and material.

The above data are based on the attributes of the facility as the essential independent variable. The intermediate value is obtained through the estimation, and the cost evaluation result is obtained through further calculation. Although the method looks more complicated, only a small part is input into the system as the essential independent variables compared with the top-down framework method.

7.1.3.2 Inputs for Risk Assessment

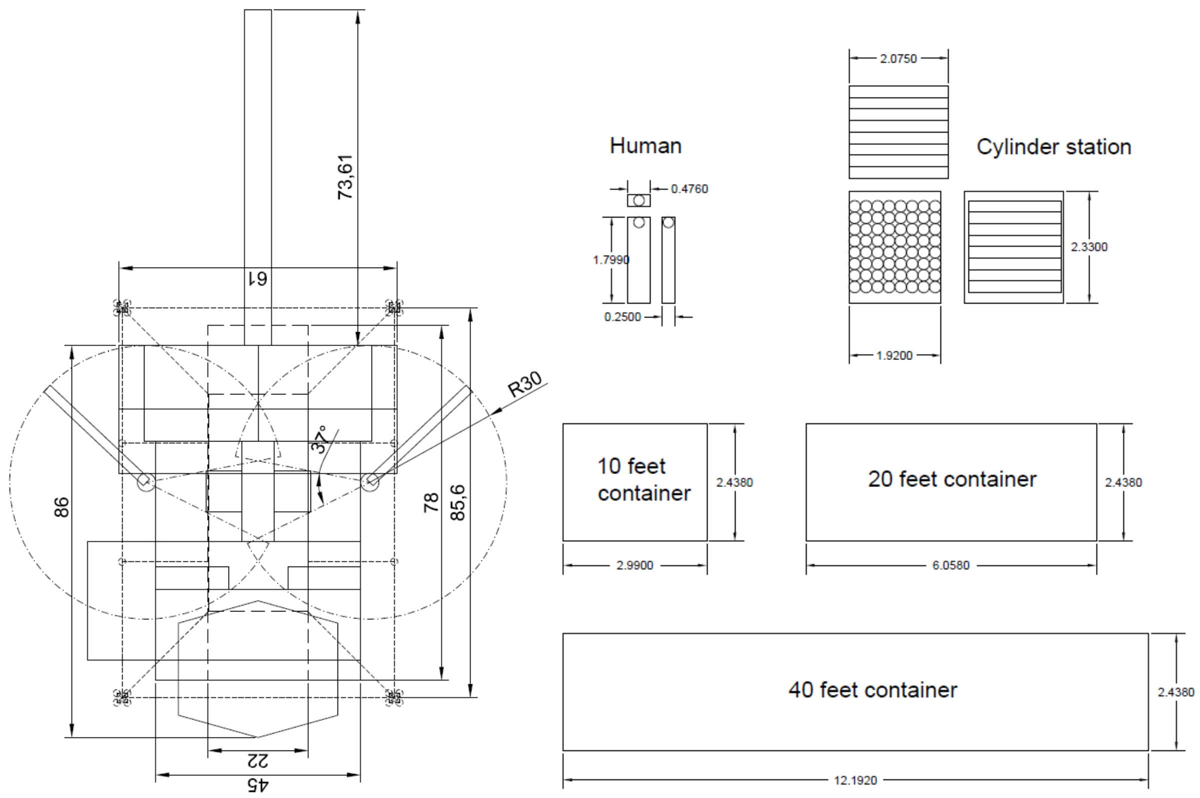
The input values required by HADES are like the type of QRA because HADES itself is an extension of QRA. The case in this study needs to be clarified when evaluating different levels and accidents. As mentioned earlier, eight major hazards facing the decommissioning of offshore facilities, and five hazards in this research was divided into primary and domino layers, detailed input categories can be assigned according to the needs of each hazard.

To evaluate hydrocarbon release accidents, it is necessary to discuss two cases of blowout accidents and equipment leakage. For a blowout accident, the basic parameters of the well and oil and gas reservoir need to be known to calculate the leakage in the worst case of the well blowout. Although a composite normal distribution of blowout volume and probability is available according to Nilsen et al.(Nilsen et al., 2014), this study can only be used during facility operation. For the decommissioning of facilities, there is few relative research about the distribution of spill rate and duration in decommissioning well p&a, so the worst situation shall be used to obtain the worst assessment results, the duration of blowout will be set as 3 days in this research.

In general, in order to obtain the blowout risk assessment results (oil and gas blowout), the necessary input data are:

- Reservoir pressure, reservoir temperature, reservoir vertical depth, reservoir type
- Tubing diameter
- Ambient atmospheric pressure, ambient temperature
- Gas and oil's density, viscosity, specific heat, molecular weight

The input data required for equipment leakage is similar to that needed for the blowout. Still, equipment leakage will only occur as DEAs, so further distributional inputs are necessary when assessing the probability of accident occurrence. As shown in Figure 43, the top view of the NWH platform is used to verify HADES and the projection of the gas cylinder group. These input values aim to obtain the geometric probability of the accident, which is also the source of the advanced probability of DEAs in the HADES system.



(a) (b)

Figure 43. (a) Top view of NWH topside; (b) views of containers, rack and worker.

Fire and explosion accidents were evaluated in HADES as the most critical DEAs. Like the hydrocarbon leakage accident, it needs to be divided into two parts: accident occurrence probability and accident consequence assessment.

The input of the probability part also requires the equipment distribution diagram in Figure 43, combined with the scope of influence of fire and explosion, to calculate the probability of the target being triggered by accident. Combined with the ignition probability used in this study, the probability of fire occurrence can be calculated.

The physical effect assessment method of fire and explosion accidents mainly adopts the fire and explosion assessment method (SINTEF, 2003), which needs to evaluate the scope of accident impact and the intensity of physical effects simultaneously. The range of accident influence refers to the geometric size of the fire and the range of damage to the explosion's shock wave and the fragments' scope. The physical effect intensity refers to the heat flux of the fire and the pressure of the explosion shock wave.

According to the calculation method of SINTEF, the calculation of these values requires inputs such as the amount of hydrocarbon leakage, the physical characteristics of the leakage material, ambient temperature, wind speed, and combustion location. For specific parameters, see the input value section in the Appendix B.

The content of ship collision accident assessment can also be divided into two categories: collision probability/frequency and accident consequence. As mentioned in the methodology for the assessment of vessel collision accidents, the required input values include the following:

- Lane width, number of lanes, lane annual vessel density, and the distance between lanes and facilities.
- Various types of vessels, the number of vessels of each type, and the quality and speed of vessels.
- Sea state data of the location of the facility.

The risk assessment of object falling accidents is also divided into two categories: the probability and the intensity of the physical effect of accident. The sources of object falling accident in the decommissioning are mainly caused by the crane hoisting accident and fixture failure, both will only occur within the range of the crane and objects movement direction. The research method for the consequence of the accident physical effect is similar to that of the ship collision accident and will not be repeated here.

Structural failure or capsize can only be risk assessed as DEAs, resulting from fire and explosion, ship collision and serious falling object accidents. So, the input value type is the output result of the above three incidents.

7.1.3.3 Inputs for Impact Assessment

In order to understand the impact of the environment and socioeconomics, the input data of this study are mainly environment-related data for the time being. Strictly speaking, the events that will directly or indirectly affect the decommissioning project are not only environmental pollution but also the employment provided by the project, the historical or political significance of the project, and so on. However, first, it is challenging to evaluate these impacts quantitatively. This study and more professional scholars in related fields are still searching for better quantitative evaluation methods; secondly, the impact of these factors on the project can be seen from historical statistical results. Concerns about marine environmental protection are shallow and unstable, and there are no relevant cases to show that these social factors will have a significant impact on decommissioning projects.

Based on the above considerations, the system constructed in this study does not consider the direct social impacts of decommissioning projects. However, it only considers the marine environmental impacts caused by decommissioning projects and the resulting indirect social impacts.

Since what analysis above, it is necessary to clarify what impact the decommissioning project will have on the marine environment:

- Spill situation. Including the amount of spill, the type of spill, the difficulty of cleaning up, the intensity of poisoning, etc., which can directly affect the marine environment of the project area and nearby areas.
- The impact of environmentally unfriendly substances on ocean protection, fisheries, and other marine industries. This needs to consider the marine protected area near the project, the location of the fishing area, the intersection of the marine life's migration path and the ocean currents' direction to explore further whether pollutants can be cleaned up before reaching the area according to the speed of ocean currents.
- Disposal methods of engineering waste and residues may cause long-term environmental pollution. Some facilities, such as leaving structures or pipelines in situ or moving them to landfills, are likely to displease environmentalists and sea users. However, many research results (Bull & Love, 2019; Cheng et al., 2017; Kaiser & Pulsipher, 2005) have shown that properly cleaned structures left in the ocean will not significantly impact the marine environment, and the construction of artificial reefs will boost the development of local fisheries.

According to the above analysis, the input types required for impact assessment in this system include spill amount, spill type, spill location, cleaning efficiency, ocean current direction and speed, location of marine life protection area, location of fishing area, migration path and time, etc.

7.2 Targets Criteria Database (TCD) Establishment

TCD is the core that HADES can construct dynamic accident sequences, and it is the embodiment of DEAs triggering necessary and sufficient condition-severity conditions. Domino effect risk quantitative assessment using HADES must first construct the limit value of each target on each physical effect according to the target of possible DEAs on the project subject.

For the NWH platform, combined with the decommissioning major hazards established in this study, it is possible to obtain which targets are likely to trigger DEAs to establish a TCD, as shown in Table 47. It should be noted that the scale of the database constructed in this study is small because the cases and major hazards studied are relatively simple, and there are few projects studied. For actual engineering, decision-makers can build a large-scale TCD according to the requirements and descriptions of each structure in the platform design documents.

Table 47. Targets criteria database of NWH platform.

Name	Temperature in 15min (°C)	Energy (kJ)	Force (MN)	Pressure (MPa)	Torque (N·m)
Jacket	450	50000	\	\	18840.78
Deck	450	5000	\	550	\
Rack	500	4240	\	15	\
Cylinder	100	6970	0.0235	150	\
Hose	100	0.46	\	6	\
Bolts (2.5")	760	\	98.9	\	\

The TCD of NWH shown in Table 47 includes the physical effect limit values of five categories of six targets, including the limit temperature within 15 minutes, the limit mechanical energy that the target can withstand, the impact force, the limit stress of the target, and only the platform jacket needs to consider the subsea sand and the overturning resistance moment endowed by its gravity. These values can be obtained according to the relevant specification values of DNV, or the design limit values provided by BP when designing the platform or can be obtained through a calculation based on the materials used.

7.3 Cost Assessment Results

This part mainly shows the performance of the cost assessment models constructed according to the two frameworks and a horizontal comparison based on the final performance of the two models. In this study, two basic frameworks described in the methodology were used to construct two cost assessment models. By using the same historical database, calculate the assessment results and compare them with the actual decommissioning costs to demonstrate the performance models. The focus of this chapter is the performance of the first bottom-up framework cost assessment model ECES.

7.3.1 Top-Down Framework Model

The section 4.1 described the top-down framework cost assessment model for offshore decommissioning, all equations are listed. By using 26 sets of data (32 facilities). The error of the results is shown in the Table 48. Compare the relative error obtained by American Association of Cost Engineers(Humphreys & Müller, 1995), 20% margin due to weather and risk and 15% for accidents are reasonable for assessment model. So, this model is suitable for North Sea offshore decommissioning, the errors are acceptable.

Table 48. Model preference and accuracy.

Platform Name	Total Cost M£	Prediction C-well M£	Prediction C-platform M£	Prediction C-pipe M£	Prediction C-sub M£	Prediction C-total M£	Error	Relative Error
Brent Field	400.61	182.39	330.16	30.79	0.00	597.69	0.49	0.49
Frigg	669.99	0.00	397.33	18.93	0.00	457.88	-0.32	0.32
Horne and Wren	21.50	7.00	8.97	6.37	0.00	24.57	0.14	0.14
Indefatigable	154.80	66.50	36.56	0.87	0.00	114.32	-0.26	0.26
Leman BH	13.80	0.00	14.58	-0.99	0.00	14.95	0.08	0.08
Maureen	150.00	70.00	256.65	13.64	3.36	378.02	1.52	1.52
Miller	300.00	102.42	141.44	11.03	0.00	280.37	-0.07	0.07
North West Hutton	246.00	165.42	190.44	19.11	0.00	412.47	0.68	0.68
Thames	96.10	38.89	38.77	11.36	4.58	102.97	0.07	0.07
Wellland	33.22	28.39	14.35	7.00	4.08	59.21	0.78	0.78
Camelot CA	21.00	42.79	11.89	-0.18	0.00	59.95	1.85	1.85
MCP-01	211.50	0.00	70.95	7.78	4.25	91.28	-0.57	0.57
Schiehallion	329.40	0.00	217.50	72.91	0.00	319.45	-0.03	0.03
Shelly	32.30	14.26	8.10	8.38	6.45	40.91	0.27	0.27
FFFA	265.90	224.71	0.00	4.37	4.37	256.80	-0.03	0.03
IVRR	429.30	340.83	0.00	154.69	5.70	551.34	0.28	0.28
Orwell	19.50	21.39	0.00	13.81	4.04	43.17	1.21	1.21
Rose	20.40	7.13	0.00	-0.06	2.68	10.73	-0.47	0.47
Stamford	16.80	7.13	0.00	1.41	2.69	12.36	-0.26	0.26
Tristan NW	11.80	14.26	0.00	1.34	2.36	19.76	0.67	0.67
Wissey	8.50	7.13	0.00	2.17	3.39	13.96	0.64	0.64
Don	150.00	49.92	0.00	30.57	3.23	92.09	-0.39	0.39
Kittiwake	8.50	0.00	0.00	11.56	3.06	16.08	0.89	0.89
Linnhe	7.56	0.00	0.00	17.45	4.08	23.69	2.13	2.13
Arthur	44.10	28.52	0.00	5.96	4.47	42.85	-0.03	0.03
Gawain	31.80	21.39	0.00	4.28	3.42	32.01	0.01	0.01
Average							0.36	0.54
Median							0.11	0.35

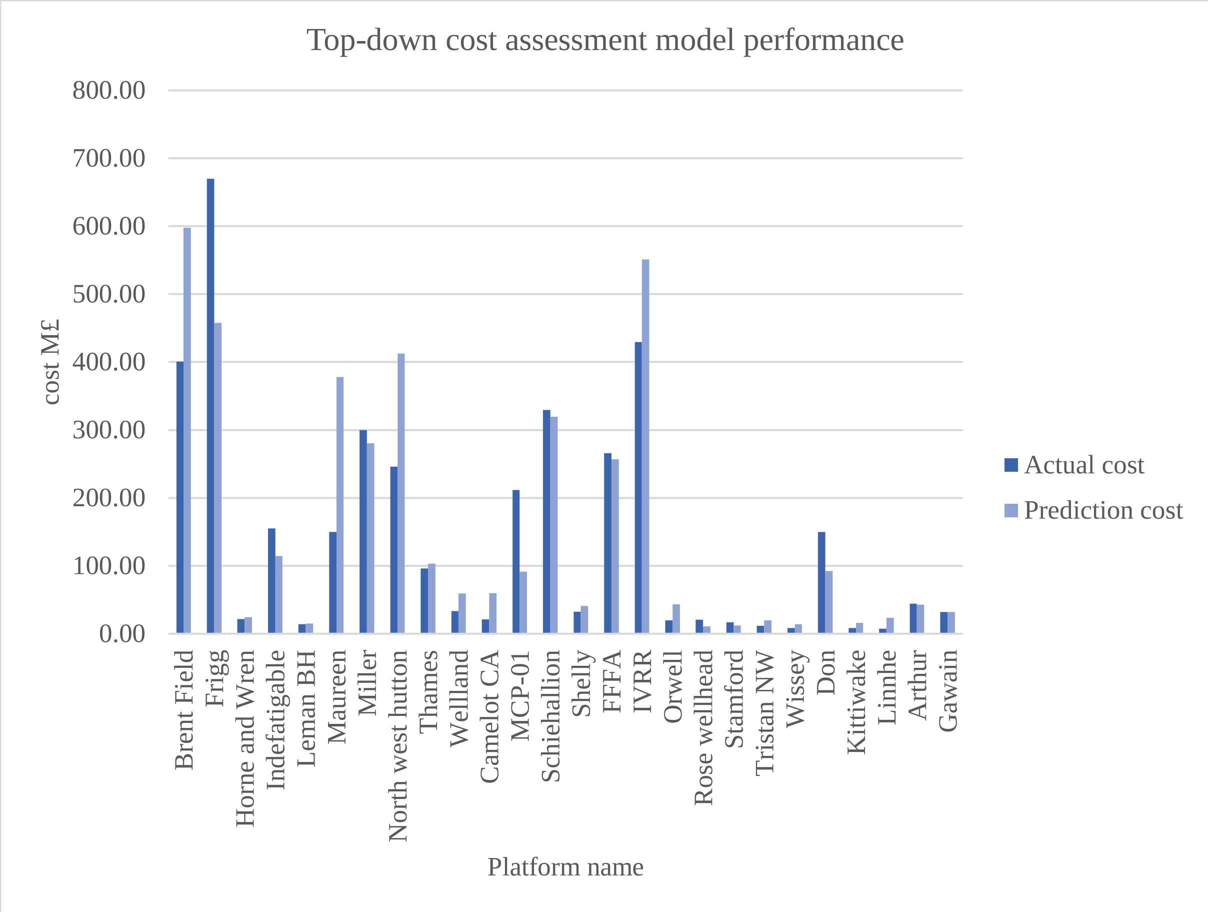


Figure 44. Top-down cost assessment model performance.

