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Research article

Bottom-up formulations for the multi-criteria decision analysis of oil and gas pipeline decommissioning in the North Sea: Brent field case study

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ABSTRACT

Many Oil and Gas (O&G) fields in the North Sea have produced their economically recoverable reserves and have entered the decommissioning phase or are close to cessation of production. The subsequent O&G decommissioning process involves a range of stakeholders with specific interests and priorities. This range of inputs to the process highlights the necessity for the development of multi-criteria decision frameworks to help guide the decision-making process. This study presents bottom-up formulations for the economic, environmental, and safety risk criteria to support the multi-criteria decision analysis within the Comparative Assessment (CA) of O&G pipeline decommissioning projects in the North Sea. The approach adapts current guidelines in the O&G industry and considers a range of parameters to provide estimations for the costs, energy usage, greenhouse gas emissions, and safety risks. To verify the effectiveness of the proposed bottom-up formulations, the longest oil export pipeline in the Brent field, PL001/N0501 is selected as a case study. The numerical results revealed the consistency of the results obtained from the proposed approach with those reported in the technical documents by industry. In most cases, the formulations provide estimates with less than 10% differences for the costs, energy usage, emissions, and safety risks. Based on the proposed multi-criteria formulations, the study also presents the use of an immersive decision-making environment within a marine simulator system to help inform the decision-making process by stakeholders.

1. Introduction

During the 1960s and 70s, many large-scale platforms, pipelines, and infrastructure assets were installed on the seabed in the UK Continental Shelf (UKCS) for Oil and Gas (O&G) production (Martins et al., 2023; Nguyen et al., 2013). Since then, many of these O&G fields have produced their economically recoverable reserves and have reached or are approaching the end of their lifetime, leaving the cessation of production as an inevitable option for operators (Vidal et al., 2022). The UK is a part of the Convention for the Protection of the Marine Environment of the North-East Atlantic, or OSPAR, which strictly forbids any offshore installations to be left on the seabed, with limited exceptions (Knights, 2024; Torabi and Tababaye Nejad, 2021). Hence, the operators must take measures to decommission their assets in the North Sea Region (NSR), cognisant of OSPAR's principles. According to current estimations, over half of all O&G fields in the UKCS are already approaching the end of their lifetime (Offshore Energy UK (OEUK)) with an estimated decommissioning cost of about £40 bn by 2050 (North Sea Transition Authority (NSTA), 2023), which reveals the scale of the economic burden of decommissioning on the country and the sector.

Engineering activities and projects have profound economic, environmental, societal, and safety impacts which should be considered within the multi-criteria decision-making models (Gherghel et al., 2020; Gitinavard et al., 2020; Man et al., 2020; Mousavi and Gitinavard, 2019; Terra dos Santos et al., 2023; Vlachokostas et al., 2021). Decommissioning refers to a set of measures and activities to remove the O&G assets and return the seabed to its original condition, where possible. Decommissioning activities may include, but are not limited to, well plugging and abandonment, asset cleaning from hydrocarbons, removal of platforms, pipelines, and subsea structures, potential repurposing as well as site restoration, and recycling. Due to the huge scale of O&G decommissioning activities, they have significant technical, economic, environmental, safety, and societal impacts. Critically, ensuring the

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Abbreviations

Accommodation Work Vessel	AWV
Business, Energy & Industrial Strategy	BEIS
Comparative Assessment	CA
Crane Support Vessel	CSV
Decommissioning Programme	DP
Department for Energy Security and Net Zero	DESNZ
Diamond Wire Cutting	DWC
Diving Support Vessel	DSV
Fatal Accident Rate	FAR
Institute of Petroleum	IoP
Jack-Up Vessel	JUV
Offshore Petroleum Regulator for Environment and Decommissioning	OPRED
Oil and Gas	O&G
Pipe-Lay Vessel	PLV
Potential Loss of Life	PLL
Remotely Operated Vessel	ROV
Rock Dumping Vessel	RDV
ROV Support Vessel	ROVSV
Technical Document	TD
Trenching Support Vessel	TSV
UK Continental Shelf	UKCS
Wait on Weather	WoW

protection of the marine environment adds additional complexities to decommissioning projects (Burdon et al., 2018; Sommer et al., 2019). Hence, any decision for O&G assets after cessation of operation should be based on a multi-impact analysis of different decommissioning scenarios to find optimum scenarios with minimal impact on the environment, economy, and society (Li and Hu, 2022, 2023a,b; Martins et al., 2020a).

The O&G decommissioning challenge involves a range of stakeholders with specific interests and priorities, which highlights the necessity of development of multi-criteria decision frameworks to help guide the decision-making process. The literature review presented by Martins et al. (2020b) identifies four main approaches for the multi-criteria decision analysis of O&G decommissioning, including the analytic hierarchy process (Na et al., 2017; Saaty, 1980), the preference ranking organisation method (Brans and Vincke, 1985), a technique for order of preference by similarity to ideal solution (Hwang and Yoon, 1981), and Comparative Assessment (CA) (Offshore Energy UK, 2015). The CA is a well-known multi-criteria decision-making approach for O&G decommissioning projects on the UKCS and has provided the basis for many decommissioning reports in the NSR, such as Brent (Shell UK Limited, 2017a,b, 2020a,b,c), Dunlin (Fairfield Betula Limited, 2018), Murchison (CNR International, 2014, 2013a,b), Heather (Enquest, 2023), and Western Isles (XODUS, 2023) . This study focusses on the CA approach for O&G pipeline decommissioning.

The Petroleum Act provides a regulatory framework for O&G decommissioning considering the UK's obligations under OSPAR Decision 98/3 (Fam et al., 2018; OSPAR, 1998), under which the operators must prepare a Decommissioning Programme (DP) regarding their obligations towards end of asset lifetime. The Department for Energy Security and Net Zero (DESNZ), formally known as the department for Business, Energy & Industrial Strategy (BEIS), published guidance notes (Department for BEIS, 2018) on the decommissioning of offshore O&G installations and pipelines that require operators to perform a CA and consider decommissioning options in terms of economic, environmental, safety, societal, and technical criteria. Although the OSPAR Decision 98/3 (OSPAR, 1998) insists on the full removal of all O&G assets, it recognises that the full removal of some assets weighing more than 10,000 tonnes (and installed before 1999), jacket footings and long steel pipelines, may be technically difficult with potential risks to the environment, economy, and environment. In such cases, the operators need to make a derogation case under different decommissioning options and show how the leave in place option (full or partial) results in lower impacts in terms of the economic, environmental, safety, societal, and technical criteria.

There is no prescribed detailed quantitative approach to prepare a CA and different operators adopt their own to evaluate each sub-criterion and assess the potential impacts. Due to the sensitivity of the data in O&G industry, the data used in CAs are considered confidential and the operators only report their detailed CA approaches and data to the Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) which is a part of DESNZ. However, due to the multi-impact nature of decommissioning projects on the environment, economy, and local communities, transparent CA approaches are needed to inform the decision-making process for O&G decommissioning projects. Well-established CA approaches will not only allow better scrutiny of the methodology, scenarios, and results, but also share learning and improve cross stakeholder engagement and understanding.