Comparing the actual total cost with the estimated total cost of the model showed in Figure 44, the evaluation model of the top-down architecture has the following characteristics:

- The model performs well. Decommissioning cost estimates are more accurate for smaller offshore facilities. Cost estimates for field decommissioning or decommissioning of larger facilities could have been better.
- Predictions are generally high. In only a small number of cases, the evaluation is lower than the actual cost, and most of the evaluation results are higher than the actual cost.
- The evaluation process is short. If the model is constructed, the evaluation process using the model is concise, and the required cost evaluation results can be quickly obtained.

However, the problems exposed when building this model are very worthy of attention:

- The original data is not uniform. The decommissioning reports issued by different energy companies often have different cost divisions. Some companies will combine the conductor removal cost with the well p&a cost, which causes misunderstanding for researchers, and the accuracy of the data used for regression will be unstable. Suppose the researcher only uses the decommissioning report issued by the same company. Due to the information being a commercial secret, they will face a severe data shortage.

- Rough division. The mathematical model constructed by the top-down framework is a functional relationship that uses historical data to perform a regression analysis to obtain cost estimates. However, historical data has a problem with clear proportion division. Researchers need to know whether the cost includes the cost of accident handling or the proportion of this cost, which is unacceptable to decision-makers.
- Overfitting and underfitting problems. The example data about offshore facilities' decommissioning cost need to be more comprehensive in various countries, so even the most mature cost assessment model, developed with only 26 sets of basic data. Fortunately, the data volume developed by Kaiser in 2014 increased to 53 sets. However, he did not state the prediction accuracy of his model nor the variance of the various regression equations. Due to the low sample size of this study, it is difficult to determine the relationship between independent and dependent variables. Sometimes, the results of correlation analysis cannot support the results of theoretical analysis. This also leads to the fact that if there is a problem with selecting independent variables, no matter whether the variance performance is excellent, the regression results may be under-fitting or over-fitting, making regression equations not worth using.

Considering the problems mentioned above, combined with the performance of the cost assessment model established in this paper and others, the top-down framework cannot provide data support for engineering planner decision-makers to make decommissioning options decisions. Therefore, a cost assessment model based on the bottom-up framework that can strip risk potential costs may be more suitable for decision-making. Moreover, it will be presented in the next section.

7.3.2 Bottom-up Framework Model, ECES

Engineering Cost Evaluation System (ECES) is a pioneering decommissioning engineering cost evaluation system based on the bottom-up framework applied to offshore decommissioning. As described in Section 4.2, ECES needs to evaluate the engineering duration and requires unit price data of equipment, vessels, and material, which is more complicated than the top-down framework model.

Unlike the 26 sets used to verify the top-down model, only 12 sets of fixed platform data are currently used to verify ECES. The reason is that the researchable projects for floating platforms and FPSOs decommissioning are insufficient. There are only two groups of cases that can be studied.

- First, there is a significant difference in the data types provided by the two sets of data on the project duration, and it is not easy to obtain the duration of each stage of floating facility decommissioning.
- Second, the use of technology, equipment and personnel cannot be obtained from these two groups of cases and may be quite different from the decommissioning of fixed facilities, cannot be estimated rashly.
- Finally, insufficient unit prices data for floating facilities decommissioning project, may because of the unclear decommissioning steps and equipment usage in floating decommissioning.

Therefore, temporarily, ECES can only be used for the fixed offshore decommissioning cost assessment. An update may be applied until there are enough floating decommissioning cases.

Table 49. Prediction engineering duration results in months.

Platform Name	P&A	Platform preparation	pipeline deco.	Topside Removal	Substru. Removal	Onshore disposal	Total duration
Brent Field	63.28	75.84	10.77	18.18	13.80	61.15	243.03
Frigg	11.30	34.96	0.65	16.85	9.49	34.03	107.28
Horne and Wren	2.26	0.07	4.53	4.17	0.18	0.37	11.59
Indefatigable	29.38	6.63	3.07	6.84	1.71	6.28	53.90
Leman BH	0.00	0.83	0.00	3.30	0.23	0.81	5.17
Maureen	22.60	0.00	3.55	16.64	0.00	0.02	42.81
Miller	36.20	22.99	0.10	17.59	7.43	24.60	108.91
North West Hutton	56.54	16.00	2.87	10.32	7.00	20.53	113.26
Thames	13.90	7.14	41.71	6.01	1.93	7.03	77.73
Wellland	10.51	0.80	5.83	4.71	0.23	0.85	22.92
Camelot CA	16.50	0.98	3.44	5.24	0.24	0.90	27.31
MCP-01	0.00	10.80	0.50	12.55	0.00	5.10	28.94

According to the duration evaluation method of each step mentioned in the Section 4.2.2, the predicted engineering duration calculated by ECES can be obtained, as shown in Table 49. Compared with the actual engineering duration, the error value in Table 50 and the average value of the predicted errors can be obtained.

Table 50. Relative error of duration prediction model.

Platform Name	P&A	Platform pre.	Pipeline deco.	Topside Removal	Substru. Removal	Onshore disposal	Total duration
Brent Field	0.34	0.23	0.69	0.52	0.53	1.55	0.02
Frigg	0.88	0.47	0.91	0.68	0.60	0.46	0.51
Horne and Wren	0.62	1.00	0.50	0.39	0.00	0.96	0.75
Indefatigable	0.30	0.75	0.96	0.77	0.86	0.84	0.75
Leman BH	0.00	0.96	0.00	2.30	0.77	0.86	0.83
Maureen	2.77	1.00	3.44	0.00	0.00	1.00	0.16
Miller	0.34	0.09	0.97	0.47	1.48	0.25	0.10
North West Hutton	1.36	0.33	0.81	1.58	1.12	0.61	0.07
Thames	0.27	0.60	1.61	0.50	0.79	0.00	0.05
Wellland	0.04	0.93	0.42	0.22	0.97	0.91	0.58
Camelot CA	7.25	0.00	4.47	21.79	0.04	0.70	3.48
MCP-01	0.00	0.72	0.00	0.37	0.00	0.86	0.69
Average	1.18	0.59	1.23	2.47	0.60	0.75	0.67
Average*	0.63	0.64	0.94	0.71	0.65	0.75	0.41

*: The average errors values except Camelot CA cases.

According to the results in Table 50, the performance of the prediction results is not good enough, and the data errors in some cases are terrible. The reasons are:

- First, the accuracy of the original data could be better. Some raw data do not contain the exact stage duration. WOW and engineering time are mixed and shown in reports. However, in other cases, only the specific engineering duration is provided without waiting time. Such inconsistent data sources lead to poor regression analysis.
- Second, the limitations of using the regression analysis. Strictly speaking, engineering duration prediction should also be carried out using the bottom-up framework method. However, professional, and experienced experts are essential to make an accurate judgment based on their engineering experience and facility conditions. Relevant quantitative research still needs to be completed, and regression analysis is the last resort.
- Third, the WOW for decommissioning offshore platforms is too difficult to determine. Theoretically, relevant assessment model needs experts' knowledge of Marine climatology. With such model, duration which is suitable for project can be determined, and then a relevant accurate engineering duration can be obtained.

At present, the specific situation of the decommissioning duration of each step still needs specific analysis by the system user. However, careful observation of the data results in Table 50 shows that, except for a few exceptional cases, such as the Camelot CA case, the performance of other cases when applying the duration evaluation model is acceptable so that the model can be used in ECES.

The available engineering duration is obtained, and the unit time cost data is given in 4.2. The unit price data and the estimated value of platform materials are shown in section 4.2 and appendix A. The cost evaluation results in Table 51 can be obtained.

Table 51. ECES cost prediction and relative error.

Platform Name	C well		C equip	C pipe	C g&c	C cont	C labo	C vessel		C onshore
	min	max						min	max	
Brent Field	36.30	383.80	36.97	2.46	5.98	66.55	45.77	77.03	77.03	37.82
Frigg	0.00	0.00	8.52	0.16	3.59	18.41	9.97	51.11	51.11	136.39
Horne and Wren	1.20	15.20	0.00	1.03	0.01	0.00	0.05	3.88	4.55	0.16
Indefatigable	11.40	144.40	0.39	0.70	0.48	0.45	1.40	17.08	17.08	3.76
Leman BH	0.00	0.00	0.01	0.00	0.06	0.01	0.02	3.76	4.42	0.48
Maureen	12.00	152.00	0.00	0.81	1.20	0.00	1.61	5.30	5.30	57.53
Miller	29.30	193.80	2.24	0.02	1.20	4.00	4.10	34.42	34.42	14.19
North West Hutton	40.10	330.60	1.56	0.65	1.20	2.78	4.27	36.57	36.57	11.25
Thames	11.70	72.20	0.31	3.73	0.53	0.55	1.42	11.51	11.51	4.13
Wellland	9.90	49.40	0.00	1.33	0.06	0.01	0.05	2.26	2.92	0.47
Camelot CA	17.40	68.40	0.01	0.78	0.07	0.01	0.07	1.38	2.05	0.55
MCP-01	0.00	0.00	0.71	0.11	0.81	1.27	0.74	17.88	17.88	4.05

(Continued)

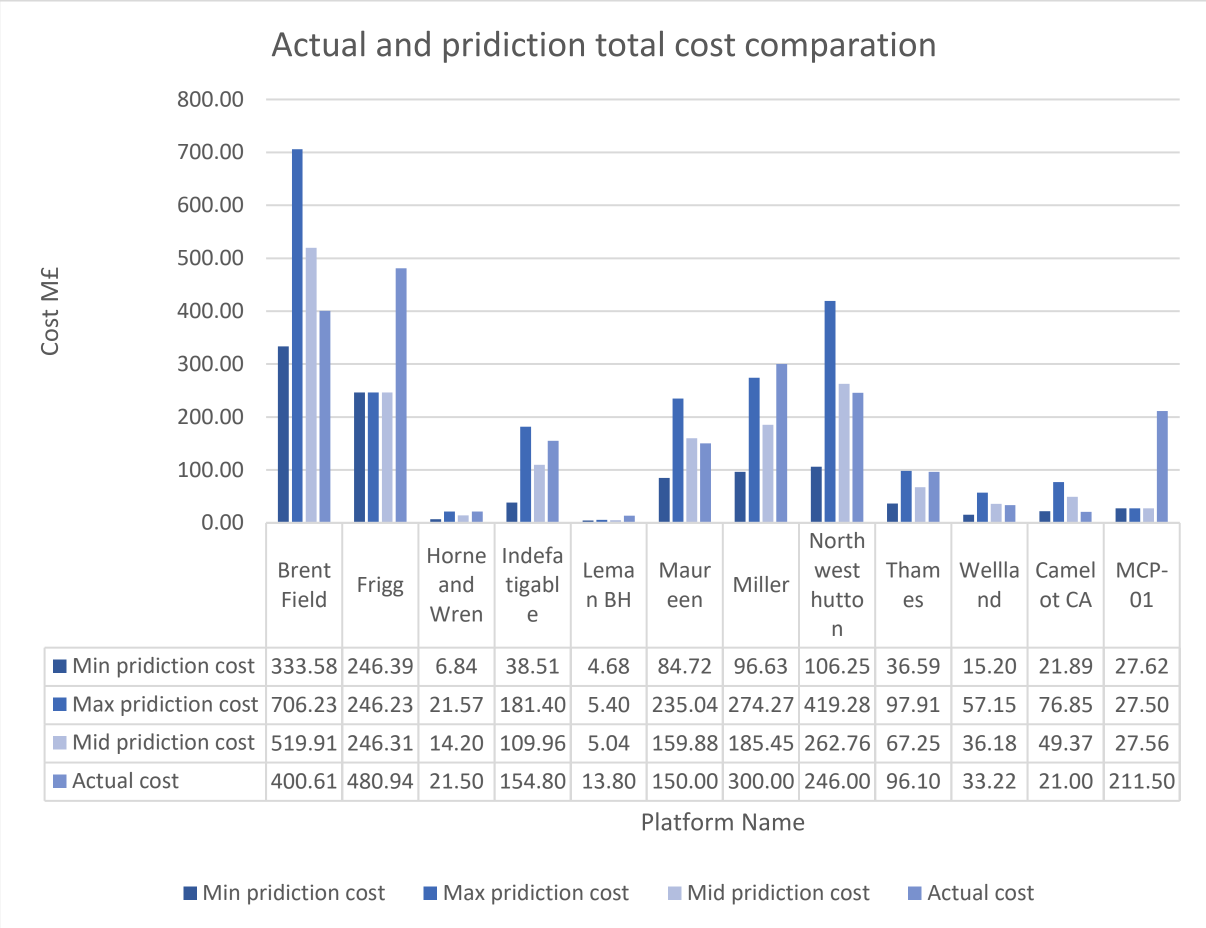
C eng		C admin		C total			Error			RE		
min	max	min	max	min	max	mid	min	max	mid	min	max	mid
308.87	653.92	24.71	52.31	333.58	706.23	519.91	-0.17	0.76	0.30	0.17	0.76	0.30
228.14	227.99	18.25	18.24	246.39	246.23	246.31	-0.49	-0.49	-0.49	0.49	0.49	0.49
6.33	19.97	0.51	1.60	6.84	21.57	14.20	-0.68	0.00	-0.34	0.68	0.00	0.34
35.66	167.96	2.85	13.44	38.51	181.40	109.96	-0.75	0.17	-0.29	0.75	0.17	0.29
4.34	5.00	0.35	0.40	4.68	5.40	5.04	-0.66	-0.61	-0.63	0.66	0.61	0.63
78.44	217.63	6.28	17.41	84.72	235.04	159.88	-0.44	0.57	0.07	0.44	0.57	0.07
89.48	253.95	7.16	20.32	96.63	274.27	185.45	-0.68	-0.09	-0.38	0.68	0.09	0.38
98.38	388.22	7.87	31.06	106.25	419.28	262.76	-0.57	0.70	0.07	0.57	0.70	0.07
33.88	90.65	2.71	7.25	36.59	97.91	67.25	-0.62	0.02	-0.30	0.62	0.02	0.30
14.08	52.92	1.13	4.23	15.20	57.15	36.18	-0.54	0.72	0.09	0.54	0.72	0.09
20.27	71.16	1.62	5.69	21.89	76.85	49.37	0.04	2.66	1.35	0.04	2.66	1.35
25.57	25.46	2.05	2.04	27.62	27.50	27.56	-0.87	-0.87	-0.87	0.87	0.87	0.87
						min	-0.87	-0.87	-0.87	0.04	0.00	0.06
						max	0.04	2.66	1.35	0.87	2.66	1.35
						Average	-0.54	0.29	-0.12	0.55	0.64	0.43

According to Table 51, a further comparison can be made to obtain the ECES prediction and actual cost comparison chart in Figure 45. The Figure compares the estimated minimum, maximum, median, and actual costs for twelve cases. The performance of ECES is outstanding. The actual cost of almost all cases is included between the lowest and highest cost obtained in the evaluation, which shows that the evaluation reliability of the model is high. More parameters can be used to reduce the cost range, for example, the difficulty factor of well decommissioning. In addition, the engineering costs' scope can be clarified further with the results obtained from risk assessment.

However, there is still a mystery when building the model. ECES is a bottom-up framework model, a crucial step in decomposing the cost components. However, to what extent have the researchers yet to mention the decomposition:

- It can be decomposed into industrial steps, following the top-down framework model, the engineering cost of each step is calculated first and then summed.
- It can also be like some operations in this study, no longer considering the engineering steps but directly decomposing the cost structure into the number of materials, equipment, and labor, multiplying it by each category's unit price.
- Alternatively, as shown in this research, combine two ideas according to the difficulty of data acquisition to build a model.

Temporarily, this research can only construct and compare some of the three models. Considering the number of cases and regional limitations used in this study, this type of comparison is minimal.



	Brent Field	Frigg	Horne and Wren	Indefatigable	Leman BH	Maureen	Miller	North west hutton	Thames	Wellland	Camelot CA	MCP-01
Min pridiction cost	333.58	246.39	6.84	38.51	4.68	84.72	96.63	106.25	36.59	15.20	21.89	27.62
Max pridiction cost	706.23	246.23	21.57	181.40	5.40	235.04	274.27	419.28	97.91	57.15	76.85	27.50
Mid pridiction cost	519.91	246.31	14.20	109.96	5.04	159.88	185.45	262.76	67.25	36.18	49.37	27.56
Actual cost	400.61	480.94	21.50	154.80	13.80	150.00	300.00	246.00	96.10	33.22	21.00	211.50

Figure 45. Comparation of ECES prediction and actual cost.