Considering the scale of the decommissioning challenge, the question is to what extent the current CA approaches can consider the economic, environmental, and other impacts of decommissioning projects during the decision-making process? In the literature, the current CA methods for the pipeline decommissioning mainly employ qualitive or score-based assessment approach (Caprace et al., 2023; Carneiro, 2024; Eke et al., 2020; Khalidov et al., 2023; Shams et al., 2023), which do not represent the real complexity of the decision-making process. On the other hand, due to the limited data availability in the O&G industry, most of the current impact analyses methods for the pipelines rely on a top-down approach (Ekins et al., 2006; Kaiser, 2017; Kaiser and Liu, 2015), which is not expected to be accurate enough. However, the multi-impact analyses of O&G decommissioning projects depend on a variety of parameters, such as field-specific data and information, operational parameters, employed technology, project strategies, and weather conditions, which should be considered within the decision frameworks. The bottom-up formulations are efficient approaches that aim to consider these operational data and site-specific information for realistic multi-impact analyses of energy projects (Jalili et al., 2024; Milne et al., 2021). Therefore, accurate bottom-up formulations are needed to be developed for a realistic multi-impact analysis of O&G pipeline decommissioning. To address this challenge, this study proposes bottom-up formulations for economic, environmental, and safety risk criteria to support the multi-criteria decision analysis within the CA of O&G pipeline decommissioning projects in the NSR, as shown in Fig. 1. The approach considers the detailed parameters for multi-impact analysis, such as site-specific data, operational durations, vessel/equipment leasing rates, vessel/equipment fuel consumption and emission factors, material recycling/replacement emissions, and probabilistic safety risk parameters. The study reviewed different O&G technical reports and derived suitable values for these parameters. Bottom-up formulations are derived for the five different decommissioning options, including leave in place with minimum and minor interventions, cut and full removal, removal using reverse installation method, and mixed trench-rock dump. To verify the effectiveness of the proposed approach, the decommissioning of the PL001/N0501 pipeline in the Brent field was selected as a case study. The multi-impact analysis results obtained from the proposed approach are compared to those reported by the Brent field Technical Document (TD) and DP (Shell UK Limited, 2020a, 2020b). The results reveal the potential effectiveness of the proposed approach for the multi-impact analysis of O&G pipeline

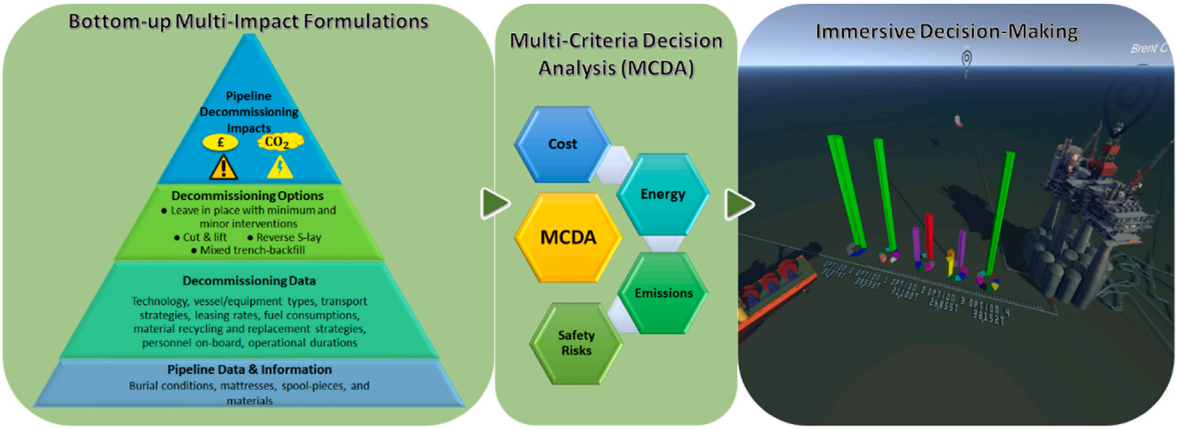

Fig. 1. Overall framework of the proposed multi-criteria bottom-up formulations and their application in the immersive decision-making for the O&G pipeline decommissioning.

decommissioning projects. The study also discusses the application of the proposed bottom-up multi-criteria formulations within a marine simulator to provide an immersive decision-making environment for stakeholders.

The paper is structured as follows. Section 2 provides a brief background on O&G pipeline decommissioning and the assumed decommissioning options. The proposed bottom-up formulations for the economic, environmental, and safety criteria are presented in Section 3. The surveyed and assumed data are summarised in Section 4. The performance of the proposed approach is assessed using a real-world case study in Section 5. The application of the proposed approach within an immersive decision-making environment is discussed in Section 6. Finally, Section 7 concludes the study.

2. Pipeline decommissioning

Although pipeline decommissioning is not part of OSPAR Decision 98/3 (OSPAR, 1998) , the DESNZ guidance notes (Department for BEIS, 2018) suggest adopting similar principles and processes for the CA of pipeline decommissioning. Based on the guidance notes (Department for BEIS, 2018), the decisions for pipeline decommissioning should be performed, on a case-by-case basis, considering their individual situation and conditions. The guidance notes (Department for BEIS, 2018) propose various criteria and sub-criteria for the CA process as shown in Table 1. This shows some of the sub-criteria, such as technical feasibility, are assessed through qualitative analyses, while most others are analysed using a quantitative approach. In this study, the focus is on the development of bottom-up formulations for the economic, environmental, and safety criteria, which are categorised as quantitative criteria.

2.1. *Decommissioning options*

Pipeline infrastructure normally consists of the pipeline itself, spool pieces, grout bags, and concrete mattresses. The decommissioning options for the pipelines need to be assessed based on the DESNZ guidance notes (Department for BEIS, 2018). In this study, the pipeline decommissioning options are considered based on currently available information reported by industry. These include five different options as explained in the following subsections.

A. Option 0: leave in place with minimum intervention

Under this scenario, the pipeline will be left in place and a derogation

Table 1
The different criteria and sub-criteria proposed by the DESNZ guidance (Department for BEIS, 2018) for the CA of O&G decommissioning (partly taken from Shell UK Limited, 2017b).

Criteria	Sub-criterion	Unit	Description
Economic	Cost	£	Cost of decommissioning options including long-term legacy costs, such as post-decommissioning surveys
Environmental	Marine impact	Score	This assesses the overall impact of decommissioning options on the marine environment.
	Other environmental consequences (including cumulative effects)	Score	This considers the long-term legacy environmental impact of abandoned assets.
	Emissions	tonnes	Emissions produced by activities, such as vessels/equipment, recycling, material replacement activities, in the different decommissioning options
	Energy usage	GJ	The energy usage resulted from different activities in the different decommissioning options
Safety	Safety risks to offshore personnel	Potential Loss of Life (PLL)	The safety risks to offshore personnel resulted from different decommissioning options.
	Safety risks to other users of sea	PLL	This assesses the safety risks to other users of sea, such as commercial ships, resulting from the legacy impact of abandoned assets
	Safety risks to those on land	PLL	This evaluates the safety risks to those working onshore decommissioning activities, such as dismantling, recycling, and supply chain activities.
Societal	Fisheries	£	This assesses the long-term economic impacts of decommissioning options on fishing activities
	Amenities	Person-year	This evaluates the impact of decommissioning options on the employment rate in the region
	Communities	Score	This assesses the impact of decommissioning options on the different communities and onshore infrastructure
Technical	Risk of major project failure	Score	The technical feasibility and failure risk of each decommissioning option, usually obtained from expert workshops.

Table 2
The list of operations for option 0: leave in place with minimum intervention.

Operations	Details	Notation	Vessel/equipment
Surveys	Pre and post removal surveys	$O_{0,0}$	ROV Support Vessel (ROVSV)
Helicopter	Helicopter operation for shuttling the personnel to and from the site	$O_{0,1}$	Helicopter

license based on the OSPAR Decision 98/3 (OSPAR, 1998) will be granted. This option has been considered in different fields with some differences, such as Brent TD (Shell UK Limited, 2020b) and the Viking DP (ConocoPhillips, 2018), for pipelines which are tied in at both ends to the platforms. This option can be considered for these pipelines if the gravity base structure or jacket footings of the platforms are to be left in place. The closed spans are left in place as they are without any additional protection and only the pipeline ends would be rock dumped. The concrete mattresses will also be left as they are on the seabed. The remaining parts of the pipeline will be marked on sea charts and notifications about the risk of abandoned pipeline will be issued to fishermen or other users of the sea. Pre- and post-removal surveys will be required for the pipeline left in place. Table 2 lists the two operations with the notations and vessel/equipment considered in this option.