7.3.3 Comparison of Model Performance of the Two Frameworks

So far, the two models constructed by different methods have been verified by practical cases, which proves that the two models have practical significance. During the construction of the two models, some similarities and differences in the construction process of the two models can be realized, which can be summarized as follows:

- The construction of the bottom-up model requires much more data categories (7 categories minimum) than that of the top-down model (5 categories minimum), which is mainly reflected in the collection of market, salary, working hours and other data. However, to make the calculation more accurate, the amount of data used in constructing the top-down model is more than that in the bottom-up model, which is speculated to be caused by the construction characteristics of top-down mainly based on regression analysis.

- Regression analysis is used in the construction of the two models, but the intensity and purpose of the use are quite different. This shows that the two methods do not limit the use of specific data analysis or research methods, which makes the integration of the two methods realized to a certain extent.

Both cost assessment models have obtained acceptable results, so comparing and judging which model is more suitable for decommissioning cost assessment of North Sea offshore facilities is necessary. Table 52 is obtained after summarizing the critical data in the results of the two models. It can be seen that:

- Compared with the cost assessment models mentioned in the literature, the Top-down and the ECES model have better performance than previous models. However, top-down method does not perform well in the analysis of relative errors, so as the ECES model.
- The improvement of the algorithm is necessary. For the top-down model, the determination of variables and regression method directly affects the accuracy of the model. In the case of limited data, careful consideration and multiple trials of variables and regression methods should be conducted. For ECES, cost assessment algorithms need to be developed by professionals to make them more realistic. The project duration evaluation algorithm should be substantially modified to improve its accuracy. Perhaps the most appropriate method is to jointly develop weather evaluation models for corresponding sea areas with Marine climate researchers.
- In either case, further data acquisition is required.

Moreover, a big problem that needs to be solved is that when the scale of facilities to be decommissioned is large, the evaluation results of both the top-down model and ECES could be better. In this case, after research, the following conjectures are obtained:

- Large-scale and complex offshore facility decommissioning projects often take long, magnifying costs such as labor and vessel usage.
- Large-scale and complex offshore facility decommissioning projects are faced with more complex unit price costs since the cost deviation is slight, but when the quantity is large, it will cause a big difference.
- Large-scale and complex offshore facility decommissioning projects often use a wide variety of equipment and technologies, requiring a more detailed cost breakdown.

Table 52. Comparation between top-down cost model and ECES.

Comparation		Top-down	ECES	Difference	Better one
Error	Min	-0.57	-0.87	0.3	Top-down
	Max	2.13	2.26	-0.13	Top-down
	Average	0.36	-0.12	0.48	ECES
Relative Error	Min	0.01	0.00	0.01	ECES
	Max	2.13	2.66	-0.53	Top-down
	Average	0.54	0.43	0.09	ECES

For this study, ECES is more suitable as a cost assessment tool. Not only because the evaluation results of ECES are more accurate but also because ECES cannot be affected by risk events. The construction process of the Top-down model cannot exclude the impact of cost increments caused by engineering accidents, and logically it is not suitable to integrate its results with the risk assessment results. Therefore, the results of this study will use the ECES assessment results.

7.4 Risk Assessment Results

After ECES can obtain excellent cost evaluation results, the basic cost range of the decommissioning project of offshore facilities can be well evaluated and determined. Possible engineering risks. Due to the significant differences in the original data reports, the risk assessment of this study only uses the NWH platform decommissioning project as a case of risk research. Although the case study only used one decommissioning project, the method used by HADES does not use empirical equations or calculation methods that are only applicable to a specific field, so there will be no evaluation differences between case samples. The comparison of results is not necessary.

The results of the risk assessment part will be displayed sequentially according to the hierarchical structure of HADES, and the results of each level will be listed correspondingly according to the decommissioning process of the facility. These results will be evaluated against other authors' assessments of similar accident scenarios or compared with historical data from industry statistics.

7.4.1 The Primary Layer

The primary layer needs to consider three main types of hazards: blowout, ship collision, and dropped objects. According to Figure 3 and Table 4 in Chapter 1, the primary layer hazards faced by different decommissioning engineering steps differ. Blowouts can only occur in the well p&a step, while ship collisions and dropped objects can occur in almost all engineering steps. Therefore, the same evaluation categories in different engineering steps can be combined to analysis to reduce the workload.

7.4.1.1 Blowout

As mentioned in the methodology section on blowouts, blowouts in offshore facilities' decommissioning projects differ from blowouts during operation. During the operation period, the oil well remains connected, and the amount of blowout will be limited by the size of the BOP and the oil pipeline itself, and it will take more time to deal with it. However, the well p&a that needs to be done when decommissioning is to seal the well completely and never use it again. According to the standard method of sealing the well, the blowout most likely occurs when the first cement plug is placed, and the BOP fails simultaneously. Then an uncontrollable blowout with a variable flow rate occurs. The blowout size is determined by the size of the cement plug's hole and the casing's size. However, there is still no relevant research on the distribution of well p&a blowout rate for decommissioning, so this thesis temporarily uses the worst blowout situation as research.

Taking the data of the NWH oil well in Appendix C into the calculation, use the research results of the Strand (Strand & Corina, 2019) as the failure probability of the 30m cement plug, and use the research results of Montgomery et al.(Montgomery et al., 2013) to obtain the BOP failure probability of 0.01/well. The worst blowout probability for a well is 1.6E-06 and the worst blowout rate for crude oil is 206.95kg/s, 24.36kg/s for natural gas. Table 53 presents the estimated values and probabilities of worst-case blowouts and the likely initial contaminated area if a subsea blowout occurs.

Table 53. NWH blowout assessment results.

Categories	Seabed spill pool diameter (m)	Spill rate (kg/s)	Probability /well	Spill volume in 3 days (m^3)
Crude oil	31.75	206.95	1.6E-06	7.67E+04
Natural gas	NA	24.36	1.6E-06	1.47E+07

These oil spills are the main sources of combustibles for fires on platforms or the sea surface. After considering the probability of being ignited, the probability of a blowout fire accident in NWH can be directly calculated. This part will be introduced in detail in the first domino layer. It should be noted that this evaluation result is the theoretical worst case rather than the actual most likely case. The current relevant research and statistical data focus on the evaluation of spill probability and spill volume during well operation and for a while after abandonment is completed. There are no studies or related statistical reports about the spill distribution during well p&a. Based on the results of spill research after some wells have been plugged(Mainguy et al., 2007; Mariann, 2018; Nichol & Kariyawasam, 2000), the author deduces that the spill distribution during the well p&a period should obey the exponential distribution. However, no experimental or practical data supports it, so this part of the work will be completed in the future.

7.4.1.2 Ship Collision

It is easy to understand that although this is an offshore project, it is still necessary to pay attention to whether passing and nearby ships will collide with the facility. Therefore, ship collision is a significant autonomous hazard that runs through facility decommissioning (removed structures are dismantled on shore stage does not need to be considered). However, due to differences in the demand and distance of engineering ships at different stages, the probability of ship collisions will increase significantly in some decommissioning engineering stages.

Based on the statistics in the NWH report, this research shows five lanes within 20km around the NWH, with an annual navigation density of about 1800. There are no military areas around and no known commercial activities. Most of the ships on the route are related to the offshore oil and gas industry, mainly tankers and supply ships, and there are no submarine cables or other facilities nearby. Fishing activity on the site is moderate, with only small shellfish production near the NWH platform. According to statistics for 2003, the fishing season in the waters near this facility is from February to August. After May is the peak period of local marine mammals, the major living area is in the west of the NWH facility and the southwest, in the waters near the Shetland Islands. The facility’s location is unsuitable for activities with excessive noise or severe risk of pollution in February, March, April, and July.

Based on the above information, combined with relevant documents on ship scale, Table C-3 in Annex C can be obtained as input values for the evaluation and calculation of collision probability and severity. According to Mujeeb-Ahmed’s research results corresponding to different ship types, using the method of calculating the collision probability mentioned in 5.2.3, Table 54 and Table 55 can be obtained, which are the collision probability and frequency between the vessels in the navigating and drifting state with the platform. Furthermore, Using the method mentioned in 5.3.7, the motion and damage of the platform after the collision can be obtained, as shown in Table 56.

Table 54. Collision probability and annual frequency of navigating vessels with platform.

Vessel types	Vessel number	Collision probability Fd	P1P2P3	P4	mitigation factors M1M2	Pcpp	Fcpp
Supply	900	2.19E-11	3.80E-04	0.451	3.60E-02	1.35E-16	1.21E-13
0-1500	180	2.19E-11	2.00E-04	0.558	3.60E-02	8.78E-17	1.58E-14
1500-40000	540	2.19E-11	9.10E-04	0.649	3.60E-02	4.65E-16	1.67E-13
>40000	0	2.19E-11	2.40E-04	0.634	3.60E-02	1.20E-16	0.00E+00
fishing	180	2.19E-11	6.50E-04	0.693	3.60E-02	3.54E-16	6.38E-14

Table 55. Collision probability and annual frequency of drifting vessels with platform.

Vessel types	Number	Mooring area (m2)	Wind & current direction Pw&c	Loss both/vessel/hr	Technical error Ptech erro	Mooring system failure Pmf	Repair failure Pdrift	Pcpd	Fcpd
Supply vessel	10	3.06E+05	0.143	1.50E-05	7.18E-07	1.00E-05	1.07E-25	7.37E-10	7.37E-09
Barges	9	9.61E+04	0.143	1.50E-05	1.44E-08	1.00E-05	2.94E-04	3.40E-05	3.06E-04
HLV	1	2.97E+05	0.143	1.50E-05	1.44E-08	1.00E-05	2.94E-04	1.18E-05	1.18E-05

Table 56. Collision results.

Vessel states	Vessel categories	Collision prob./yr/vessel	Collision frequency/yr	Collision energy (MJ)	Impact force (MN)	Impact torque (MNm)	Linear acceleration (m/s2)	Max. Angular acceleration (rad/s2)
Drifting	Supply	7.37E-10	7.37E-09	4.76	19.04	2805.68	0.023	7.99E-04
	Barges	3.40E-05	3.40E-04	1.40	5.60	825.20	0.010	3.50E-04
	SSCV	1.18E-05	1.18E-05	12.93	51.71	7620.41	0.037	1.21E-03
Navigating	Supply	1.35E-16	1.21E-13	59.84	152.32	22445.44	0.093	2.27E-03
	0-1500	8.78E-17	1.58E-14	38.97	99.20	14618.42	0.071	1.67E-03
	1500-40000	4.65E-16	2.51E-13	101.77	259.05	38172.93	0.122	3.13E-03
	>40000	1.20E-16	0.00E+00	133.50	339.81	50073.96	0.137	3.60E-03
	Fishing	3.54E-16	6.38E-14	0.40	1.01	148.54	0.001	2.24E-05

By comparing the data in Table 56 with the TCD and combining the data of the objects on the platform for calculation, it can be concluded whether the platform will be damaged or capsized by collision. Furthermore, whether the fixed or unfixed objects on the platform will break through the limit to move.

7.4.1.3 Dropped Objects

Falling objects are always a significant hazard for industrial activities with vertical projects. Therefore, dropped objects need to be considered in offshore commissioning as long as there are vertical operations. As for the accident of the primary layer, there is only one mechanism for dropped objects to occur: the crane has an accident, the sling breaks, and the object falls. Other accidents that may lead to the breakage of fixtures or slings will be evaluated in domino layers as DEAs.

Although it is common to drop objects in the various steps of the decommissioning project, there are significant differences in the objects that will drop in each step.

- In the well p&a stage, hoisting operations are required, but the amount is small, mainly for small equipment for well closure, new BOP, etc. Well-plugging work is usually handed over to professional engineering ships for processing.
- The conductor removal stage must cut off the conductors and hoist them to the barge. However, the conductor removal in NWH decommissioning could have given more precise engineering time and data. However, it was only mentioned in the close-out report, so it is tentative in this study Not be considered.
- Platform preparation is the most frequent stage of hoisting small-mass objects, and it is also one of the main stages of research on dropped object accidents in this study. The content of the research includes two aspects: one is the probability of various objects falling and hitting the deck, personnel, and the assessment of deck damage; the other is evaluating the probability of various objects hitting the target that can cause DEAs and the physical damage effect, these targets are mainly cylinders and hoses protected by racks. Due to the need for more research sources, this topic only focuses on vertical drop accidents. It does not consider collision with other targets when the object is swinging during hoisting.
- In addition, the decommissioning engineering steps related to the falling object accident are the pipeline, topside, and substructure removal stages, and the shore dismantling stage. For pipeline removal, the fall accident will only happen on the engineering ship or fall into the sea, so it is not an engineering risk that the energy company itself needs to consider, but the related company that assigns the engineering ship. Both topside and

substructure removal are lifting operations of large-mass objects, and the consequences of accidents are apparent. The main concern is whether the falling objects will cause the platform structure to fail and cause the platform to overturn. When the topside is removed, there may still be platform workers continuing to split the modules. However, when the substructure is removed, there is no need to consider the situation of personnel in the work area. In the end, the risk of falling objects in the dismantling process on shore is entirely borne by the ship dismantling company rather than the entrusting energy company, so it cannot be assessed.

The respective evaluation contents of the primary and domino layers can be clarified. The data of the area swept by the crane, the total area of the platform deck, and the projected area of each target on the horizontal plane are obtained in Appendix C. Combined with the distribution map mentioned in the input, the possibility of the target being hit can be calculated.

According to the layout plan of NWH, there are two cranes with a radius of 30m on the platform to carry out the lifting work before the topside is removed. The platform's topside will be removed according to the module, using the semi-submersible HLV of Hermond, a subsidiary of Heerema Marine Contractors, and five barges to transport the components to the shore. The jacket part also used Hermond, with a total of 58 hoisting, and four barges were used to transport the 9,200-ton steel jacket to the shore.

The failure probability of these cranes, combined with the number and position of each target object on the platform, can calculate the probability of a falling object collision accident, as mentioned in 5.2.4. According to the data of DNV-PR-F107, for platform cranes, there is a 0.7 chance that the object will fall on the platform and a 0.3 chance that it will fall into the sea. The falling probability of each hanging object is 2.2E-05/lift for objects below 20 tons; for objects higher than 20 tons, the falling probability of each hanging is 3.0E-05/lift. The probability of falling when HLV lifts objects below 100 tons is 7.33E-05/lift; when lifting objects above 100 tons, the probability of falling is 5.00E-03/lift (DNV, 2010). The data of the area swept by the crane, the total area of the platform deck, and the projected area of each target on the horizontal plane are obtained in Appendix C. Combined with the distribution map mentioned in the input, the possibility of the target being hit can be calculated.

By substituting the input quantities mentioned above, the probability of the two types of containers falling is shown in Table 57, and the probability of hitting the rack loaded with cylinders, workers, and hose can be obtained. The IRPA value of the platform preparation stage is obtained, which is one of the primary sources of fatality. Correspondingly, Table 58 shows the energy and pressure of two kinds of containers dropped vertically and obliquely from heights of 30m and 10m under full and empty conditions. According to Ali et al.(Ali & Sachin, 2020), objects larger than 2 tons and much larger than 8 tons are usually inclined at an angle between 2° and 5° when falling. And according to Ramberg(Ramberg, 2022), 8m height is the lowest height of lifting and 24m is the highest. A container falling onto the deck at an angle will exert more pressure on the deck in the contact area, causing more severe damage. Comparing these results with the data in the TCD can tell whether these crashes are likely to cause DEAs on the target.

Table 57. The frequency of accidents caused by falling containers.

Containers' types	Objects hit deck frequency	Objects hit targets frequency			IRPA pp0	PPL pp0
		Rack and cylinders	Human	Hose		
20 feet	5.63E-03	2.80E-05	3.11E-05	7.95E-05	2.19E-09	2.45E-07
40 feet	2.10E-03	1.80E-05	2.00E-05	5.11E-05	1.40E-09	1.57E-07

Table 58. Physical effects caused by falling containers.

Posture	Containers' types	Height 24m				Height 8m			
		Impact energy (MJ)		Pressure (MPa)		Impact energy (MJ)		Pressure (MPa)	
		Full	Net	Full	Net	Full	Net	Full	Net
Vertical	20 feet	7.06	0.54	0.43	0.03	2.35	0.18	0.14	0.01
	40 feet	7.17	1.11	0.22	0.03	2.39	0.37	0.07	0.01
Tilted	20 feet	7.06	0.54	26.15	2.00	2.35	0.18	8.72	0.67
	40 feet	7.17	1.11	26.57	4.10	2.39	0.37	8.86	1.37
Corner	20 feet	7.06	0.54	637.52	48.88	2.35	0.18	212.51	16.29
	40 feet	7.17	1.11	647.72	99.88	2.39	0.37	215.91	33.29

Table 59. Accident assessment results during offshore structure decommissioning.

Structure part	Modules' info.	Lifting number	Min weight (t)	Max weight (t)	Objects hitting	Energy (MJ)		IPRA td0 min	IRPA td0 max	PLL td0 min	PLL td0 max
						Min	Max				
Topside	See table 45	22	17	2780	7.36E-02	4.00	653.86	2.05E-06	4.05E-05	2.30E-04	4.53E-03
Jacket	NA	58	NA	2250	2.03E-02	23.52	529.20	NA	NA	NA	NA

During the topside and substructure decommissioning stages, there may also be dropped objects accidents during module transfer. The difference is that during the topside decommissioning stage, workers on the platform may still perform module-cutting work, which may result in death. If a heavier module hits the platform, it completely exceeds the bearing capacity of the platform structure itself. Assume that the platform will be overturned to be on the safe side. According to statistics on the number of deaths caused by platform overturning accidents in history, if the platform overturns, the fatality rate of the staff on the platform is as high as 71.32%. This study assumes that if the platform capsizes (Reid, 2020; France, 2019; Sheppard & Young, 2022; Li et al., 2020; Daley, 2013; Kelly, 2013), 70% of the workers on the platform will die. The results in Table 59 can be obtained from the above analysis.

The above calculation methods are straightforward primary evaluations, and DNV gives more complex and accurate methods in its three specifications, DNV-RP-C204 (Det Norske Veritas, 2010), DNV-RP-C208 (DNV, 2013) and DNV-OS-A101 (DNV, 2019). Furthermore, the result of finite element simulation can also be used here. From these results, the container's falling posture greatly influences the pressure during impact. If the corner of the container hits the deck, it will cause more severe damage to both sides of the collision. This result is consistent with Ramberg's simulation results. By comparing DNV's requirements for deck strength, when a fully loaded container falls from a high place and hits the deck with the corner of the container, it will break through the deck. When the deck is hit with the short side of the container, it may be deformed but not penetrated, and the container will most likely collapse. The pressure to the deck with no tilt is shallow and will not threaten the deck.

7.4.1.4 Causality Matrix Update

After obtaining the major hazard assessment results of the above three primary layers, it is necessary to compare the assessed physical effects of the accident with the standards in the TCD to determine whether DEAs will be triggered. Table 60 to 62 compares the physical effects of the three accidents with the target criteria in the TCD.

Table 60. Blowout DEAs triggering judgement.

Location	Categories	Blowout	TCD for blowout
		Probability	Ignition probability
Platform	Crude oil	1.60E-06	8.00E-02
	Nature gas	1.60E-06	3.00E-01
Subsea	Crude oil	1.60E-06	8.00E-02
	Nature gas	1.60E-06	0

Table 61. Ship collision DEAs triggering judgement.

<table>
<tr><th colspan="2">Categories</th><th>Ship collision</th><th>TCD for ship collision</th><th rowspan="9">DEAs judgement</th><th>Capsize</th><th>Structure failure</th><th>Bolts failure-linear</th><th>Bolts failure-angular</th></tr>
<tr><td rowspan="3">Drifting</td><td>Supply</td><td rowspan="8">See Table 56</td><td rowspan="8">See Table 47</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td>Barges</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td>HLV</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td rowspan="5">Navigating</td><td>Supply</td><td>Yes</td><td>Yes</td><td>No</td><td>No</td></tr>
<tr><td>0-1500</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td>1500-40000</td><td>Yes</td><td>Yes</td><td>No</td><td>No</td></tr>
<tr><td>>40000</td><td>Yes</td><td>Yes</td><td>No</td><td>No</td></tr>
<tr><td>Fishing</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
</table>

Table 62. Dropped objects DEAs triggering judgement.

<table>
<tr><th rowspan="2">Categories</th><th rowspan="2">Targets</th><th rowspan="2">Dropped objects results</th><th rowspan="2">TCD for dropped objects</th><th colspan="2">DEAs judgement</th></tr>
<tr><th>24m height</th><th>8m height</th></tr>
<tr><td rowspan="3">20 feet</td><td>Rack and cylinders</td><td rowspan="6">See Table 57 & 58</td><td rowspan="7">See Table 47</td><td>No</td><td>No</td></tr>
<tr><td>Hose</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Deck</td><td>Yes</td><td>No</td></tr>
<tr><td rowspan="3">40 feet</td><td>Rack and cylinders</td><td>No</td><td>No</td></tr>
<tr><td>Hose</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Deck</td><td>Yes</td><td>No</td></tr>
<tr><td>Modules</td><td>Structure</td><td>See Table 59</td><td>Yes</td><td>NA</td></tr>
</table>

According to the judgment results obtained, the following conclusions can be obtained, and the causality matrix can be constructed to reduce the workload:

- The only DEAs for blowouts are fire and explosion accidents. The mechanism by which crude oil and natural gas are ignited as combustibles is very complicated, so this study directly uses the ignited probability mentioned in section 5.2.2, combined with the probability of blowout, to calculate the probability of fire and explosion accidents. In this study, the default fire and explosion as DEAs must meet the conditions to be triggered. The improvement of relevant judgment mechanisms will be carried out in future work.

- It is not difficult to see from the analysis of Table 61 that the collision intensity between the ship and the platform in the drifting state will not be too high, and there is no need to worry about structural failure or capsizing of the platform. However, the supply vessel in the navigating state and the collision between a ship with a mass of more than 1,500 tons and the platform will cause serious accidents. The platform structure is invalid, and 70% of the personnel would be considered dead.
- However, a significant conclusion can also be obtained from Table 61: no matter what kind of collision occurs, the bolts fixing the objects on the platform will not break due to shear failure, and the fixed objects will not move.
- It can be concluded from the analysis of Table 62. The cylinders in the rack protection will not be damaged if the 20ft container is fully loaded and dropped from any height. However, 40ft containers have always been acceptable.
- The analysis of Table 62 shows that the hose will inevitably leak after being hit by the falling container.
- From the analysis of Table 62, when the container transportation height is 8m, the deck will not be damaged by the falling full container. However, it will destroy the deck when falling from 24m. The lifting height of the modules in the structure decommissioning stages keep to 24m.

According to the above analysis and conclusions, the causality matrix of all accidents in the primary and first domino layers at each engineering stage can be obtained, as shown in Figure 46. The arrows indicate the causal relationship between accidents. The matrix below represents the causal matrix corresponding to the causal relationship between the primary and the first domino layer. This matrix means relying on results rather than assumptions between the primary layer and the first domino layer, establishing a reliable domino causality relationship, allowing users to know how to evaluate further DEAs, which can significantly reduce the task of evaluation work, in theory, it can also make the evaluation result more accurate.

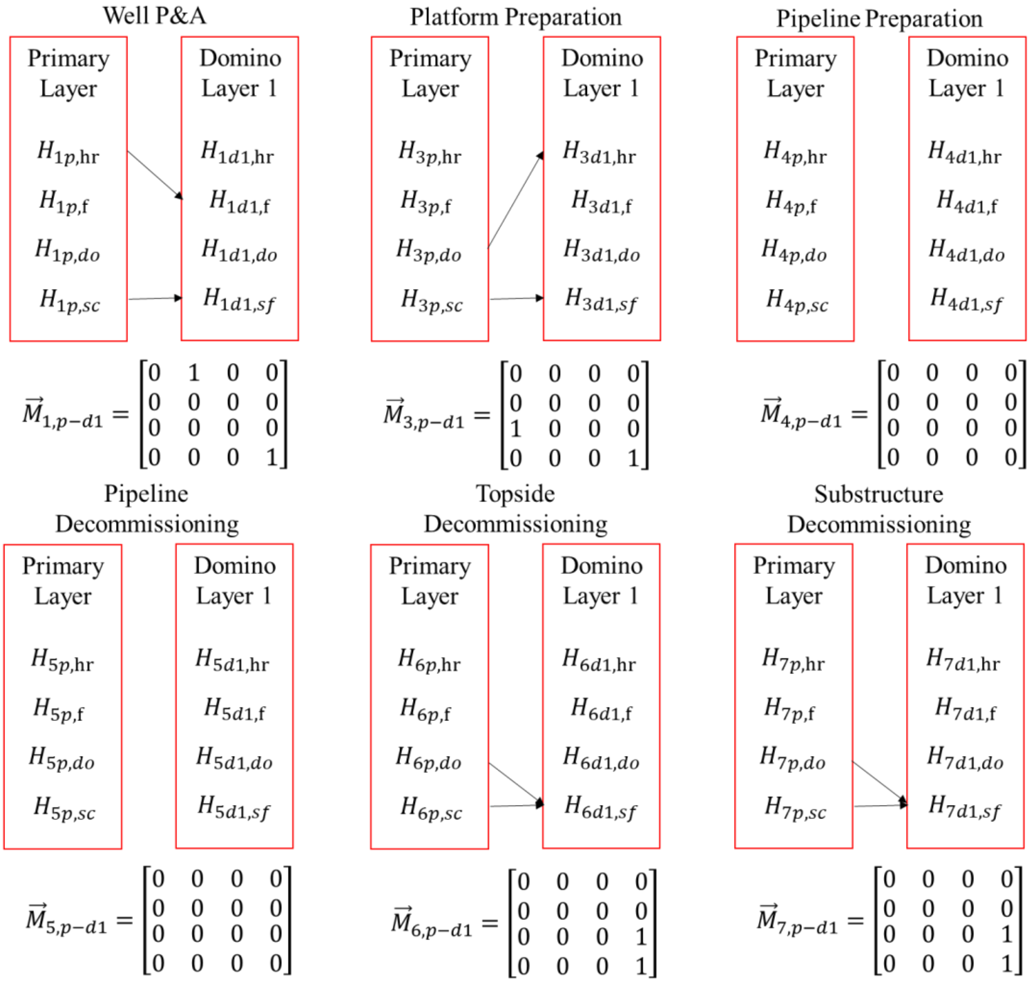


Figure 46. Causality matrixes of the primary and 1st domino layer.

7.4.2 The 1st Domino Layer

According to the results of section 7.1.3.2, for the NWH decommissioning project, the accidents that should be considered in the first domino layer are mainly:

- In the Well P&A stage, fire and explosion accidents caused by blowouts are mainly considered. The platform capsized as well as the structural failure caused by the ship collision.
- The Platform preparation stage mainly considers the hydrocarbon leakage accident caused by the falling object accident. As well as the failure of the results caused by the ship's collision, the platform capsized.
- The main operation subjects in the pipeline preparation and decommissioning stages are not on the platform but on the engineering vessels, so there is no need to consider any DEAs being triggered on the platform.
- The topside and substructure decommissioning stages mainly consider possible structural failure accidents caused by the HLV lifting module falling and hitting the

remaining structure. Moreover, the ship collided with the facilities undergoing decommissioning operations, resulting in structural failure and capsizing of the platform.

After obtaining the hazards that need to be evaluated by the 1st domino layer, it is necessary to use the physical effects of the evaluation results of the major hazards of the primary layer as input and conduct a new round of risk assessment according to the method mentioned in the methodology.

7.4.2.1 Hydrocarbon Leakage

The hydrocarbon leakage in this layer is caused by the falling object accident in the previous layer. According to the causality matrix, the triggering can only happen in the platform preparation stage. Then, according to the judgment results in Table 62 and the frequency assessment results in Table 57, there is a low probability that the cylinders protected in the rack will leak due to objects impacting. The hose will leak regardless of the impact of any container's type, height, and mass, and the total frequency of leakage during the entire platform preparation stage is 1.31E-04. Since the size of the falling object and the impact energy are much larger than the size and the tolerant energy that the pipe wall can withstand, it is considered that the hose will produce a leak with the inner diameter of the pipe when it is hit.

Next, calculate the hose gas leakage rate according to the calculation method mentioned in the methodology. Platform decommissioning primarily uses gases for thermal cutting work, with acetylene and oxygen being the most used. Gases or liquids that may be used by other cutting techniques (such as waterjet cutting) can be set according to the needs of the case. Bring in the hose data in Appendix B and the gas properties, the leakage results are shown in Table 63.

Table 63. Hose leakage rate and frequency.

Gas type	Leakage area (m^2)	Frequency	Leakage rate (kg/s)
Acetylene	7.85E-05	1.31E-04	7.12E-03
Oxygen	7.85E-05	1.31E-04	7.41E-03

The diameter of the hose will significantly limit the flow rate of the hose leakage. Due to the huge pressure difference between the inside and outside, the leaked gas or liquid will mostly form a conical jet flow. This conical jet flow may develop a jet fire if ignited, but the flame will not form a backfire due to the excessive pressure difference and ignite the fuel in the gas bottle. Oxygen will not be ignited and will only support combustion, but you need to worry about explosion due to high cylinder pressure caused by high temperature. This kind of fire accident will be evaluated in the second domino layer, not analyzed in this layer.

7.4.2.2 Fire and Explosion

As mentioned above, in the present case study, the prerequisite for fire and explosion was hydrocarbon leakage. The only hydrocarbon accident that can occur in the primary layer is a blowout accident, which will leak a large amount of crude oil or natural gas. For the NWH project, crude oil is mainly extracted from the reservoir. Of course, there must be some natural gas in the oil field, but there are other ones besides this. Therefore, the consequences of a fire after the crude oil is ignited are mainly considered at this stage.

As mentioned above, there are two leak locations: on the platform and underwater. Crude oil will first fill the mining area when spilt on the platform. Too much will overflow and spread over the platform, eventually falling into the sea. If there is a high-speed eruption accident, it will directly cover the platform. Since it is impossible to know the parameters of the specific oil spill prevention structure of the NWH platform, this study treats the oil spill on the platform as having no safety barrier for the time being. For submarine blowout, the formula mentioned in 5.3.1 can roughly calculate the area of oil pollution formed by crude oil on the sea surface. However, fires on the sea's surface may not necessarily affect the platform's safety because ocean currents and waves will deflect the oil spill by a certain distance. Next, it is necessary to obtain information such as the size of the pool fire formed under the worst blowout scenario, the geometry of the flame, and the heat flux released. Then, it is necessary to calculate the estimated casualties of the people affected by the fire within a certain period and how the target object will react.

Table 64 presents the results of the geometric evaluation of the fire for the worst blowout and continuous oil spill. Table 65 shows that in the face of this kind of fire, people and objects can still guarantee safety thresholds under thermal radiation within a certain time and safe distance.

Table 64. Blowout fire properties.

Spill location	Rate of heat release Q (KW)	Surface emissive power Ep (KW/m²)	Fire probability	Wind speed uw	Exit speed ue	Flame tilt α	Effective Mach number Mef	Exit diameter De (m)
Deck	3.04E+06	791.88	1.28E-07	25.9	6.32	0.49	2.00	0.24
Sea surface	6.52E+05	791.88	1.28E-07	25.9	6.32	0.49	2.00	0.24

(continued)

Spill location	Flame height L (m)	Fuel burning velocity v-finf (m/s)	Equivalent diameter D-eq (m)	Burning rate per unit pool area (kg/m²s)	Pool area A (m²)	Relative humidity of atmo.	Plume rise velocity (m/s)	Drift distance (m)
Deck	40.65	8.00E-05	68.60	0.06	3695.62	0.50	0.23	0.00
Sea surface	24.35	8.00E-05	31.75	0.06	791.53	0.50	0.23	461.53

Table 65. Targets' fire responses.

Targets	Heat radiation in 15mins (kW/m²)	Safe distance in 15min	Safe distance for 3s	IRPA wp&a1
Deck	88.66	52.25	NA	NA
Cylinder	44.78	73.53	NA	NA
Hose	46.03	72.52	NA	NA
Human	NA	NA	125.70	1.01E-09

According to the results of the two tables, the following conclusion can be obtained:

- The primary dimension of the platform deck is 78mx61m. If the most severe blowout accident occurs, the personnel in the facility cannot escape within 3 seconds, which means that nearly all of the people on the platform will be hurt. Although in the well p&a stage, the IRPA value caused by the worst blowout of a single well blowout is meagre because the probability of the worst blowout scenario is extremely low. Once an accident occurs, the consequences are catastrophic.
- In a blowout fire, almost all targets on the deck will be destroyed by the fire within fifteen minutes, including the dedicated fireproof structures. Therefore, if a blowout fire occurs, many DEAs will be triggered, and the facility will be completely dragged into the abyss of disaster.
- If the submarine oil spill is ignited on the sea surface due to the effect of ocean currents, the oil slick will be separated from the platform area by about 460m. Even if a fire occurs, it will not cause damage to the platform structure and personnel.

These results are very informative and alarming. However, this is the worst catastrophic blowout scenario. The author believes that its practical significance is to remind construction workers to pay attention to safety and to evaluate the maximum economic loss that the energy company may bear in the event of a catastrophic accident on the platform. The impact assessment of small and medium oil spills will have more practical engineering reference value and safety protection research value. Research in this area will be supplemented and improved in the future.