B. Option 1: leave in place with minor intervention

In option 1, the pipeline will be left in place, but with further remediations. This option assumes all concrete mattresses will be removed across the pipeline length, where possible. The spool pieces will also be cut and removed from the pipeline ends using a Diamond Wire Cutting (DWC) tool. Therefore, the pipeline ends, if buried, will need to be excavated using a water jet operation. The exposed and spanned sections of the pipelines will be rock dumped. Table 3 lists the operations assumed for option 1.

C. Option 2: cut and full removal by CSV

This option considers full removal of the pipeline in several lifts using a Crane Support Vessel (CSV). All mattresses will be removed where possible to facilitate the cut and lift operation. Then, the pipeline will be cut into several sections using a Remotely Operated Vessel (ROV) with DWC or shear cutting tools. Trenching tools will be required to expose the pipeline sections from the natural burial, rock-dumps, and trenches. The pipeline sections will be lifted by a CSV and placed on a ROVSV or DSV to be shipped to shore for recycling. Thus, several cut and lift operations are required in this option. Following the removal operation, the platform ends need to be rock dumped. Table 4 shows the operations for this option.

D. Option 3: Full removal using reverse installation method

Like option 2, all mattresses and spool pieces will be removed in this option and the whole pipeline will be exposed using a TSV. The main assumption of option 3 is to remove the entire pipeline through the reverse S-lay method by using a Pipe-Lay Vessel (PLV). The retrieved pipelines will be cut into smaller sections on the vessel's deck space and shipped to shore for recycling. Although the S-lay installation method is a well-developed pipeline installation method (Gong and Xu, 2016; O'Grady and Harte, 2013) , the reverse S-lay pipeline removal has not currently been performed in the NSR. However, this method is expected to be a feasible operation considering current technology in the industry (Shell UK Limited, 2020b). Table 5 summarises the list of operations and employed vessels/equipment for Option 3.

E. Option 4: mixed trench-rock dump

In some cases, it is difficult to trench and backfill the entire pipeline length due to the seabed condition at given locations. It is also not possible to trench and backfill short length isolated pipelines due to the transition length required for the trenching tools. This option assumes the long sections with the top of the pipeline at seabed level or less than 0.6 m below the seabed will be trenched and backfilled by a TSV. The short pipeline sections are assumed to be rock dumped to a depth of 0.5

Table 3
The list of operations for option 1: leave in place with minor intervention.

Operations	Details	Notation	Vessel/equipment
Preparation	Cleaning operation and accommodation for personnel	$O_{1,0}$	Accommodation Work Vessel (AWV)/Jack-Up Vessel (JUV)
Mattress removal	Removal of all mattresses across the entire length of the pipeline	$O_{1,1}$	Diving Support Vessel (DSV)
Water jet	Water jet operation to discover the pipeline ends by divers	$O_{1,2}$	DSV
Spool piece removal	Cutting and removal of spool pieces with DWC and divers	$O_{1,3}$	DSV
Rock dumping- pipeline ends	Rock dumping on the dredged area to cover the pipeline ends	$O_{1,4}$	Rock Dumping Vessel (RDV)
Rock dumping- infield	Rock dumping on the exposed and closed spans across the whole pipeline length	$O_{1,5}$	RDV
Surveys	Pre and post removal surveys	$O_{1,6}$	ROVSV
Helicopter	Helicopter operation for shuttling the personnel to and from the site	$O_{1,7}$	Helicopter

Table 4
The list of operations for option 2: cut and full removal by CSV.

Operations	Details	Notation	Vessel/equipment
Preparation	Cleaning operation and accommodation for personnel	$O_{2,0}$	AWV/JUV
Mattress removal	Removal of all mattresses across the entire length of the pipeline	$O_{2,1}$	DSV
Trenching	Trenching operation of whole pipeline length	$O_{2,2}$	Trenching Support Vessel (TSV)
Spool piece removal	Cutting and removal of spool pieces with DWC and divers	$O_{2,3}$	DSV
Cut and lift	Cutting pipeline sections using DWC and shipping them to the shore	$O_{2,4}$	CSV/JUV
Rock dumping	Rock dumping at the platform ends	$O_{2,5}$	RDV
Survey	Pre and post removal surveys	$O_{2,6}$	ROVSV
Helicopter	Helicopter operation for shuttling the personnel to and from the site	$O_{2,7}$	Helicopter

Table 5
The list of operations for option 3: removal using reverse installation method.

Operations	Details	Notation	Vessel/equipment
Preparation	Cleaning operation and accommodation for personnel	$O_{3,0}$	AWV/JUV
Mattress removal	Removal of all mattresses across the entire length of the pipeline	$O_{3,1}$	DSV
Trenching	Trenching operation of whole pipeline length	$O_{3,2}$	TSV
Spool piece removal	Cutting and removal of spool pieces with DWC and divers	$O_{3,3}$	DSV
Reverse S-lay	Removing the pipeline using reverse installation method and cutting on the deck	$O_{3,4}$	PLV
ROV Support	ROV support for the reverse installation-based removal	$O_{3,5}$	ROVSV
Rock dumping	Rock dumping at the platform ends	$O_{3,6}$	RDV
Survey	Pre and post removal surveys	$O_{3,7}$	ROVSV
Helicopter	Helicopter operation for shuttling the personnel to and from the site	$O_{3,8}$	Helicopter

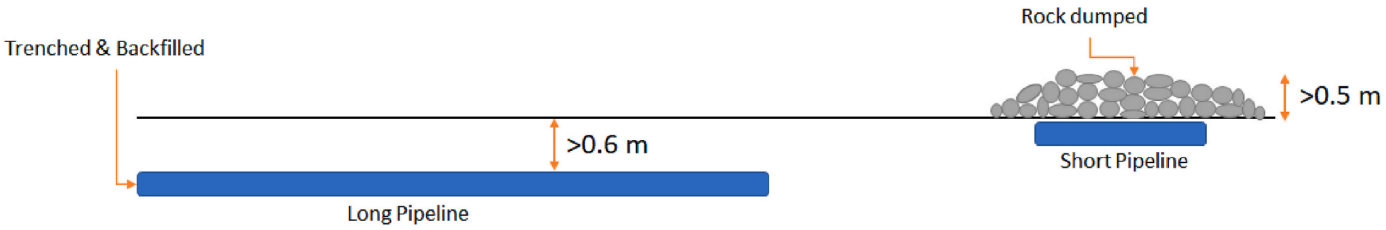

Fig. 2. Required burial depth and rock-dump height for the long and short pipelines (adapted from Brent TD (Shell UK Limited, 2020b).

m. The concrete mattresses and spool-pieces are fully removed. Fig. 2 illustrates the required burial depth and rock-dump height for the long and short pipelines in option 4. The list of operations in this option are listed in Table 6.

3. Bottom-up multi-criteria formulations

In the CA for O&G projects, the performance of each decommissioning option should be assessed in terms of the criteria listed in Table 1. As the focus of this study is on the economic, environmental, and safety criteria, this section provides bottom-up cost, energy usage, emission, and safety formulations for the pipeline decommissioning options described in Section 2.1. It should be noted that the definitions and units for the parameters used in this section are summarised in Table A. 1 of Appendix A.

3.1. Economic

The overall cost of each decommissioning option can be expressed as:

$$C_i^{\mathrm{V}} = \sum_{j=0}^{n_i^o-1} c_{i,j} \tag{1}$$

where $c_{i,j}$ indicates the costs of j th operation for the i th option which are calculated for each option as below.