7.4.2.3 Structure Failure

Structural failure is a multi-mechanism DEAs. The failure mechanism may be that the overall toppling is caused by insufficient stable resistance or that the jacket is seriously damaged and cannot support the upper structure, causing the structure to fall. However, the result can be considered the same: the most severe and irreparable catastrophic accident.

According to the results of 7.1.4, the primary layer accidents that may trigger structural failure are the falling of heavy modules and the collision of large ships.

According to Table 61 and Table 54, the jacket will be severely damaged if the ship collision torque exceeds the platform resistance torque. Therefore, the two mechanisms can be considered together, and the annual frequency of structural failure accidents due to this mechanism is 1.21E-13. If an accident occurs, it will be handled as a catastrophic accident. 70% of the workers on the platform will die, the structure will be completely damaged, and the economic loss will be maximized.

Tables 62 and 59 show that only the heavy mass module falling will damage the structure. Tables 45 and 59 show the hoisting number of the topside and jacket modules of the NWH and the large-mass module quantity. The occurrence frequency of this mechanism is 7.35E-02. The consequences of the accident are the same as mentioned in the previous paragraph. The Table 66 shows the results.

Table 66. Structure failure results.

Mechanism	Frequency	Facility loss (M£)	IRPA 1	PLL 1
Ship collision	3.72E-13	100	2.05E-15	2.29E-13
Dropped objects	9.38E-02	100	5.16E-04	5.78E-02

To illustrate the assessment setting and interpret the results:

- Issues such as the division of responsibility for insurance compensation are not the focus of this study, so the economic losses caused by obesity are not calculated here.
- The facility loss represents the platform construction cost set by the decision-maker or the value of the maximum economic loss, which is temporarily set at £100M for convenience of calculation.
- If such an accident occurs, there is no need to proceed with further QRA, and all losses can be maximized. Therefore, the accident does not trigger any other DEAs and directly outputs the evaluation results.

- The seriousness of the falling object accident is a cause for concern! According to the current results, falling objects are the leading cause of casualties.

9.2.4 Causality Matrix Update

According to the above evaluation results, comparing the data in TCD, we can know which DEAs will be triggered, see Table 67. Correspondingly, the causality matrix can be further updated, as shown in Figure 47.

Table 67. DEAs judgement.

Accidents	Targets	Triggering frequency	TCD criteria	DEAs judgement
Hydrocarbon release	Ignition	3.92E-05	NA	Yes
Blowout fire	Deck	1.28E-07	See Table 47	Yes
	Cylinders	1.28E-07		Yes
	Hose	1.28E-07		Yes

Some explanations for these results:

- The main body of the hydrocarbon leakage accident in this layer is the hose, which will not leak until the container hits it. Combined with the probability of the gas being ignited on the offshore platform, the likelihood of a hose jet fire in the 2nd domino layer can be obtained.
- The coverage area of a blowout fire on the platform is the entire platform, and the result of calculating the coverage is more than 1, which means that all targets must be covered, and DEAs must be triggered, so the coverage is calculated as 1.
- According to the above two points, if a complete blowout fire occurs, it will lead to structural failure, so in fact, it is meaningless to explore DEAs such as cylinder explosion and hose hydrocarbon leakage caused by blowout fire. However, to reduce the number of domino layers in this case study, the third layer will still discuss the physical consequences of cylinders being heated at high temperatures and exploding.

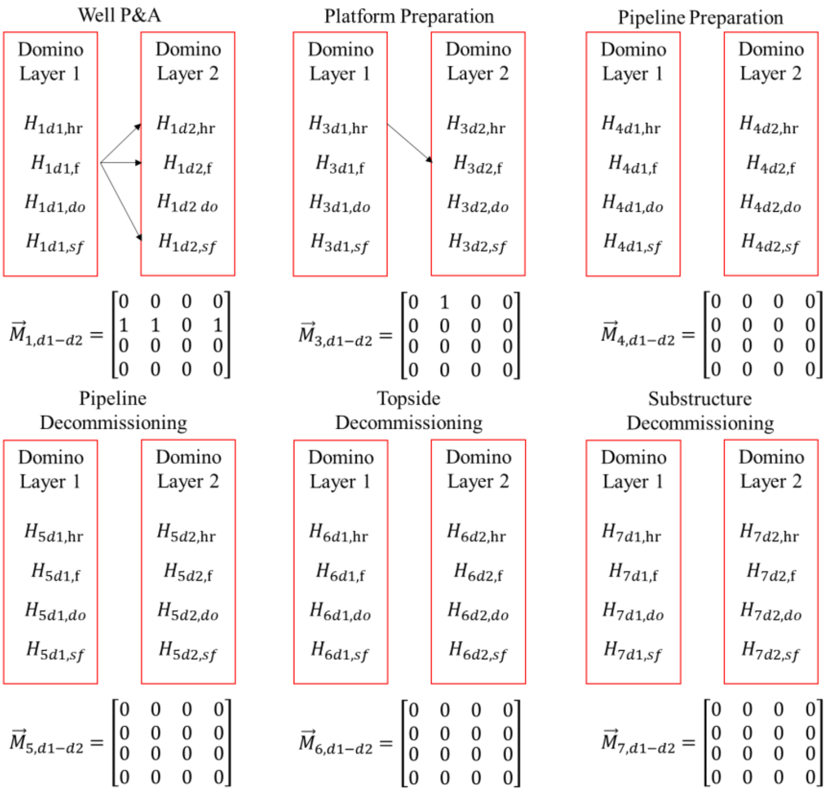


Figure 47. Updated causality matrix for the 1st and 2nd domino layers.

7.4.3 The 2nd Domino Layer

According to 9.2.4, there are three main things to consider in the 2nd domino layer:

- The physical effects of VCE and BLEVE of cylinders caused by blowout fires.
- Physics of jet fires that occur when hose leaks are ignited during platform preparation.
- Verify that the cylinder explosion shock wave may cause the fixing bolt to break.

As mentioned at the end of the above, some evaluation content in this part is not necessary for this case but for extensive case analysis. However, this section's issue of hydrocarbon leakage due to fire is no longer assessed. The reason is that if a fire causes hydrocarbon leakage, the accident will be directly upgraded to a fire instead of a simple hydrocarbon leakage accident that may not develop into a fire. However, this logical sequence still exists in HADES, so Figure 47 shows the causal link between fire and explosion accidents and hydrocarbon leakage accidents.

7.4.3.1 VCE and BLEVE of Cylinders

According to the description and calculation method of VCE and BLEVE in 5.3.7, when the cylinders are not damaged, VCE will occur first when encountering a fire. The explosion itself is overpressure, and the combustible gas will not deflagrate. After meeting an open flame,

BLEVE will happen, and the high-density flammable gas is ignited and deflagrated. However, the transition between these two explosions is speedy, and the boundary needs to be clarified.
For example, suppose a high-pressure cylinder filled with acetylene is affected by a fire, and an overpressure explosion occurs, according to the experimental results(Mirzaei, 2008). In that case, the cylinder will not be completely broken, but a rupture will happen in the upper middle and bottom. At the moment of rupture, high-pressure and high-concentration acetylene gas is released instantly and is ignited when it comes into contact with a fire source. The flame is transmitted to the inside of the cylinder, causing the acetylene to react violently with the air, resulting thermal explosion. The connection between the two blasts is high-speed, so in the analysis, the explosion of the flammable gas cylinder can be directly processed according to BLEVE, and the non-combustible gas, such as the oxygen cylinder, can be processed according to the VCE calculation method.
Table 68 is the physical analysis results of the cylinders' explosion filled with two kinds of gases. Table 69 shows the maximum pressure that three types of explosions can cause to containers at different distances. Table 70 shows the safe distance of different targets for three kinds of explosions.

Table 68. Physical effects of cylinders' explosion.

Gases type	Explosion type	TNT-equivalent weight (kg)	Overpressure at 1m (MPa)	Overpressure at 5m (MPa)	Overpressure at 10m (MPa)	Initial fragments kinetic (KJ)	Explosion Heat (MJ)
Acetylene	VCE	0.88	1.82	0.05	0.02	9.52	NA
Acetylene	BLEVE	74.67	25.39	1.36	0.28	122.56	234.77
Oxygen	VCE	0.52	1.22	0.04	0.01	5.71	NA

Table 69. Explosion effect to targets.

Containers' type	Area (m^2)	Explosion force on container wall in 1m (MN)		
		Acetylene VCE	Oxygen VCE	Acetylene BLEVE
20 ft	15.70	38.61	19.19	398.56
40 ft	31.59	57.56	28.60	802.12
Explosion force on container wall in 5m (MN)		Acetylene VCE	Oxygen VCE	Acetylene BLEVE
20 ft	15.70	0.84	0.62	21.41
40 ft	31.59	1.69	1.24	43.10
Explosion force on container wall in 10m (MN)		Acetylene VCE	Oxygen VCE	Acetylene BLEVE
20 ft	15.70	0.29	0.23	4.33
40 ft	31.59	0.59	0.47	8.70

Table 70. The safe distance of different targets for explosion.

Targets	Safe distance (m)		
	Acetylene VCE	Oxygen VCE	Acetylene BLEVE
Human	3.6	3	16
Structure	0	0	0
Cylinder	0	0	0
Bolts for			
20 feet	0	0	1
40 feet	0	0	1.61

The above analysis temporarily ignores the fragments produced by the cylinder explosion. Because the cylinder's material and purpose differ from the shell's, the fragments produced by the cylinder are tiny. In most cases, there is little or no debris. The cylinder is just cracked and not shattered.

From the above results, the power of VCE is insignificant. As long as the personnel are not too close, there will be no security risk. Other targets will take minor damage too. It is essential to pay attention to the BLEVE of the flammable gas in the tank, which will generate a large amount of explosion energy, including heat energy and shock waves, and the impact range is vast. And it will cause all the fixing bolts of the container to break.

7.4.3.2 Jet Fire of Hose Leakage

According to the DEAs trigger judgment results in 9.2.4, the hose damage caused by the falling accident of the object in the primary layer and hitting the hose will appear as hydrocarbon leakage in the 1st domino layer and be ignited in the 2nd domino layer. Jet fire will occur.

The characteristics of jet fire are also briefly introduced in 5.3.4. The flame is longer and has a clear front. Table 71 shows the dimensions and physical effects of an acetylene hose jet fire. At the same time, Table 72 shows the impact of the fire on various targets.

Table 71. Size of jet fire.

Fire type	Flame surface area of a frustum of a cone Af (m^2)	Rate of heat release Q (KW)	Surface emissive power Ep (KW/m^2)	Heat radiation of fire centre (KW/m^2)	Flame length L (m)	Combustion source diameter Ds (m)	Fame tilt α (°)
Jet fire	5.46E-04	1.43E+02	7.20E+04	952.56	1.45E-03	1.30E-05	82.46
Ignition frequency	Equivalent diameter Deq (m)	Vertical flame length LBV (m)	Width of frustum base W1 (m)	Width of frustum tip W2 (m)	Fraction radiated factor	Relative humidity of atmo.	Location of virtual source zo (m)
3.92E-05	1.72E-02	2.78E-04	1.31E-04	1.86E-02	0.11	0.80	5.87E-01

Table 72. Assessment results for targets and human.

Assessment results	Safe heat radiation for deck in 15 mins (kW/m2)	Safe distance for deck in 15 mins (m)	Safe heat radiation for cylinder in 15 min (kW/m2)	Safe distance for cylinder in 15 mins (m)
	8.87E+01	0.36	4.48E+01	0.50
Safe distance for human in 3 s (m)	Safe heat radiation for hose in 15 mins (kW/m2)	Safe distance for hose in 15 mins (m)	IRPA pp2	PLL pp2
0.86	4.60E+01	0.50	5.51E-11	6.17E-09

According to the results in Tables 71 and 72, it can be seen that the scale of the jet fire caused by the acetylene hose leakage being ignited is very small, and the scope of influence is also very small. However, due to the problem of air flow velocity on the platform, the flame deflection will be severe, thereby accelerating the burning of the hose, which may cause a more serious accident. The distance to cause significant damage to humans and other targets is very small, no more than one meter. However, it should be noted that if there is a cylinder around the jet fire, further DEAs may still occur.

7.4.3.3 Causality Matrix Update

Summarizing the 2nd domino layer's assessment results, fires and explosions are accidents worthy of attention. Once a blowout fire occurs, successive DEAs will cause the misfortune to fall into a vicious circle. Although small fires will not lead to severe accidents, they may continue to escalate into catastrophic accidents if left unchecked.

Figure 48 is drawn based on the results of the 2nd domino layer and the causal matrix between the accidents of the 3rd domino layer. This part will no longer show the process of using TCD to judge because the case study is set to the end of the 2nd domino layer. This cycle can be continued if the user needs to know more domino layers' evaluation results.

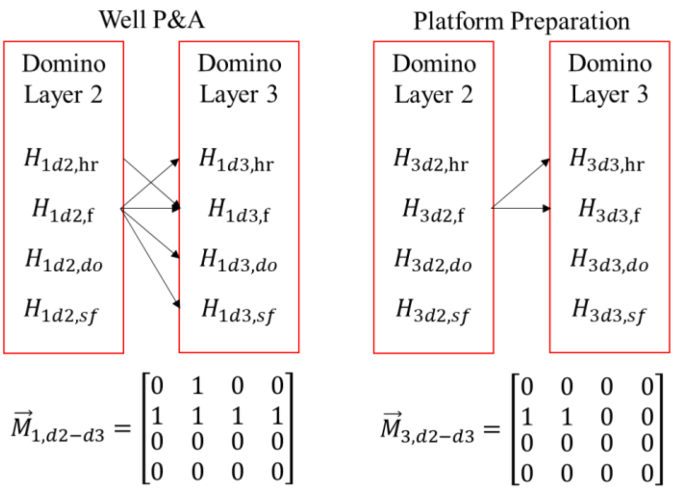


Figure 48. Updated causality matrix for the 2nd and 3rd domino layers.

7.4.4 Summary

After completing the three levels of assessment work, it is necessary to summarize the results to show the engineering risks that decision-makers must face when the NWH project is to take the option of complete removal, as assessed by HADES. Details of the results can refer to the content of the previous part of this chapter. Here directly show the final results of the entire project evaluation.

Table 73. HADES results for NWH decommissioning.

Layers	Accidents	Frequency	IRPA	
			Min	Max
Primary	Hydrocarbon release	1.60E-06	0.00E+00	0.00E+00
	Ship collision	3.52E-04	0.00E+00	0.00E+00
	Dropped objects	5.12E-05	2.05E-06	4.05E-05
1st Domino layer	Hydrocarbon release	1.31E-04	0.00E+00	0.00E+00
	Fire and explosion	1.28E-07	1.01E-09	1.01E-09
	Structural failure	9.38E-02	5.16E-04	5.16E-04
2nd Domino layer	Fire and explosion	3.92E-05	5.51E-11	5.51E-11
	Structural failure	8.00E-05	6.29E-07	6.29E-07
Summary			5.19E-04	5.57E-04

Comparing this result with the IRPA evaluation result 7.00E-04 provided by BP, the order of magnitude is the same, and the result is very close. The author believes that the difference is that HADES didn't consider the risk in onshore dismantling and about vessels themselves, so the value is slight low. However, the characteristics of DEAs— High-impact Low-probability (HILP)—make the result increment in the final evaluation not particularly obvious. Comparing this result with ALARP Standard-1E-03, both evaluation results fully meet the requirements. Comparing some evaluation results with the data of relevant DEAs researchers(Khakzad et al., 2013; Abdolhamidzadeh et al., 2011), it can be found that the magnitude of the evaluation results of HADES in DEAs is consistent with that of related research, such as fire accidents. This shows that the DEAs evaluation performance of HADES is acceptable.

In addition, according to the analysis of the results, the following conclusions can be drawn. The author believes that it is not only of great significance for the comprehensive decommissioning project of NWH but also has reference value for the decommissioning of other facilities:

- By comparing the IRPA result of 4.05E-05 with only the primary layer and the evaluation result of 5.57E-04 considering DEAs, there is a large gap between the two, which shows the necessity of considering DEAs when performing QRA.
- It can be seen from the results that some accidents occur less frequently but cause the same consequences, which leads to a significant increase in the frequency of accidents corresponding to the consequences. For example, in the results, the ship collision and dropped objects of the primary layer may cause structural failure accidents in the 1st domino layer. At the same time, a blowout fire can also lead to structural failure. This leads to a significant increase in the possibility of structural failure accidents.

- Although some accidents occur less frequently, the direct IRPA due to accident characteristics is higher, such as dropped objects accidents. The prevention of such accidents should be one of the critical points in the process of project implementation.
- Blowouts and the resulting fire are undoubtedly the most terrible disaster, and special attention should be paid to preventing blowout accidents during well p&a.
- This result is not shown, but through the analysis of the results of the 2nd domino layer, it can be found that although the scope and intensity of the hose fire are extremely low, if it is not controlled, coupled with the blessing of some special environments, small accidents will gradually be magnified into catastrophic accidents. And the latter is often not obtained by 2 layers' DEAs analysis. The author believe it may need 4 or even 6 layers of domino analysis. At this time, the probability of an accident may have been as low as 10^{-7} or even lower, and it is easy to be ignored but the consequence is also severe.

In summary, HADES has obtained excellent results in evaluating the NWH complete decommissioning project. The author believes that similar methods need to be used in the risk assessment of other facility decommissioning projects for further verification and improvement.

7.5 Impact Assessment Results

Researching the possible environmental and social impacts of decommissioning projects is the last evaluation part of this study. Its practical effect is obtaining the project cost range more accurately to help make better and retrograde decisions. According to the impact assessment methods mentioned in Chapter 6, the focus of this study on the quantitative assessment of adverse impacts is currently focused on the economic losses of energy companies caused by marine pollution caused by engineering accidents. However, some social influences that are very difficult to quantify will not be considered in this study.

First, the environmental status of the NWH facility needs to be clarified. NWH is in the depths of the North Sea, 130km from the shore. The surrounding waters are not used for military purposes, fishing activity is moderate, and only a tiny number of shellfish is produced in the waters near the facility. However, a large number of marine organisms migrate every year in the sea area near the facility. Based on the above information, the sea area near the NWH facility should belong to the open waters of the open sea, and the oil spill may pollute the coastline very little. Still, it is necessary to consider that the drift of the seabed oil spill may cause adverse effects on nearby fisheries and marine animals. The choice of oil spill cleaning methods is not the focus of this study, and decision-makers need to make choices based on the opinions of relevant experts.

According to the equations (151) to (153) and the data in Tables 41 to 43, combined with the blowout volume of the significant blowout accident on the NWH platform for three days - about 76632 cubic meters of crude oil, weighing 53643 tons. Tables 74 to 77 show the cost estimates for different water areas and cleaning methods.

Table 74. Impact assessment results for NWH for near shore oil spill.

	Methods	Ce (M£)	Cs (M£)	Ci (M£)
Near shore	Dispersants	3.29	6.58	9.87
	Burning	1.79	3.58	5.37
	Mechanical	6.58	13.16	19.75
	Manual	13.52	27.04	40.57
	Natural	0.72	1.43	2.15

Table 75. Impact assessment results for NWH for sanctuary oil spill.

	Methods	Ce (M£)	Cs (M£)	Ci (M£)
Sanctuary	Dispersants	3.83	7.66	11.50
	Burning	2.08	4.17	6.25
	Mechanical	7.66	15.33	22.99
	Manual	15.75	31.49	47.24
	Natural	0.83	1.67	2.50

Table 76. Impact assessment results for NWH for fishing oil spill.

	Methods	Ce (M£)	Cs (M£)	Ci (M£)
Fishing	Dispersants	4.96	9.92	14.88
	Burning	2.70	5.39	8.09
	Mechanical	9.92	19.84	29.76
	Manual	20.38	40.75	61.13
	Natural	1.08	2.16	3.23

Table 77. Impact assessment results for NWH for open water oil spill.

	Methods	Ce (M£)	Cs (M£)	Ci (M£)
Open water	Dispersants	2.03	4.06	6.09
	Burning	1.10	2.21	3.31
	Mechanical	4.06	8.12	12.17
	Manual	8.34	16.67	25.01
	Natural	0.44	0.88	1.32

According to the above results, if a blowout and oil leakage accident occurs, the worst case will require an additional cost of 61.13 million pounds, and the minimum additional charge will be 1.32 million pounds. These results can be directly integrated with those obtained by ECES to refine further the basic decommissioning cost estimates obtained by ECES.

7.6 Summaries and Discussions

To date, all MADM-Q assessments have been completed. The engineering cost evaluation conducted by the ECES module obtained the engineering duration and engineering cost evaluation results of the complete removal and decommissioning of 12 fixed facilities. The complete decommissioning of the NWH platform was assessed by HADES, and risks faced by the complete removal of the NWH platform were obtained. Based on the results obtained by HADES, the additional environmental and socioeconomic costs of the complete removal of the NWH platform were assessed by CIES.

The multi-attribute quantitative evaluation decision-making support system composed of these three core modules outperforms the existing multi-attribute evaluation decision-making support system. In some aspects, the pioneering architecture of this system has made a qualitative leap in the accuracy of multi-attribute quantitative evaluation, the depth of evaluation content, and the generality of the system.

However, the above assessments are only for completely removing fixed facilities. As stated in the introduction to Chapter 1, there are several options for decommissioning offshore facilities, and more than simply studying, a complete removal is needed to make the system practical. Therefore, this part will take the NWH platform as a case again, adopt different decommissioning methods to evaluate again, and compare the evaluation results.

7.6.1 Decommissioning Options and Results

In Chapter 1, it was mentioned that there are generally three decommissioning options for offshore facilities, which are complete removal, removal of the topside only, and no removal at all. Although according to the conventions and regulations implemented by the countries around the North Sea, it is only possible to remove them at all, and most of the non-concrete gravity structure facilities cannot meet the standard of partial removal and must be removed entirely. As a multi-attribute quantitative evaluation decision support system, it should still be able to evaluate the other two options.

The NWH platform is still used as the research object. The following will show the cost, risks and compound impact cost increment of the NWH platform when it is not removed at all and only the upper part is removed.

7.6.1.1 Leave Situ.

Leaving the facility completely in place means many engineering steps can be omitted. However, some are indistinguishable from complete removal:

- Well p&a still needs to be done. Regardless of the decommissioning option, a complete and complete closure of the well is required to ensure that the marine environment will not be polluted in the future. Therefore, the cost, time, equipment, workers and other parameters spent on well p&a will not change, and the evaluation results when the option is completely removed can be directly used.
- The time required for platform preparation is similar because even if the platform does not need to be removed, the equipment still needs to be dismantled, all oil storage tanks need to be cleaned, and the conductors still need to be removed after sealing the well. However, a lot of extra work, such as welding lugs on the modules and thermal cutting work for pre-separation of the modules, can be avoided. However, detailed statistics on the time and cost of cutting and welding work in platform decommissioning need to be detailed. Therefore, in this study, the author generally believes that the time and cost of platform preparation, when left in place, are 70% of those required for complete removal.
- Pipeline preparation is still required, only the pipeline needs to be cleaned, and the exposed pipeline will be trenched and buried in the seabed. This does save a lot of time. However, according to Table 36, trenching and burying also require a cost of £25,000/km.
- The remaining parts are not needed, so the engineering duration and cost of the remaining steps and the corresponding risks do not need to be evaluated.

The differences mentioned above in decommissioning steps lead to significant differences in the data entered the evaluation system, see the Appendix Table C-4. After calculation, the comprehensive evaluation results in Table 78 can be obtained. The final cost range is £58.30-730.71M without catastrophic accident, and the IRPA of whole project is 2.50E-09, much lower than facility totally remove.

Table 78. Assessment results for NWH leave situ. option.

Duration prediction (months)	P&A	Platform preparation	Pipeline deco.	Topside removal	Substru. removal	Onshore disposal	Total duration
	56.54	16	2.871	0	0	0	75.41
ECES (M£)	C eng		C admin		C total		
	min	max	min	max	min	max	mid
	53.98	344.48	4.32	27.56	58.30	372.04	215.17
HADES-IRPA	Dropped objects	Fire and explosion	Structural failure	Sum	CIES	C min (M£)	C max (M£)
	1.80E-09	7.04E-10	2.05E-15	2.50E-09		1.32	61.13

7.6.1.2 Topside Removal Only

Removing only the topside without removing the sub-structure is an allowed decommissioning option for CGBS and large fixed platforms. The only difference between this option and complete removal is whether the underwater part of the platform is cut and removed. In terms of engineering steps, it means:

- Well p&a has the exact needs as before, and the corresponding assessment methods for blowout accidents and environmental pollution risks are also the same.
- The platform preparation stage is the same as the complete removal, and the module needs to be pre-separated, so the evaluation method is the same as the complete removal.
- It is more flexible about whether to remove the pipeline. Decision makers can choose to dig a trench to bury it or decide to remove it completely. The evaluation method will be kept from being repeated here. In this case, the option of trenching and burying is used.
- Substructure does not need special treatment since it still does not need to be removed.
- After the topside is removed, it must be moved to the shore for dismantling, so this cost needs to be considered.

Finally, according to the option of removing only the topside, the evaluation results obtained are shown in Table 79. The total cost is expected to be between 77.69-756.23 M£ with an IRPA of 5.16E-04. Compared with no removal, the engineering cost and risk have been significantly improved, especially the engineering risk, which is the same as that of complete removal.

Table 79. Assessment results for NWH topside removal only.

Duration prediction (months)	P&A	Platform preparation	Pipeline deco.	Topside removal	Substru. removal	Onshore disposal	Total duration
	56.54	16.00	2.87	10.32	0	7.47	93.20
ECES (M£)	C eng		C admin		C total		
	min	max	min	max	min	max	mid
	71.94	368.11	5.76	29.45	77.69	397.56	237.63
HADES-IRPA	Dropped objects	Fire and explosion	Structural failure	Sum	CIES	C min (M£)	C max (M£)
	3.59E-09	7.04E-10	5.16E-04	5.16E-04		1.32	61.13

7.6.2 Summary and Discussion

Finally, by summarizing the results of the three decommissioning options, Table 80 and Figures 48 to 50 can be obtained to compare the evaluation results of the three options for NWH platform decommissioning.

Table 80. NWH three decommissioning options assessment results.

Options	ECES			HADES	CIES-Cost increment	
	Total duration	Total Cost				
		min	max	IRPA	min	max
Totally removal	113.26	133.38	418.45	5.57E-04	1.32	61.13
Topside only	93.20	77.69	397.56	5.16E-04	1.32	61.13
Leave situ.	75.41	58.30	372.04	2.50E-09	1.32	61.13

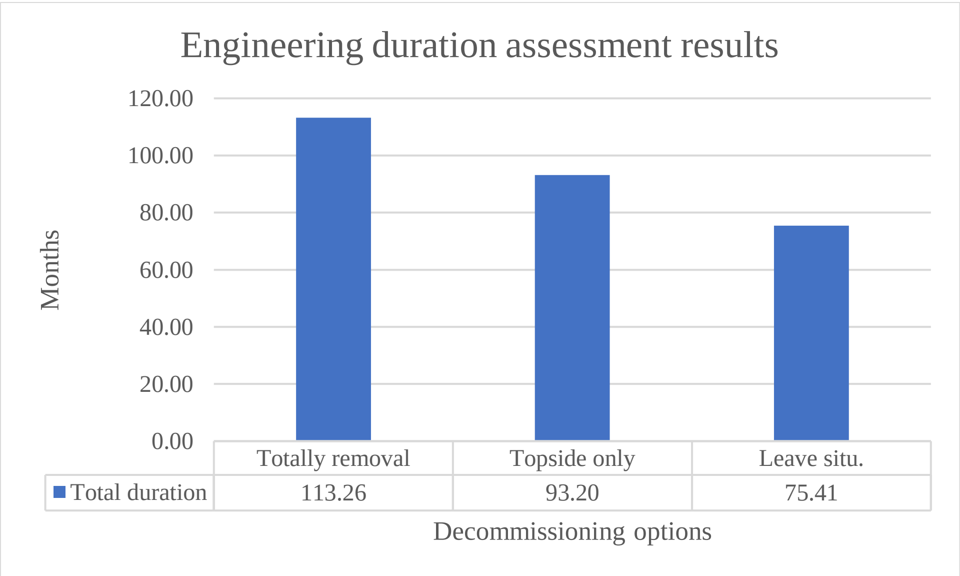


Figure 49. Engineering duration assessment results for three decommissioning options.

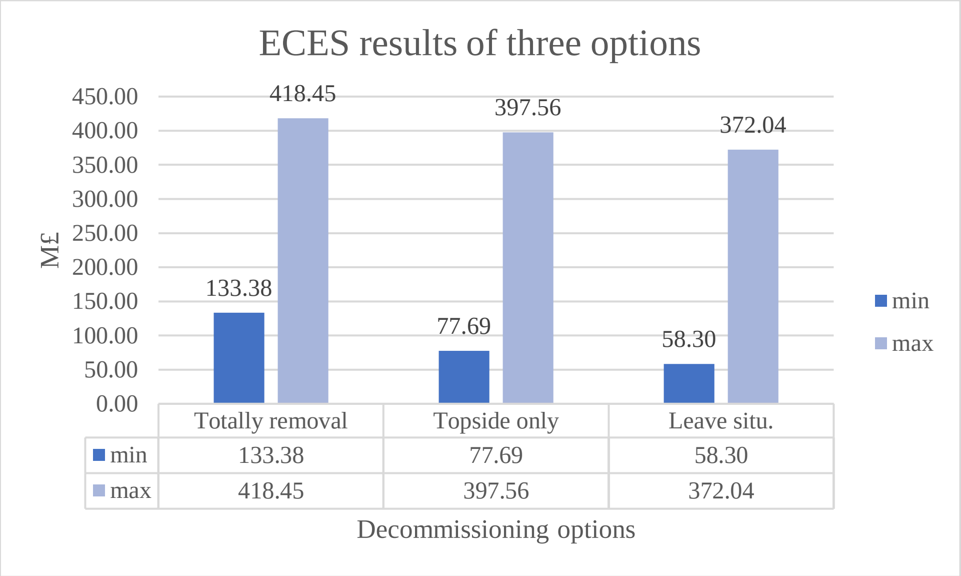


Figure 50. ECES results of three decommissioning options.

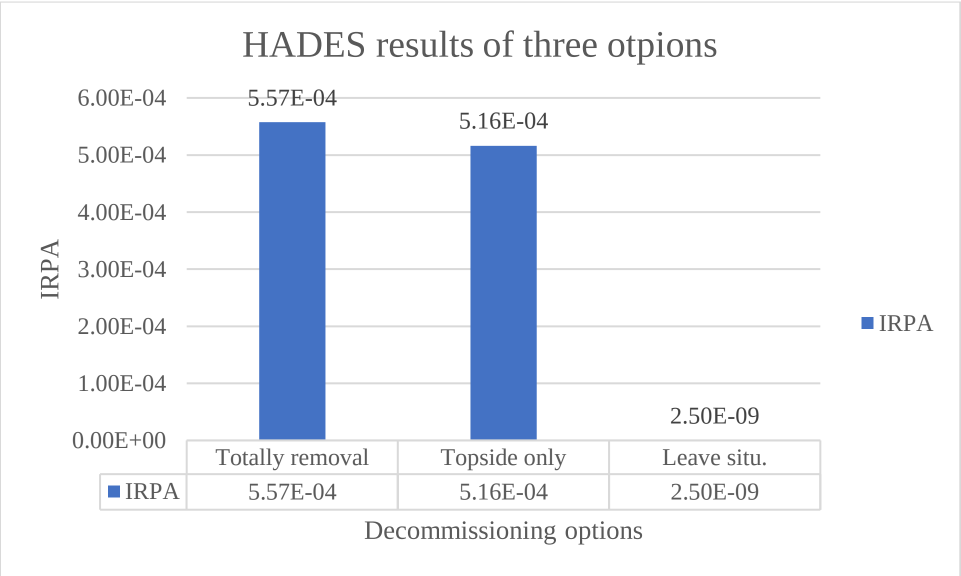


Figure 51. HADES results of three decommissioning options.

The following conclusions can be drawn from the comparison:

- The heavier the facility to be decommissioned, the more time it will take, and the corresponding cost and engineering risk will be more. This is the law of compound common sense.
- Comparing the cost of decommissioning options, it is easy to find that the difference between only removing the topside and leaving it in place or completely removing it is not too significant because the cost of well decommissioning accounts for the majority of the decommissioning. For the three options, no matter how much the weight of the

removed facility is, all wells must be blocked entirely, so the final cost difference can only be reflected in the difference in ship leasing, labor wages and material usage costs.

- Unlike the slight disparity in decommissioning costs, the engineering risk associated with the legacy in-situ option is much lower than the other two options. The reason for this phenomenon is that the time workers are exposed to hazardous environments has been dramatically reduced.
- Since all three options require the complete closure of the wells, the projected incremental cost in adverse effects is the same. As for the pollution caused by typical engineering, this paper does not evaluate it. According to relevant data, this part of the pollution is insignificant, and compared with the pollution caused by blowout accidents, it can usually be ignored.