A. Option 0: leave in place with minimum intervention

$$c_{0,0} = C_{\mathrm{D}}^{\mathrm{ROVSV}} t_{0,0} = C_{\mathrm{D}}^{\mathrm{ROVSV}} \left(t_{\mathrm{m,S}}^{\mathrm{ROVSV}} + t_{\mathrm{tr,S}}^{\mathrm{ROVSV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{S}}^{\mathrm{ROVSV}} \right) \tag{2}$$

$$c_{0,1} = C_{\mathrm{D}}^{\mathrm{H}} t_{0,1} = C_{\mathrm{D}}^{\mathrm{H}} t_{0,0} \tag{3}$$

in which:

$$t_{\mathrm{S}}^{\mathrm{ROVSV}} = r_{\mathrm{S}} L \tag{4}$$

B. Option 1: leave in place with minor intervention

In this option, the survey cost and duration will be the same as in option 0, i.e., $c_{1,6} = c_{0,0}$ and $t_{1,6} = t_{0,0}$. The costs for the remaining operations are expressed as:

$$c_{1,0} = C_{\mathrm{D}}^{\mathrm{JUV}} t_{1,0} = C_{\mathrm{D}}^{\mathrm{JUV}} \left(t_{\mathrm{m,P}}^{\mathrm{JUV}} + t_{\mathrm{tr,P}}^{\mathrm{JUV}} + t_{\mathrm{P}}^{\mathrm{JUV}} \right) \tag{5}$$

$$c_{1,1} = C_{\mathrm{D}}^{\mathrm{DSV}} t_{1,1} = C_{\mathrm{D}}^{\mathrm{DSV}} \left(t_{\mathrm{m,MR}}^{\mathrm{DSV}} + t_{\mathrm{tr,MR}}^{\mathrm{DSV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{MR}}^{\mathrm{DSV}} \right) \tag{6}$$

$$c_{1,2} = C_{\mathrm{D}}^{\mathrm{DSV}} t_{1,2} = C_{\mathrm{D}}^{\mathrm{DSV}} \left(t_{\mathrm{m,EX}}^{\mathrm{DSV}} + t_{\mathrm{tr,EX}}^{\mathrm{DSV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{EX}}^{\mathrm{DSV}} \right) \tag{7}$$

$$c_{1,3} = C_{\mathrm{D}}^{\mathrm{DSV}} t_{1,3} = C_{\mathrm{D}}^{\mathrm{DSV}} \left(t_{\mathrm{m,SP}}^{\mathrm{DSV}} + t_{\mathrm{tr,SP}}^{\mathrm{DSV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{SP}}^{\mathrm{DSV}} \right) \tag{8}$$

$$c_{1,4} = C_{\mathrm{D}}^{\mathrm{RDV}} t_{1,4} = C_{\mathrm{D}}^{\mathrm{RDV}} \left(t_{\mathrm{m,RDSP}}^{\mathrm{RDV}} + t_{\mathrm{tr,RDSP}}^{\mathrm{RDV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{RDSP}}^{\mathrm{RDV}} \right) \tag{9}$$

$$c_{1,5} = C_{\mathrm{D}}^{\mathrm{RDV}} t_{1,5} = C_{\mathrm{D}}^{\mathrm{RDV}} \left(t_{\mathrm{m,RDEX}}^{\mathrm{RDV}} + t_{\mathrm{tr,RDEX}}^{\mathrm{RDV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{RDEX}}^{\mathrm{RDV}} \right) \tag{10}$$

$$c_{1,7} = C_{\mathrm{D}}^{\mathrm{H}} t_{1,7} = C_{\mathrm{D}}^{\mathrm{H}} \sum_{j=0}^{n_1^o-2} t_{1,j} \tag{11}$$

Table 6
The list of operations for option 4: mixed trench-rock dump.

Operations	Details	Notation	Vessel/equipment
Preparation	Cleaning operation and accommodation for personnel	$O_{4,0}$	AWV/JUV
Mattress removal	Removal of all mattresses across the entire length of the pipeline	$O_{4,1}$	DSV
Trenching	Trenching and backfilling operation of exposed pipeline length	$O_{4,2}$	TSV
Offshore support	Offshore support vessel with ROV spread for the trenching operation	$O_{4,3}$	ROVSV
Spool piece removal	Cutting and removal of spool pieces with DWC and divers	$O_{4,4}$	DSV
Rock dumping	Rock dumping at the platform ends	$O_{4,5}$	RDV
Survey	Pre and post removal surveys	$O_{4,6}$	ROVSV
Helicopter	Helicopter operation for shuttling the personnel to and from the site	$O_{4,7}$	Helicopter

in which:

$$t_{\mathrm{P}}^{\mathrm{JUV}} = r_{\mathrm{p}} L \tag{12}$$

$$t_{\mathrm{MR}}^{\mathrm{DSV}} = r_{\mathrm{m}} n_{\mathrm{Me}} \tag{13}$$

$$t_{\mathrm{EX}}^{\mathrm{DSV}} = 2 r_{\mathrm{EX}} \tag{14}$$

$$t_{\mathrm{SP}}^{\mathrm{DSV}} = r_{\mathrm{SP}} n_{\mathrm{SP}} \tag{15}$$

$$t_{\mathrm{RDSP}}^{\mathrm{RDV}} = 2 r_{\mathrm{RDSP}} \tag{16}$$

$$t_{\mathrm{MR}}^{\mathrm{DSV}} = r_{\mathrm{m}} n_{\mathrm{M}} \tag{17}$$

$$t_{\mathrm{RDEX}}^{\mathrm{RDV}} = r_{\mathrm{RDEX}} L_{\mathrm{ex}} \tag{18}$$

C. Option 2: cut and full removal by CSV

In the option, the costs and durations for a set of operations are same as the previous options, i.e., $c_{2,0} = c_{1,0}$, $c_{2,1} = c_{1,1}$, $c_{2,3} = c_{1,3}$, $c_{2,5} = c_{1,4}$, and $c_{2,6} = c_{0,0}$. These equalities are also true for the corresponding operational durations, i.e., $t_{2,0} = t_{1,0}$, $t_{2,1} = t_{1,1}$, $t_{2,3} = t_{1,3}$, $t_{2,5} = t_{1,4}$, and $t_{2,6} = t_{0,0}$. The cost and duration for the rest of operations are calculated as:

$$c_{2,2} = C_{\mathrm{D}}^{\mathrm{TSV}} t_{2,2} = C_{\mathrm{D}}^{\mathrm{TSV}} \left(t_{\mathrm{m,T}}^{\mathrm{TSV}} + t_{\mathrm{tr,T}}^{\mathrm{TSV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{T}}^{\mathrm{TSV}} \right) \tag{19}$$

$$c_{2,4} = C_{\mathrm{D}}^{\mathrm{CSV}} t_{2,4} = C_{\mathrm{D}}^{\mathrm{CSV}} \left(t_{\mathrm{m,L}}^{\mathrm{CSV}} + t_{\mathrm{tr,L}}^{\mathrm{CSV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{L}}^{\mathrm{CSV}} \right) \tag{20}$$

$$c_{2,7} = C_{\mathrm{D}}^{\mathrm{H}} t_{2,7} = C_{\mathrm{D}}^{\mathrm{H}} \sum_{j=0}^{n_2^{\mathrm{o}}-2} t_{2,j} \tag{21}$$

in which:

$$t_{\mathrm{T}}^{\mathrm{TSV}} = r_{\mathrm{T}} L \tag{22}$$

$$t_{\mathrm{L}}^{\mathrm{CSV}} = r_{\mathrm{L}} L \tag{23}$$

D. Option 3: removal using reverse installation method

In the option, the costs and durations for a set of operations are same as the previous options, i.e., $c_{3,0} = c_{1,0}$, $c_{3,1} = c_{1,1}$, $c_{3,2} = c_{2,2}$, $c_{3,3} = c_{1,3}$, $c_{3,6} = c_{1,4}$, and $c_{3,7} = c_{0,0}$, and these equalities are also true for the corresponding operational durations, i.e., $t_{3,0} = t_{1,0}$, $t_{3,1} = t_{1,1}$, $t_{3,2} = t_{2,2}$, $t_{3,3} = t_{1,3}$, $t_{3,6} = t_{1,4}$, and $t_{3,7} = t_{0,0}$. The costs for the rest of operations are written as:

$$c_{3,4} = C_{\mathrm{D}}^{\mathrm{PLV}} t_{3,4} = C_{\mathrm{D}}^{\mathrm{PLV}} \left(t_{\mathrm{m,RI}}^{\mathrm{PLV}} + t_{\mathrm{tr,RI}}^{\mathrm{PLV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{RI}}^{\mathrm{PLV}} \right) \tag{24}$$

$$c_{3,5} = C_{\mathrm{D}}^{\mathrm{ROVSV}} t_{3,5} = C_{\mathrm{D}}^{\mathrm{ROVSV}} t_{3,4} = C_{\mathrm{D}}^{\mathrm{ROVSV}} \left(t_{\mathrm{m,RI}}^{\mathrm{PLV}} + t_{\mathrm{tr,RI}}^{\mathrm{PLV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{RI}}^{\mathrm{PLV}} \right) \tag{25}$$

$$c_{3,8} = C_{\mathrm{D}}^{\mathrm{H}} t_{3,8} = C_{\mathrm{D}}^{\mathrm{H}} \sum_{j=0}^{n_3^{\mathrm{o}}-2} t_{3,j} \tag{26}$$

in which:

$$t_{\mathrm{RI}}^{\mathrm{PLV}} = r_{\mathrm{R}} L \tag{27}$$

E. Option 4: mixed trench-rock dump

In option 4, the costs and durations for a set of operations are the same as the previous options, i.e., $c_{4,0} = c_{1,0}$, $c_{4,1} = c_{1,1}$, $c_{4,4} = c_{1,3}$, $c_{4,5} = c_{1,4}$, and $c_{4,6} = c_{0,0}$. These equalities are also true for the corresponding operational durations, i.e., $t_{4,0} = t_{1,0}$, $t_{4,1} = t_{1,1}$, $t_{4,4} = t_{1,3}$, $t_{4,5} = t_{1,4}$, and $t_{4,6} = t_{0,0}$.

In the operation 2 of this option, only the exposed parts of the pipeline are trenched and backfilled. Thus, the trenching duration is written as:

$$t_{\mathrm{T}}^{\mathrm{TSV}} = r_{\mathrm{TB}} L_{\mathrm{ex}} \tag{28}$$

Then, the cost $c_{4,2}$ and duration $t_{4,2}$ for the operation 2 are calculated similar to $c_{2,2}$ and $t_{2,2}$ equation (19), respectively. The costs and durations for the rest of operations are obtained as:

$$c_{4,3} = C_{\mathrm{D}}^{\mathrm{ROVSV}} t_{4,3} = C_{\mathrm{D}}^{\mathrm{ROVSV}} t_{4,2} = C_{\mathrm{D}}^{\mathrm{ROVSV}} \left(t_{\mathrm{m,T}}^{\mathrm{TSV}} + t_{\mathrm{tr,T}}^{\mathrm{TSV}} + (1+\alpha_{\mathrm{w}}) t_{\mathrm{T}}^{\mathrm{TSV}} \right) \tag{29}$$

$$c_{4,7} = C_{\mathrm{D}}^{\mathrm{H}} t_{4,7} = C_{\mathrm{D}}^{\mathrm{H}} \sum_{j=0}^{n_4^{\mathrm{o}}-2} t_{4,j} \tag{30}$$

This subsection provided the cost of each decommissioning option in terms of vessel/equipment day rates and duration parameters. The cost formulations consider the weather delays which can be different for different operations. The values of the day rate and duration parameters used within the cost formulations will be discussed in subsections 4.1 and 4.2.

3.2. Environmental

The environmental criterion in this study assesses fuel consumptions, emissions, and energy usages. The overall fuel consumption, energy usage, and emission resulted from each option can be expressed as:

$$F_i = \sum_{j=0}^{n_i^{\mathrm{o}}-1} f_{i,j} \tag{31}$$

$$\mathscr{E}_i = \sum_{j=0}^{n_i^{\mathrm{o}}-1} \varepsilon_{i,j} + \mathscr{E}_i^{\mathrm{rp}} = \sum_{j=0}^{n_i^{\mathrm{o}}-1} \varepsilon_{\mathrm{f}} f_{i,j} + \mathscr{E}_i^{\mathrm{rp}} \tag{32}$$

$$E_i = \sum_{j=0}^{n_i^{\mathrm{o}}-1} e_{i,j} + E_i^{\mathrm{rp}} = \sum_{j=0}^{n_i^{\mathrm{o}}-1} e_{\mathrm{f}} f_{i,j} + E_i^{\mathrm{rp}} \tag{33}$$

The fuel consumption, represented by $f_{i,j}$, as well as the material recycling/replacement emissions and energy usages, indicated by $\mathscr{E}_i^{\mathrm{rp}}$ and E_i^{rp}, are obtained for each option as below.

A. Option 0: leave in place with minimum intervention

$$f_{0,0} = f_{\mathrm{m}}^{\mathrm{ROVSV}} t_{\mathrm{m,S}}^{\mathrm{ROVSV}} + f_{\mathrm{tr}}^{\mathrm{ROVSV}} t_{\mathrm{tr,S}}^{\mathrm{ROVSV}} + f_{\mathrm{o}}^{\mathrm{ROVSV}} t_{\mathrm{S}}^{\mathrm{ROVSV}} \tag{34}$$

$$f_{0,1} = f^{\mathrm{H}} t_{0,1} = f^{\mathrm{H}} t_{0,0} \tag{35}$$

As the pipelines will be left in place, the emission and energy usage related to reproduction/replacement of same amount of material in this option can be expressed as:

$$\mathscr{E}_0^{\mathrm{rp}} = w_{\mathrm{s}} \varepsilon_{\mathrm{s}} + w_{\mathrm{c}} \varepsilon_{\mathrm{c}} + w_{\mathrm{co}} \varepsilon_{\mathrm{co}} \tag{36}$$

$$E_0^{\mathrm{rp}} = w_{\mathrm{s}} e_{\mathrm{s}} + w_{\mathrm{c}} e_{\mathrm{c}} + w_{\mathrm{co}} e_{\mathrm{co}} \tag{37}$$

in which the emissions and energy usage parameters for different materials are given in Section 4.3.

B. Option 1: leave in place with minor intervention

In this option, $f_{1,6} = f_{0,0}$. The fuel consumptions for the rest of the operations are obtained as:

$$f_{1,0} = f_{\mathrm{m}}^{\mathrm{JUV}} t_{\mathrm{m,P}}^{\mathrm{JUV}} + f_{\mathrm{tr}}^{\mathrm{JUV}} t_{\mathrm{tr,P}}^{\mathrm{JUV}} + f_{\mathrm{o}}^{\mathrm{JUV}} t_{\mathrm{P}}^{\mathrm{JUV}} \tag{38}$$

$$f_{1,1} = f_{\mathrm{m}}^{\mathrm{DSV}} t_{\mathrm{m,MR}}^{\mathrm{DSV}} + f_{\mathrm{tr}}^{\mathrm{DSV}} t_{\mathrm{tr,MR}}^{\mathrm{DSV}} + f_{\mathrm{o}}^{\mathrm{DSV}} t_{\mathrm{MR}}^{\mathrm{DSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{DSV}} t_{\mathrm{MR}}^{\mathrm{DSV}} \tag{39}$$