Summarizing the entire case study, the author believes that all the results from Chapter 7 to Chapter 11 can illustrate some issues and concerns that policymakers should give to decommissioning offshore facilities. These issues are divided into decommissioning options, engineering duration, cost, risk, and impact. These four aspects will be expanded upon below:

- This thesis merely evaluates three mainstream decommissioning options for offshore facilities. Some more practical methods may apply to certain offshore facilities in the North Sea. For example, the platform can be converted into a hotel or offshore entertainment facility, or it can be converted and towed to the vicinity of the wind farm as an operation and maintenance center, etc. You can also think of Southeast Asia. After being reinforced, they sank into the seabed as artificial reefs. Some options can significantly reduce the cost and risk of decommissioning and are worth considering by countries around the North Sea.
- In all reports, the construction period for the decommissioning of offshore facilities has reached several years, but the actual construction time may be only a few months. There are two main reasons for this low efficiency. One is that the sea climate is changeable, and the construction party needs to grasp the weather at the construction site accurately; the other is that some critical equipment and ships cannot be in place on time. The industry has given an appropriate answer to this kind of problem: joint decommissioning, that is, multiple facilities belonging to multiple operating companies in a particular area, are decommissioned together within a certain period. This kind of joint decommissioning can even be transnational. This operation can effectively reduce the waste of the construction period and correspondingly reduce certain costs. However, as mentioned above, a large part of the cost of decommissioning offshore facilities is

the cost of well p&a, especially the number of subsea wells that plays a decisive role. Hence, the cost-saving effect of joint decommissioning has yet to be verified.

- As mentioned above, the cost of decommissioning is significantly affected by the number of wells in the facility. So, in addition to improving engineering efficiency and reducing waiting time, developing new cheap well p&a technologies is also a very effective method. The use of new technologies not only reduces construction costs but also reduces the possibility of construction risks. In addition, cost assessments rely on extensive, fresh market data. Decision makers should frequently update the market data to ensure the assessment results' accuracy.
- According to the assessment results of HADES, it is indispensable to consider DEAs in offshore decommissioning projects. Judging from the joint evaluation results of HADES and CIES, preventing blowout accidents should be the biggest concern of energy companies to avoid unexpected economic losses. In addition, by comparing the HADES evaluation results of leave situ. and the other two decommissioning options, unmanned equipment should be promoted as much as possible, and real-time monitoring of high-altitude operations should be carried out to prevent falling objects from causing damage. Casualties. During decommissioning, a standby ship should be arranged near the facility to patrol to prevent uncontrolled passing vessels from colliding with the platform.

Chapter 8. Conclusions

8.1 Research Findings and Conclusions

Through the research on this subject and the comparison and analysis of the model results, the author found that the MADM-Q with the three modules of cost, risk and impact as the core can quickly and accurately obtain the evaluation results.

- Among them, the bottom-up framework cost assessment model is more accurate and can combine the results of risk and impact assessment, making the model assessment results more accurate.
- Through the QRA model construction process of offshore facility decommissioning risk, it is found that the evaluation of DEAs is necessary for the operation of offshore facility decommissioning risk assessment. The hierarchical domino risk assessment method is intuitive, and the causal relationship is clear.
- The impact of engineering accidents on the environment may be very significant, and the quantitative relationship between them needs to be further studied.

In general, the original intention of this study, the purpose of establishing a multi-attribute quantitative evaluation auxiliary decision-making system for decommissioning offshore facilities in the North Sea, has been achieved. Based on the decommissioning cases of various North Sea facilities and other researchers' results, this study proposes a multi-attribute quantitative evaluation system centered on cost assessment, risk assessment, and composite impact assessment. The three modules in the system use quantitative evaluation methods, which can quickly obtain more accurate evaluation results after inputting data. The accuracy of the results is higher than that of other similar evaluation tools at present, and the author believes that energy companies can directly use it after appropriate upgrades.

8.2 Highlights

This research consists of many innovations and highlights, some of which are even the first in academia and industry, including:

- For the first time, a multi-attribute decision-making support system for decommissioning offshore facilities in the North Sea is constructed fully quantitatively.
- The whole system has strong versatility and uses industrial and empirical equations subject to conditions as much as possible, so it can be applied to other sea areas by slightly modifying the data.
- The system has a wide range of input data sources, and the modular design allows the system to use simulation data to obtain more accurate evaluation results.

- This system framework can be applied to other similar industrial fields and only needs to be modified according to the operating procedures of the industry.
- A top-down cost assessment model based on North Sea data was constructed for the first time.
- A bottom-up cost evaluation model based on the Beihai case was constructed for the first time.
- The cost evaluation models of the two architectures are compared in detail, and the advantages and disadvantages of the two models are elaborated.
- For the first time, a quasi-dynamic, analytic hierarchy process DEAs quantitative risk assessment system HADES is constructed. The system quickly and efficiently captures the engineering risks faced by decommissioning offshore facilities.
- Application of a CIES to the decommissioning of offshore facilities in the North Sea as an unexpected cost incremental correction for cost assessment results.

8.3 Future Works

The author mentioned in many places above that there are still some areas that can be improved in this research and upgraded to more advanced technologies. These upgrades will be gradually realized so that the study can be genuinely put into industrial use.

First of all, although the evaluation result of ECES in this study is better than that of the top-down model, the deviation of the evaluation result of ECES still needs to be corrected in the face of complex decommissioning situations. The reason is that the structure of ECES could be better, and there are few data sources, so it is impossible to obtain real-time and accurate data. Energy companies using their engineering experience and market data access, can refine this in the future.

Second, HADES is still a quasi-dynamic DEAs quantitative evaluation system. Bayesian belief network technology, digital twin technology, machine vision and other state-of-the-art technologies can be combined to make HADES become a real-time dynamic domino risk quantitative assessment system. In addition, HADES cannot quantitatively determine the elements in the causality matrix at present, so the causal factors between accidents can only be established by expert evaluation or the method of bisecting the causal factors. For example, 3 upper-layer events will trigger 1 event in this layer, these initial events will equally divide the causal factors of one triggered event, that is, the causal factor of each trigger chain is 0.33. However, this method is unscientific. The causal factors should be determined by values such as spatial distance, accident propagation speed, and accident intensity attenuation. Even if multiple accidents can trigger a certain domino accident, there are differences in sequence or contribution. It should be these differences that determine the causal factors between accidents.

Finally, CIES needs to be better because it involves socioeconomic issues that are difficult to quantify. Therefore, it is imperative to conduct quantitative research on the attitudes of the public, government, and stakeholders towards accidents and normal pollution in decommissioning projects.

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Appendices

Appendix A. Decommissioned Facilities' Data in North Sea

Table A-1. North Sea Decommissioned Facilities Data.

Platform Name	Water Depth (m)	Type of Facility fixed=1,floater=2, other=3	Decommissioning Total Weight (tons)	Engineering Programme	Well P&A	Pipe and subsea	Platform preparation	Distance to the Coast (km)	Topsides Weight (tons)	Jacket Weight (tons)	Wells Number	Subsea Wells No.	Platform Wells No.	Pipe Length (km)
Brent Field	141.00	1.00	126053.00	120.00	114.00	60.00	63.00	136.00	94600.00	31453.00	49.00	3.00	46.00	97.94
Frigg	98.00	1.00	454630.00	105.00	0.00	12.00	69.00	195.00	57201.00	397429.00	0.00	0.00	0.00	5.87
Horne and Wren	40.60	1.00	545.00	21.00	9.00	7.00	3.00	65.00	90.00	455.00	2.00	0.00	2.00	41.20
Indefatigable	31.00	1.00	12548.00	72.00	42.00	42.00	42.00	94.00	8283.00	4265.00	19.00	0.00	19.00	27.90
Leman BH	37.50	1.00	1605.00	48.00	0.00	0.00	7.00	50.00	1039.00	566.00	0.00	0.00	0.00	0.00
Maureen	95.60	1.00	191750.00	42.00	7.00	2.00	21.00	260.00	19000.00	92750.00	20.00	0.00	20.00	32.30
Miller	103.00	1.00	47316.00	96.00	27.00	2.00	60.00	230.00	28732.00	18584.00	22.00	7.00	15.00	0.90
North west hutton	144.00	1.00	37500.00	132.00	25.00	15.00	48.00	130.00	20000.00	17500.00	40.00	7.00	33.00	26.10
Thames	32.50	1.00	13752.00	60.00	27.00	16.00	39.00	80.00	8929.00	4823.00	8.00	3.00	5.00	149.20
Wellland	37.00	1.00	1570.00	15.00	10.00	9.00	12.00	72.00	1000.00	570.00	5.00	3.00	2.00	53.00
Camelot CA	11.00	1.00	1820.00	10.00	2.00	0.50	4.50	80.00	1220.00	600.00	6.00	6.00	0.00	31.32
MCP-01	94.00	1.00	13500.00	36.00	0.00	3.00	18.00	175.00	13500.00	0.00	0.00	0.00	0.00	4.50
Schiehallion	425.00	2.00	0.00	27.00	0.00	18.00	1.00	130.00	154000.00	6000.00	0.00	0.00	0.00	75.45
Shelly	94.00	2.00	0.00	6.00	1.00	2.00	2.00	192.00	0.00	0.00	2.00	2.00	0.00	2.02
FFFA	71.00	2.00	0.00	45.00	23.00	40.00	0.00	330.00	0.00	0.00	12.00	12.00	0.00	0.00
IVRR	140.00	2.00	0.00	72.00	45.00	66.00	0.00	193.00	0.00	0.00	18.00	18.00	0.00	77.91
Orwell	30.00	3.00	0.00	48.00	9.00	9.00	0.00	99.50	0.00	0.00	3.00	3.00	0.00	102.30

Rose wellhead	24.00	3.00	0.00	18.00	2.00	6.00	0.00	54.00	0.00	0.00	1.00	1.00	0.00	18.67
Stamford	36.10	3.00	0.00	5.00	1.00	2.00	0.00	140.00	0.00	0.00	1.00	1.00	0.00	15.25
Tristan NW	35.50	3.00	0.00	1.00	0.30	0.50	0.00	76.00	0.00	0.00	2.00	2.00	0.00	15.50
Wissey	36.00	3.00	0.00	48.00	8.00	7.00	0.00	100.00	0.00	0.00	1.00	1.00	0.00	20.00
Don	160.00	3.00	0.00	72.00	66.00	42.00	0.00	230.00	0.00	0.00	7.00	7.00	0.00	70.20
Kittiwake	85.00	3.00	0.00	22.00	0.00	21.00	0.00	135.00	0.00	0.00	0.00	0.00	0.00	3.00
Linnhe	122.00	3.00	0.00	3.00	0.00	0.30	0.00	354.00	0.00	0.00	0.00	0.00	0.00	28.15
Arthur	11.00	3.00	0.00	16.00	8.00	6.00	0.00	42.00	0.00	0.00	4.00	4.00	0.00	70.14
Gawain	31.00	3.00	0.00	12.00	6.00	4.00	0.00	86.00	0.00	0.00	3.00	3.00	0.00	39.80

(continued)

Platform Name	2” length	2.5” length	3” length	3.5” length	4” length	5” length	6” length	8” length	10” length	12” length	14” length	16” length	18” length	20” length
Brent Field	0.00	0.00	0.00	0.00	12.82	0.00	0.00	5.03	6.80	0.00	0.00	8.59	0.00	4.00
Frigg	0.88	0.00	0.00	0.00	1.37	0.00	0.00	1.09	0.00	0.00	0.00	0.00	0.00	0.00
Horne and Wren	0.00	20.60	0.00	0.00	0.00	0.00	0.00	0.00	20.60	0.00	0.00	0.00	0.00	0.00
Indefatigable	0.00	0.00	6.00	0.00	0.00	0.00	0.00	0.00	2.40	3.30	0.00	3.20	0.00	3.90
Leman BH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maureen	10.00	0.00	0.00	0.00	10.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Miller	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.27	0.00
North west hutton	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	13.00	0.00	0.00	0.00	0.00	12.85
Thames	0.00	0.00	0.00	0.00	14.10	15.70	0.00	29.90	0.00	0.00	0.00	0.00	0.00	0.00
Wellland	0.00	0.00	17.50	0.00	0.00	0.00		18.00	0.00	0.00	0.00	17.50	0.00	0.00
Camelot CA	0.00	0.00	1.24	14.42	0.00	0.00	1.23	0.00	0.00	14.42	0.00	0.00	0.00	0.00
MCP-01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00
Schiehallion	0.53	0.00	1.10	0.00	3.05	0.00	0.82	16.56	49.96	3.43	0.00	0.00	0.00	0.00

Shelly	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.02	0.00	0.00	0.00	0.00	0.00	0.00
FFFA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IVRR	0.53	0.00	0.00	0.00	3.90	3.41	0.00	30.07	0.00	0.00	40.00	0.00	0.00	0.00
Orwell	0.00	0.00	33.90	0.00	34.50	0.00	0.00	0.00	0.00	0.00	0.00	33.90	0.00	0.00
Rose wellhead	0.00	0.00	0.00	0.00	9.40	0.00	0.00	0.00	9.27	0.00	0.00	0.00	0.00	0.00
Stamford	0.00	0.00	0.00	0.00	0.00	7.68	7.57	0.00	0.00	0.00	0.00	0.00		0.00
Tristan NW	0.00	0.00	0.00	0.00	0.00	0.00	15.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wissey	0.00	0.00	0.00	0.00	10.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00
Don	0.00	0.00	17.70	0.00	17.70	0.00	0.00	34.80	0.00	0.00	0.00	0.00	0.00	0.00
Kittiwake	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Linnhe	0.00	0.00	0.00	0.00	0.00	0.00	28.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arthur	0.00	0.00	5.97	0.00	0.00	0.00	29.20	5.97	0.00	29.00	0.00	0.00	0.00	0.00
Gawain	0.00	0.00	0.00	0.00	0.00	19.90	0.00	0.10	0.00	19.80	0.00	0.00	0.00	0.00

(continued)

Platform Name	24” length	26” length	28” length	30” length	32” length	36” length	flushing water /gal	flushing water /m³	250% flushing volume/m³	leave situ pipe length km	remove pipe length	Subsea Structure Number	Subsea structure Weight	Trenching Vessel (days)
Brent Field	13.40	0.00	3.00	40.30	0.00	4.00	7.57E+06	2.86E+04	7.16E+04	90.67	7.27	4.00		114.00
Frigg	0.47	2.07	0.00	0.00	0.00	0.00	2.36E+05	8.93E+02	2.23E+03	0.00	5.87	0.00	0.00	0.00
Horne and Wren	0.00	0.00	0.00	0.00	0.00	0.00	2.93E+05	1.11E+03	2.77E+03	41.20	0.00	0.00	0.00	0.00
Indefatigable	9.10	0.00	0.00	0.00	0.00	0.00	1.12E+06	4.25E+03	1.06E+04	27.90	0.00	0.00	0.00	0.00
Leman BH	0.00	0.00	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00
Maureen	2.30	0.00	0.00	0.00	0.00	0.00	2.52E+05	9.55E+02	2.39E+03	32.30	0.00	1.00	79.20	0.00
Miller	0.00	0.00		0.27	0.00	0.00	5.63E+04	2.13E+02	5.33E+02	0.00	0.90	0.00	0.00	0.00
North west hutton	0.00	0.00	0.00	0.00	0.00	0.00	8.63E+05	3.27E+03	8.17E+03	26.10	0.00	0.00	0.00	29.00

Thames	89.50	0.00	0.00	0.00	0.00	0.00	7.24E+06	2.74E+04	6.85E+04	149.20	0.00	5.00	405.00	0.00
Wellland	0.00	0.00	0.00	0.00	0.00	0.00	7.75E+05	2.93E+03	7.33E+03	53.00	0.00	3.00	210.00	0.00
Camelot CA	0.00	0.00	0.00	0.00	0.00	0.00	3.09E+05	1.17E+03	2.93E+03	31.32	0.00	0.00	0.00	0.00
MCP-01	0.00	0.00	0.00	0.00	4.00	0.00	5.70E+05	2.16E+03	5.39E+03	4.50	0.00	1.00	256.00	0.00
Schiehallion	0.00	0.00	0.00	0.00	0.00	0.00	8.89E+05	3.36E+03	8.41E+03	75.45	0.00	0.00	0.00	0.00
Shelly	0.00	0.00	0.00	0.00	0.00	0.00	1.73E+04	6.55E+01	1.64E+02	2.02	0.00	2.00	4574.87	0.00
FFFA	0.00	0.00	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	4.00	300.00	0.00
IVRR	0.00	0.00	0.00	0.00	0.00	0.00	1.33E+06	5.02E+03	1.26E+04	0.00	77.91	5.00	1659.30	0.00
Orwell	0.00	0.00	0.00	0.00	0.00	0.00	1.28E+06	4.83E+03	1.21E+04	102.30	0.00	1.00	200.00	21.00
Rose wellhead	0.00	0.00	0.00	0.00	0.00	0.00	1.44E+05	5.46E+02	1.37E+03	18.67	0.00	1.00	33.70	0.00
Stamford	0.00	0.00	0.00	0.00	0.00	0.00	6.22E+04	2.35E+02	5.89E+02	15.25	0.00	1.00	33.70	0.00
Tristan NW	0.00	0.00	0.00	0.00	0.00	0.00	7.47E+04	2.83E+02	7.07E+02	15.50	0.00	1.00	22.00	0.00
Wissey	0.00	0.00	0.00	0.00	0.00	0.00	1.07E+05	4.05E+02	1.01E+03	20.00	0.00	1.00	85.00	0.00
Don	0.00	0.00	0.00	0.00	0.00	0.00	3.57E+05	1.35E+03	3.38E+03	70.20	0.00	1.00	64.40	0.00
Kittiwake	0.00	3.00	0.00	0.00	0.00	0.00	2.71E+05	1.03E+03	2.57E+03	0.00	3.00	1.00	53.60	0.00
Linnhe	0.00	0.00	0.00	0.00	0.00	0.00	1.36E+05	5.13E+02	1.28E+03	28.08	0.07	1.00	200.00	0.00
Arthur	0.00	0.00	0.00	0.00	0.00	0.00	7.58E+05	2.87E+03	7.17E+03	70.14	0.00	4.00	355.00	0.00
Gawain	0.00	0.00	0.00	0.00	0.00	0.00	4.49E+05	1.70E+03	4.25E+03	39.80	0.00	1.00	89.00	0.00