$$f_{1,2} = f_{\mathrm{m}}^{\mathrm{DSV}} t_{\mathrm{m,EX}}^{\mathrm{DSV}} + f_{\mathrm{tr}}^{\mathrm{DSV}} t_{\mathrm{tr,EX}}^{\mathrm{DSV}} + f_{\mathrm{o}}^{\mathrm{DSV}} t_{\mathrm{EX}}^{\mathrm{DSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{DSV}} t_{\mathrm{EX}}^{\mathrm{DSV}} \tag{40}$$

$$f_{1,3} = f_{\mathrm{m}}^{\mathrm{DSV}} t_{\mathrm{m,SP}}^{\mathrm{DSV}} + f_{\mathrm{tr}}^{\mathrm{DSV}} t_{\mathrm{tr,SP}}^{\mathrm{DSV}} + f_{\mathrm{o}}^{\mathrm{DSV}} t_{\mathrm{SP}}^{\mathrm{DSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{DSV}} t_{\mathrm{SP}}^{\mathrm{DSV}} \tag{41}$$

$$f_{1,4} = f_{\mathrm{m}}^{\mathrm{RDV}} t_{\mathrm{m,RDSP}}^{\mathrm{RDV}} + f_{\mathrm{tr}}^{\mathrm{RDV}} t_{\mathrm{tr,RDSP}}^{\mathrm{RDV}} + f_{\mathrm{o}}^{\mathrm{RDV}} t_{\mathrm{RDSP}}^{\mathrm{RDV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{RDV}} t_{\mathrm{RDSP}}^{\mathrm{RDV}} \tag{42}$$

$$f_{1,5} = f_{\mathrm{m}}^{\mathrm{RDV}} t_{\mathrm{m,RDEX}}^{\mathrm{RDV}} + f_{\mathrm{tr}}^{\mathrm{RDV}} t_{\mathrm{tr,RDEX}}^{\mathrm{RDV}} + f_{\mathrm{o}}^{\mathrm{RDV}} t_{\mathrm{tr,RDEX}}^{\mathrm{RDV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{RDV}} t_{\mathrm{RDEX}}^{\mathrm{RDV}} \tag{43}$$

$$f_{1,7} = f^{\mathrm{H}} t_{1,7} = f^{\mathrm{H}} \sum_{j=0}^{n_1^{\mathrm{o}}-2} t_{1,j} \tag{44}$$

The emission and energy usage related to the material reproduction/replacement for this option are the same as the previous option, i.e., $\mathscr{E}_1^{\mathrm{rp}} = \mathscr{E}_0^{\mathrm{rp}}$ and $E_1^{\mathrm{rp}} = E_0^{\mathrm{rp}}$.

C. Option 2: cut and full removal by CSV

In the option, the fuel consumptions for a set of operations are the same as the previous options, i.e., $f_{2,0} = f_{1,0}, f_{2,1} = f_{1,1}, f_{2,3} = f_{1,3}, f_{2,5} = f_{1,4}$, and $f_{2,6} = f_{0,0}$. The fuel consumptions for the rest of parameters are calculated as:

$$f_{2,2} = f_{\mathrm{m}}^{\mathrm{TSV}} t_{\mathrm{m,T}}^{\mathrm{TSV}} + f_{\mathrm{tr}}^{\mathrm{TSV}} t_{\mathrm{tr,T}}^{\mathrm{TSV}} + f_{\mathrm{o}}^{\mathrm{TSV}} t_{\mathrm{T}}^{\mathrm{TSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{TSV}} t_{\mathrm{T}}^{\mathrm{TSV}} \tag{45}$$

$$f_{2,4} = f_{\mathrm{m}}^{\mathrm{CSV}} t_{\mathrm{m,L}}^{\mathrm{CSV}} + f_{\mathrm{tr}}^{\mathrm{CSV}} t_{\mathrm{tr,L}}^{\mathrm{CSV}} + f_{\mathrm{o}}^{\mathrm{TSV}} t_{\mathrm{L}}^{\mathrm{CSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{TSV}} t_{\mathrm{L}}^{\mathrm{CSV}} \tag{46}$$

$$f_{2,7} = f^{\mathrm{H}} t_{2,7} = \sum_{j=0}^{n_2^{\mathrm{o}}-2} t_{2,j} \tag{47}$$

As this option will take the pipeline for recycling, the emission and energy usage related to recycling of recovered material are obtained as:

$$\mathscr{E}_2^{\mathrm{rp}} = w_{\mathrm{s}} \varepsilon_{\mathrm{rs}} + w_{\mathrm{c}} \varepsilon_{\mathrm{rc}} + w_{\mathrm{co}} \varepsilon_{\mathrm{rco}} \tag{48}$$

$$E_2^{\mathrm{rp}} = w_{\mathrm{s}} e_{\mathrm{rs}} + w_{\mathrm{c}} e_{\mathrm{rc}} + w_{\mathrm{co}} e_{\mathrm{rco}} \tag{49}$$

in which the emissions and energy usage of recycling per unit weight of materials are given in Section 4.3.

D. Option 3: removal using reverse installation method

In this option, the fuel consumptions for a set of operations are the same as the previous options, i.e., $f_{3,0} = f_{1,0}, f_{3,1} = f_{1,1}, f_{3,2} = f_{2,2}, f_{3,3} = f_{1,3}, f_{3,6} = f_{1,4}$, and $f_{3,7} = f_{0,0}$. The fuel consumptions for the remaining operations are obtained as:

$$f_{3,4} = f_{\mathrm{m}}^{\mathrm{PLV}} t_{\mathrm{m,RI}}^{\mathrm{PLV}} + f_{\mathrm{tr}}^{\mathrm{PLV}} t_{\mathrm{tr,RI}}^{\mathrm{PLV}} + f_{\mathrm{o}}^{\mathrm{PLV}} t_{\mathrm{RI}}^{\mathrm{PLV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{PLV}} t_{\mathrm{RI}}^{\mathrm{PLV}} \tag{50}$$

$$f_{3,5} = f_{\mathrm{m}}^{\mathrm{ROVSV}} t_{\mathrm{m,RI}}^{\mathrm{ROVSV}} + f_{\mathrm{tr}}^{\mathrm{ROVSV}} t_{\mathrm{tr,RI}}^{\mathrm{ROVSV}} + f_{\mathrm{o}}^{\mathrm{ROVSV}} t_{\mathrm{RI}}^{\mathrm{ROVSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{ROVSV}} t_{\mathrm{RI}}^{\mathrm{ROVSV}} \tag{51}$$

$$f_{3,8} = f^{\mathrm{H}} t_{3,8} = f^{\mathrm{H}} \sum_{j=0}^{n_3^{\mathrm{o}}-2} t_{3,j} \tag{52}$$

The recycling emissions and energy usage in this option are same as option 2, i.e., $\mathscr{E}_3^{\mathrm{rp}} = \mathscr{E}_2^{\mathrm{rp}}$ and $E_3^{\mathrm{rp}} = E_2^{\mathrm{rp}}$.

E. Option 4: Mixed trench-rock dump

The fuel consumptions for a set of operations in option 4 are the same as the previous options, i.e., $f_{4,0} = f_{1,0}, f_{4,1} = f_{1,1}, f_{4,4} = f_{1,3}, f_{4,5} = f_{1,4}$, and $f_{4,6} = f_{0,0}$. The fuel consumptions for the remaining operations are as follows:

$$f_{4,2} = f_{\mathrm{m}}^{\mathrm{TSV}} t_{\mathrm{m,T}}^{\mathrm{TSV}} + f_{\mathrm{tr}}^{\mathrm{TSV}} t_{\mathrm{tr,T}}^{\mathrm{TSV}} + f_{\mathrm{o}}^{\mathrm{TSV}} t_{\mathrm{T}}^{\mathrm{TSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{TSV}} t_{\mathrm{T}}^{\mathrm{TSV}} \tag{53}$$

$$f_{4,3} = f_{\mathrm{m}}^{\mathrm{ROVSV}} t_{\mathrm{m,T}}^{\mathrm{TSV}} + f_{\mathrm{tr}}^{\mathrm{ROVSV}} t_{\mathrm{tr,T}}^{\mathrm{TSV}} + f_{\mathrm{o}}^{\mathrm{ROVSV}} t_{\mathrm{T}}^{\mathrm{TSV}} + \alpha_{\mathrm{w}} f_{\mathrm{w}}^{\mathrm{ROVSV}} t_{\mathrm{T}}^{\mathrm{TSV}} \tag{54}$$

$$f_{4,7} = f^{\mathrm{H}} t_{4,7} = f^{\mathrm{H}} \sum_{j=0}^{n_4^{\mathrm{o}}-2} t_{4,j} \tag{55}$$

This subsection formulated the energy usage and emissions caused by each option in terms of emission factors, fuel consumption rates, and duration parameters. The values of emission factors and fuel consumption rates are discussed in Section 4.3.