(continued)

Platform Name	DSV (days)	HLV (days)	SSCV (days)	Support Vessel (days)	Vessel speed m/s	Containers 20ft	Containers 40ft	Containers 20ft Open	Racks	Oxygen Cylinders	Acetylene Cylinders	Workers	Experts	Managers
Brent Field	371.00	152.00	0.00	543.00	2.00	1000	500	350	1000	1500	2500	500	50	10
Frigg	57.00	0.00	248.00	500.00	2.00	600	300	210	600	900	1500	250	20	6
Horne and Wren	43.00	14.00	0.00	100.00	2.00	2	0	2	2	2	5	10	1	1
Indefatigable	7.00	61.00	0.00	343.00	2.00	80	40	24	80	120	200	60	15	2
Leman BH	67.00	67.00	0.00	95.00	2.00	10	5	3	10	15	25	10	2	1
Maureen	119.00	105.00	0.00	200.00	2.00	200	100	68	200	300	500	100	10	2
Miller	0.00	100.00	50.00	228.00	2.00	200	100	68	200	300	500	100	10	2
North west hutton	0.00	143.00	52.00	314.00	2.00	200	100	68	200	300	500	100	10	2

Thames	110.00	40.00	0.00	120.00	2.00	89	45	30	89	134	223	45	4	4
Wellland	45.00	28.00	0.00	35.00	2.00	10	5	3	10	15	25	5	1	1
Camelot CA	20.00	14.00	0.00	0.00	2.00	12	6	4	12	18	31	6	1	1
MCP-01	20.00	120.00	0.00	240.00	2.00	135	68	46	135	203	338	68	7	2
Schiehallion	14.00	14.00	0.00	64.00	2.00	1540	770	524	1540	2310	3850	770	77	5
Shelly	28.00	21.00	0.00	40.00	2.00									
FFFA	60.00	60.00	0.00	107.00	2.00									
IVRR	72.00	62.00	0.00	342.00	2.00									
Orwell	21.00	21.00	0.00	228.00	2.00									
Rose wellhead	28.00	7.00	0.00	43.00	2.00									
Stamford	36.00	3.00	0.00	45.00	2.00									
Tristan NW	5.00	0.00	0.00	3.00	2.00									
Wissey	21.00	14.00	0.00	114.00	2.00									
Don	100.00	114.00	0.00	171.00	2.00									
Kittiwake	50.00	0.00	0.00	60.00	2.00									
Linnhe	7.00	7.00	0.00	7.00	2.00									
Arthur	50.00	18.00	0.00	60.00	2.00									
Gawain	30.00	9.00	0.00	30.00	2.00									

(continued)

Platform Name	Drill Cutting Pile (m³)	Preparation/Removal and Disposal Cost (M£)	Well P&A Cost (M£)	Pipelines Cost (M£)	Subsea Installation Cost (M£)	Drill Cutting Cost (M£)	Waste Cost (M£)	Seabed Clean up (M£)	Post DE Cost (M£)	Total Cost (M£)
Brent Field	37755/9m £									400.61
Frigg	0.00	633.43	0.00	22.70	0.00	0.00	0.00	8.46	5.40	669.99
Horne and Wren	0.00	13.00	8.00	0.00	0.00	0.00	0.00	0.00	0.50	21.50
Indefatigable	0.00	137.60		17.20	0.00	0.00	0.00	0.00	0.00	154.80
Leman BH	0.00	13.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.80
Maureen	0.00	142.50		7.50						150.00
Miller	0.00									300.00
North west hutton	0.00	230.00		15.00						246.00
Thames	0.00	43.00	40.00	6.60	6.00				0.50	96.10
Wellland	0.00	10.82	13.94	5.76	2.70					33.22
Camelot CA	0.00	6.30	7.50	4.70	0.00					21.00
MCP-01	0.00	201.10	0.00	0.00	5.00				5.40	211.50
Schiehallion	0.00	217.50	0.00	74.10	0.00		37.80		0.00	329.40
Shelly	0.00	8.10	15.30	3.30	4.60				1.00	32.30
FFFA	0.00	44.60	221.30							265.90
IVRR	0.00	85.40	343.90							429.30

Orwell	0.00	0.00	14.00		5.00				0.50	19.50
Rose wellhead	0.00	0.00	12.30	8.00					0.10	20.40
Stamford	0.00	0.00	10.20	6.60					0.00	16.80
Tristan NW	0.00	0.00	6.90		2.90				2.00	11.80
Wissey	0.00	0.00	5.00		3.00				0.50	8.50
Don	0.00	0.00				0.00		0.00		150.00
Kittiwake	0.00	0.00	0.00	2.80	5.70	0.00	0.00	0.00	0.00	8.50
Linnhe	0.00	0.00	0.00	0.00	3.87	0.00	0.00	0.00	0.00	7.56
Arthur	0.00	0.00	33.00	3.40	3.50	0.00			0.20	44.10
Gawain	0.00	0.00	25.00	1.70	4.60	0.00			0.50	31.80

Appendix B. General Data

Table B-1. Material Data.

Categories	Density (kg/m3)	Young's module (MP)	Yield strength (MP)	Ultimate Tensile Strength (MP)	Module of Rupture (Mpa)	KIC (Mpa/m2)	GIC (KJ/m2)	Possion's ratio	Elongation	Yield Strain	Thermal elongation	Dynamic yeild strength (Mpa)	Critical temperature (℃)
Structure steel	7850	200000	350	400	205	150	112.5	0.265	0.15	0.02	0.007	490	500
Stainless steel	7860	180000	502	860	205	50	14	0.25	0.4	0.02	0.010	490	760
NBR	1100	4	0	36			13		5.65				100
Crude oil	700												550
Nature gas/methane	0.43												
Acetylene	1.1												
Oxygen	1.43												
Propane	493												

(continued)

Categories	Specific heat ratio	Specific heat (KJ/kgK)	Molecular weight (kg/kmol)	Heat of vaporisation (KJ/kg)	Latent Heat of Vaporization (kJ/mol)	Combustion efficiency	Heat of combustion (kJ/kg)	Flame temperature (℃)	Emissivity of air	Stefan-Boltzmann Constant (KW/m2K4)	Gas constant (KJ/KgK)	Coefficient discharge Cd
Structure steel		0.46							0.8	5.67E-12		
Stainless steel		0.50							0.8	5.67E-12		
NBR		2.00							0.8	5.67E-12		
Crude oil	0.5	0.00	100	250		0.35	42000	3815	0.8	5.67E-12		0.62
Nature gas/methane	1.3	2.25	16	510	8160	0.10	55500	1015.85	0.8	5.67E-12	8.314	0.62
Acetylene	1.25	1.67	26	614	15964	0.40	50200	3480	0.8	5.67E-12	8.314	0.62
Oxygen	1.4	0.92	32	106	3.41	na	na	na	0.8	5.67E-12	8.314	0.62
Propane	1.13	1.63	45	444	19980	0.27	50340	2526	0.8	5.67E-12	8.314	0.62

Table B-2. Vessels' info.

Vessel states	Vessel categories	Number	length (m)	width (m)	weight (t)	distance (m)	speed (m/s)	lane width (m)
Drifting	supply vessel	10	167.20	25.00	27200	1000	0.50	0
	barges	10	91.40	27.40	8000	20	0.50	0
	HLV	1	154.00	86.00	73877	20	0.50	0
Navigating	supply	900	167.20	25.00	27200	10000	2.00	1600
	0-1500	180	139.95	21.50	17715	10000	2.00	1600
	1500-40000	540	211.90	29.80	46259	10000	2.00	1600
	>40000	0	204.90	32.20	60681	10000	2.00	1600
	fishing	180	20.00	12.40	180	10000	2.00	1600

Table B-3. Containers' info.

waste containers	length (m)	width (m)	height (m)	full weight (kg)	net weight (kg)	shadow area (m2)	Number
10 feet	2.991	2.438	2.591	10320	2010	7.29	0
20 feet 1	6.058	2.438	2.591	24000	2150	14.77	100
20 feet 2	6.058	2.438	2.896	24000	2420	14.77	100
20 open 1	6.058	2.438	2.591	30480	2350	14.77	34
20 open 2	6.058	2.438	2.591	30480	2300	14.77	34
40 feet	12.192	2.438	2.591	30480	4700	29.72	100

Table B-4. Human body info.

	Height (m)	Width (m)	Thickness (m)	Mass (kg)	Total number	Working hour
Human	1.799	0.476	0.25	80	112	260000

Table B-5. Bolts info.

	Diameter (m)	Length (m)	Material	Number per equip.	Shear strength (Mpa)	Thread area (m2)
Bolts info	0.0635	0.1	stainless steel	4	620	0.02

Table B-6. Hose info.

	Diameter (m)	Inner diameter (m)	Working pressure (MP)	Burst pressure (MP)	Thickness (m)	Density (kg/m)	Length (m)	Shadow area (m2)
Hose info.	0.017	0.01	2	6	0.0035	0.205	2000	34

Table B-7. Rack info.

	Dimension (m)	Thickness (m)	Cylinder number	Number	Gross weight (kg)	Net weight (kg)
Rack	2.075*1.92*2.335	0.018	64	200	8000	6500

Table B-8. Cylinder info.

Cylinder info	Pressure (MP)	Temperature (℃)	Thickness (m)	Volume (m3)	Diameter (m)	Height (m)	Inner diameter (m)	Gross weight (kg)	Acetone contents (kg)	Gas capacity (m3)	Net weight (kg)	Kic mini (Mpa/m-2)	Gic (KJ/m2)
	15	16	0.018	0.04	0.23	1.36	0.194	18.6	12.4	6.2	6.2	93.5	53.37

Appendix C. North West Hutton Platform Data

Table C-1. NWH Platform Info.

Name	Location	Distance form land (km)	Water depth (m)	Facility category	Platform width (m)	Platform length (m)	Platform height (m)	Platform height LAT (m)	Platform weight (t)	Platform stiffness (MN/m)	Natural frequency	Containers	Failure loss (M£)
North West Hutton	61 06’23.950” N, 01 18’32.974”E	130	144.3	Jacket	78	61	254	109.7	37500	3746456.693	0.316078332	368	100

Sea & weather	Significant wave height (m)	Current speed (m/s)	Wind speed (m/s)	Current direction	Wind direction	Average temperature (℃)	Ambient pressure (MP)
	11.6	0.73	25.9	list	list	16	0.1

Topside	Weight (t)	Thickness (m)	Module number	Modules weight	total deck area (m2)	Section factor (/m)	crane number	crane height LAT (m)	crane radius (m)	crane deck area (m2)	crane sea area (m2)	lifting height (m)	lifting number	friction factor	main deck LAT (m)	second deck LAT (m)	MSF LAT (m)	evaporation rate (kg/m2s)
	20160	0.025	22	list	13024.627	300	2	53.7	30	2370.7	2700.4	26	568	0.3	44.7	33.7	24.7	0.094

Jacket	Weight (t)	Pile diameter (m)	Pile thickness (m)	Pile penetration depth (m)	Footing area diameter (m)	Seabed resistance torque (MNm)	Gravity stabilizing moment (MNm)	Resistance torque (MNm)	Pieces
	17470	1.54	0.0022	62	92.5477707	1835.13	17005.65	18840.78	248

Well	Well number	Well depth (m)	Reservoir pressure (MPa)	Reservoir temperature (℃)	Plug length L (m)	Tube casing diameter (m)	Cross-section of cement 1 (㎡)	Cement 1 top depth (m)	Cement 2 top depth (m)	Surface cement top depth (m)	Coefficient discharge Cd	BOP failure probability
	40	3657	52	137	30	0.244	0.05	0	-200	-3657.6	0.62	0.01

Table C-2. Lane info. of NWH.

Lane info.	Lane number	Lane distance	Vessel number	Lane width	Ship categories	Speed (m/s)	Ship length	Ship width
	5	10000	1800	1600	C-3	2	C-3	C-3

Table C-3. Vessels' data for collision assessment.

Vessel states	Vessel categories	Number	length (m)	width (m)	weight (t)	distance (m)	speed (m/s)	lane width (m)
Drifting	supply vessel	10	167.20	25.00	27200	1000	0.50	0
	barges	10	91.40	27.40	8000	20	0.50	0
	SSCV	1	154.00	86.00	73877	20	0.50	0
Navigating	supply	900	167.20	25.00	27200	10000	2.00	1600
	0-1500	180	139.95	21.50	17715	10000	2.00	1600
	1500-40000	540	211.90	29.80	46259	10000	2.00	1600
	>40000	0	204.90	32.20	60681	10000	2.00	1600
	fishing	180	20.00	12.40	180	10000	2.00	1600

Table C-4. Data for leave situ. option.

North West Hutton	Water depth (m)	Type of facility fixed=1, floater=2, other=3	Decommissioning total weight (t)	Operating period (months)	P&A	Platform preparation	Pipeline preparation	Pipeline & sub-facilities deco.	Topside deco.	Substru. Deco.	Onshore disposal	To the coast (km)	Topsides weight (tons)	Jacket weight (tons)	Wells number
	144	1	0	122.3	24	24	0	15	4	3.3	52	130.00	20000.00	0.00	40.00
	Subsea wells No.	Platform wells No.	Pipe length (km)	2” length	2.5” length	3” length	3.5” length	4” length	5” length	6” length	8” length	10” length	12” length	14” length	16” length
	7.00	33.00	26.10	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	13.00	0.00	0.00	0.00
	18” length	20” length	24” length	26” length	28” length	30” length	32” length	36” length	Flushing water /gal	Flushing water /m³	250% flushing volume/ m³	Leave situ pipe length (km)	Remove pipe length (km)	Subsea structure number	Subsea structure weight (t)
	0.00	12.85	0.00	0.00	0.00	0.00	0.00	0.00	8.63E+05	3267.79	8169.47	26.10	0.00	0.00	0.00

	Trenching vessel (days)	DSV (days)	HLV (days)	SSCV (days)	Support vessel (days)	Vessel speed (kn)	Containers 20ft	Containers 40ft	Containers 20ft Open	Racks	Oxygen cylinders	Acetylene cylinders	Workers	Experts	Managers
	29.00	0.00	0.00	0.00	226.23	12.00	100	50	34	0	0	0	100	10	2

Table C-5. Data for topside removal only.

North West Hutton	Water depth (m)	Type of facility fixed=1, floater=2, other=3	Decommissioning total weight (t)	Operating period (months)	P&A	Platform preparation	Pipeline preparation	Pipeline & sub-facilities deco.	Topside deco.	Substru. Deco.	Onshore disposal	To the coast (km)	Topsides weight (tons)	Jacket weight (tons)	Wells number
	144	1	20000.00	122.3	24	24	0	15	4	3.3	52	130.00	20000.00	0.00	40.00
	Subsea wells No.	Platform wells No.	Pipe length (km)	2” length	2.5” length	3” length	3.5” length	4” length	5” length	6” length	8” length	10” length	12” length	14” length	16” length
	7.00	33.00	26.10	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	13.00	0.00	0.00	0.00
	18” length	20” length	24” length	26” length	28” length	30” length	32” length	36” length	Flushing water /gal	Flushing water /m³	250% flushing volume/ m³	Leave situ pipe length (km)	Remove pipe length (km)	Subsea structure number	Subsea structure weight (t)
	0.00	12.85	0.00	0.00	0.00	0.00	0.00	0.00	8.63E+05	3267.79	8169.47	26.10	0.00	0.00	0.00
	Trenching vessel (days)	DSV (days)	HLV (days)	SSCV (days)	Support vessel (days)	Vessel speed (kn)	Containers 20ft	Containers 40ft	Containers 20ft Open	Racks	Oxygen cylinders	Acetylene cylinders	Workers	Experts	Managers
	29.00	0.00	70.00	0.00	226.23	12.00	200	100	68	200	300	500	100	10	2