3.3. *Safety*

The safety risks of offshore operations in O&G industry are measured by the PLL value which is a function of activity durations and the number of personnel exposed to the risk. The PLL values do not represent the exact safety risks for a given option, rather, they provide the approximate level of risk to facilitate the initial assessment of a given option. Further studies will be required to assess the safety risks associated with the selected decommissioning option.

In the CAs prepared by industry, the PLL values are calculated based on the Fatal Accident Rate (FAR) values provided by the joint industry statistical risk analysis project (Myrheim et al., 2005). The report (Myrheim et al., 2005) provides the FAR values for different offshore activities. In this study, a similar approach is adopted for quantitative assessment of safety risks associated with each decommissioning option.

The PLL value for each decommissioning option PLL_i can be written in terms of $FAR_{i,j}$, the number of personnel onboard $P_{i,j}$, and the duration $t_{i,j}$ parameters as:

$$PLL_i = \sum_{j=0}^{n_i^{\mathrm{o}}-1} pll_{i,j} = \frac{24}{10^8} \sum_{j=0}^{n_i^{\mathrm{o}}-1} P_{i,j} FAR_{i,j} t_{i,j} \tag{56}$$

where the values of $P_{i,j}$ and $FAR_{i,j}$ parameters are different for different vessel and activity types, which are discussed in Section 4.4.

Table 7
Available data collected from various sources and selected values for the leasing rates of vessel/equipment used for pipeline decommissioning.

Parameter	Notation	Unit	Possible ranges		Selected
			Min	Max	
Day rate of JUV	$C_{\mathrm{D}}^{\mathrm{JUV}}$	£/day	£150,000 (ConocoPhillips, 2018)	N/A	£150,000
Day rate of DSV	$C_{\mathrm{D}}^{\mathrm{DSV}}$	£/day	£150,000 (ConocoPhillips, 2018; Faroe Petroleum, 2018)	£156,000 (Shell UK Limited, 2020b)	£156,000
Day rate of RDV	$C_{\mathrm{D}}^{\mathrm{RDV}}$	£/day	£75,000 (Faroe Petroleum, 2018)	£150,000 (ConocoPhillips, 2018)	£150,000
Day rate of ROVSV	$C_{\mathrm{D}}^{\mathrm{ROVSV}}$	£/day	£50,000 (Faroe Petroleum, 2018)	£60,000 (ConocoPhillips, 2018)	£60,000
Day rate of CSV	$C_{\mathrm{D}}^{\mathrm{CSV}}$	£/day	£120,000 (Fairfield Betula Limited, 2018)	£150,000 (ConocoPhillips, 2018)	£150,000
Day rate of TSV	$C_{\mathrm{D}}^{\mathrm{TSV}}$	£/day	£150,000 (ConocoPhillips, 2018)	N/A	£150,000
Helicopter rent	$C_{\mathrm{D}}^{\mathrm{H}}$	£/hour	£4600 (ConocoPhillips, 2018)	N/A	£4600
Day rate of PLV	$C_{\mathrm{D}}^{\mathrm{PLV}}$	£/day	£520,000 (ConocoPhillips, 2018)	N/A	£520,000

Table 8

Available ranges, adapted values, and assumptions collected from the various technical sources for the different duration parameters.

Option	Operation	Parameter	Notation	Unit	Possible range		Selected	Comments
					Min	Max		
Option 0	$O_{0,0}$	Pipeline preparation and cleaning rate using an JUV	r_{p}	day/km	0.42	N/A	0.42	Calculated based Viking VDP2 CA (ConocoPhillips, 2018): 168.9 days/400 km = 0.42 day/km (it does not include weather delays)
	$O_{0,1}$	Mattress removal rate	r_{m}	day/unit	1/24 (Faroe Petroleum, 2018)	0.50 (Faroe Petroleum, 2018)	2/24	• 1 per hour for new mattresses and up to 12 h for old mattresses, based on Schooner DP (Faroe Petroleum, 2018) • 2 per day is assumed
	$O_{0,2}$	The rate of exposing pipeline end using the water jet technique	r_{EX}	day/unit	0.2025 (ConocoPhillips, 2018)	N/A	0.2025	Calculated by dividing the operational time in the Viking VDP2 CA (ConocoPhillips, 2018) by the No. of pipeline ends: 4.86/24 = 0.21
	$O_{0,3}$	Spool piece removal rate	r_{SP}	day/unit	1.55 (ConocoPhillips, 2018)	N/A	1.55	Calculated based on Viking VDP2 CA (ConocoPhillips, 2018): 30.9/20 = 1.55 (it does not include the weather delays)
	$O_{0,4}$	The rock dumping rate for the spool piece locations at platform ends	r_{RDSP}	day/unit	0.346 (ConocoPhillips, 2018)	N/A	0.346	Calculated by dividing the operational time in the Viking VDP2 CA (ConocoPhillips, 2018) by the No. of pipeline ends: 8.30/24 = 0.346 day/unit
	$O_{0,5}$	The pre- and post-decommissioning survey rate for leave in situ pipelines	r_{S}	day/km	0.10775 (ConocoPhillips, 2018)	0.141 (XODUS, 2023)	0.141	• Calculated by dividing the operational time in the Viking VDP2 CA (ConocoPhillips, 2018) by the pipeline overall length: 43.10/400 = 0.10775 • Western Isles (XODUS, 2023) assumes 5.3 days survey duration for the 11.3 km of pipeline. Considering 70% of WoW, it would be 0.141 day/km.
Option 1	$O_{1,5}$	The rock-dumping rate on the exposed parts of the pipeline	r_{RDEX}	day/km	0.77 (ConocoPhillips, 2018)	N/A	0.77	The Viking VDP2 CA (ConocoPhillips, 2018) assumed 11.60 days of rock-dumping activity for the pipelines with 15.16 km of exposed length. Therefore: 11.60/15.16 = 0.77 day/km
Option 2	$O_{2,2}$	The deburial/trenching rate of the pipeline	r_{T}	day/km	0.10 (ConocoPhillips, 2018)	0.37 (XODUS, 2023)	0.10	• The Viking VDP2 CA (ConocoPhillips, 2018) assumed 39.70 days of trenching activity using TSV for the 400 km long pipelines. Hence: 39.70/400 = 0.10 • Western Isles CA (XODUS, 2023)reported 13.9 days for 11.3 km of pipeline as deburial duration using an CSV. Considering 70% of WoW, it would be 0.37 days/km
	$O_{2,4}$	Cut and lift rate of the pipelines	r_{L}	day/km	5.00 (Enquest, 2023)	5.95 (ConocoPhillips, 2018)	5.95	• The Viking VDP2 CA (ConocoPhillips, 2018)assumed 2379 days of cut and lift activities for the 400 km long pipelines. • Heather CA (Enquest, 2023) assumes 200 m/day for pipeline cut and lift
Option 3	$O_{3,4}$	Pipeline removal rate using the reverse installation method- S-lay	r_{R}	day/km	0.25[a] (Kaiser, 2018)	0.50[a] (Kaiser, 2018)	1.5	It is assumed that the pipeline retrieval using reverse S-lay will take three times longer, due to the age of pipelines and decommissioning difficulties.
Option 4	$O_{4,2}$	The trench and backfill rate of the pipeline using TSV	r_{TB}	day/km	0.20[b]	N/A	0.2	

[a] Assumed same as installation due to lack of experience/data in decommissioning sector.

[b] Assumed as two times of only trenching rate.

Table 9

Fuel consumption rates for the different operational modes of vessels/equipment (tonnes/day, unless otherwise stated)

Vessel	Mobilisation/De-mobilisation		In transit		In field/operation		WoW	
	Notation	Value	Notation	Value	Notation	Value	Notation	Value
JUV	f_m^{JUV}	2 (ConocoPhillips, 2018)	f_{tr}^{JUV}	16 (ConocoPhillips, 2018)	f_o^{JUV}	18 (ConocoPhillips, 2018)	f_w^{JUV}	9 (ConocoPhillips, 2018)
DSV	f_m^{DSV}	3 (Institute of Petroleum IOP, 2000)	f_{tr}^{DSV}	20 (Institute of Petroleum IOP, 2000)	f_o^{DSV}	18 (Institute of Petroleum IOP, 2000)	f_w^{DSV}	10 (Institute of Petroleum IOP, 2000)
RDV	f_m^{RDV}	2 (Institute of Petroleum IOP, 2000)	f_{tr}^{RDV}	10 (Institute of Petroleum IOP, 2000)	f_o^{RDV}	15 (Institute of Petroleum IOP, 2000)	f_w^{RDV}	15 (Institute of Petroleum IOP, 2000)
ROVSV	f_m^{ROVSV}	2 Institute of Petroleum (IOP), 2000; CNR International (2013b)	f_{tr}^{ROVSV}	15 (Fairfield Energy, 2021)	f_o^{ROVSV}	30 (Fairfield Energy, 2021)	f_w^{ROVSV}	5 Institute of Petroleum (IOP), 2000; CNR International (2013b)
TSV	f_m^{TSV}	2 (ConocoPhillips, 2018)	f_{tr}^{TSV}	26 (ConocoPhillips, 2018)	f_o^{TSV}	18 (ConocoPhillips, 2018)	f_w^{TSV}	19 (ConocoPhillips, 2018)
CSV	f_m^{CSV}	2 (ConocoPhillips, 2018)	f_{tr}^{CSV}	26 (ConocoPhillips, 2018)	f_o^{CSV}	18 (ConocoPhillips, 2018)	f_w^{CSV}	9 (ConocoPhillips, 2018)
PLV	f_m^{PLV}	3 (Institute of Petroleum IOP, 2000)	f_{tr}^{PLV}	40 (Institute of Petroleum IOP, 2000)	f_o^{PLV}	20 (Institute of Petroleum IOP, 2000)	f_w^{PLV}	14 (Institute of Petroleum IOP, 2000)
Helicopter	f_p^H	0.824 tonnes/hr*						

* 1023 lit/hr=0.824 tonnes/hr. For helicopter activities, it is assumed that a round trip from and to site takes places everyday with an hour of overall trip duration.

4. Data mapping

The bottom-up formulations for the economic, environmental, and safety criteria are functions of a range of parameters. In this section, appropriate values for these parameters are adopted based on the information available from various technical sources and current experience in the O&G industry. The data reported in this section are all publicly available on the web, and the references and weblinks for the technical documents are provided for readers.

4.1. Cost parameters

The cost parameters include the day rates of different vessels/equipment. Table 7 lists the minimum and maximum ranges for the vessel/equipment leasing rates alongside the selected values in this study. The vessel/equipment rates vary over time and depend on the demand and supply levels in O&G industry. The source of the values is referred to in the table. In addition, the Wait on Weather (WoW) parameter, represented by α_w, is assumed as 1.70 for subsea operations, 1.50 for CSV, and rock-placement activities, and 1.20 for operations at the sea surface, based on the Viking CA (ConocoPhillips, 2018).

4.2. Duration parameters

The activity duration parameter, $t_{i,j}$, are functions of the mobilisation/de-mobilisation, transit, and removal rates. Table 8 summarises the available ranges for the removal duration parameters from the technical reports alongside the selected values assumed in this study. It is worth noting that, due to the limited data availability and variations across different projects, 1 day is assumed for all transit and mobilisation/demobilisation duration parameters, except for the PLV. It is assumed that the PLV will be mobilised over 5 days, and it will spend 4 days in transit between site and shore in the reverse removal optionn Table 9.

Table 10

The replacement emissions and energy usages produced per tonne of material (Institute of Petroleum IOP, 2000).

Material	Steel	Concrete (cement)	Coating
Emissions (tonnes of CO_2/tonnes)	1.889	0.88	N/A
Energy usage (GJ/tonnes)	32	1.3	N/A

Table 11

The recycling emissions and energy usages per tonne of material (Institute of Petroleum IOP, 2000) .

Material	Steel	Concrete (cement)	Coating
Emissions (tonnes)	0.96	N/A	N/A
Cement (GJ/tonnes)	15	N/A	N/A

4.3. Environmental parameters

As explained in Section 3.2, the environmental criterion depends on the fuel consumption, emission, and energy factors that need to be appropriately assigned. The current practice of the industry is based on the emissions and energy factors available from the guidelines published by the Institute of Petroleum (IoP) (Institute of Petroleum IOP, 2000). In this study, a combination of fuel consumption factors proposed by the IoP guidelines (Institute of Petroleum IOP, 2000) and other technical reports are adopted for different operational modes of vessels/equipment as listed in.

Table 10 and Table 11 list the emission and energy factors related to the material replacement and recycling processes. It should be noted that the energy usage and emissions related to the pipeline coating materials are excluded in this study due to the absence of data. In this study, the emissions and energy factors are considered the same for both vessel and aviation fuels. The emissions factor, ε_f, is considered as 3.17 tonnes of CO_2/tonnes of fuel and the energy factor, e_f, is assumed to be 45.4 GJ/tonnes (Institute of Petroleum IOP, 2000).

4.4. Safety parameters

As explained in Section 3.3, the safety risk for each option, represented by PLL_i, depends on the numbers of personnel onboard and the FAR values, denoted by $P_{i,j}$ and $FAR_{i,j}$, respectively. Table 12 presents the FAR values related to different operations based on the report available from industry (Myrheim et al., 2005). The numbers of personnel onboard are assumed for different vessels/equipment based on the data available from various industry reports as listed in Table 13.

5. Brent field case study

The PL001/N0501 pipeline in the Brent field was selected in this study to test the effectiveness of the proposed bottom-up formulations. The PL001/N0501 is a 35.9 km long 30-inch oil export pipeline that

Table 12
The Fatal Accident Rate (FAR) values for the different operations across different decommissioning options.

Activities	Notation	Category (Myrheim et al., 2005)	FAR (Myrheim et al., 2005)
JUV- pipeline preparation and cleaning	$FAR_{1,0}, FAR_{2,0}, FAR_{3,0}, FAR_{4,0}$	Equipment decommissioning operations - offshore	1.90
DSV- mobilisation, transit, and removal activities	$FAR_{1,1}, FAR_{1,2}, FAR_{1,3}, FAR_{2,1}, FAR_{2,2}, FAR_{2,3}, FAR_{3,1}, FAR_{3,3}, FAR_{4,1}, FAR_{4,2}, FAR_{4,3}, FAR_{4,4}$	Marine operations – Diving Support	7.50
RDV- rock-dumping	$FAR_{1,4}, FAR_{1,5}, FAR_{2,5}, FAR_{3,6}, FAR_{4,5}$	Deconstruction operations – offshore (comparable to construction works)	4.10
ROVSV- pipeline survey	$FAR_{0,0}, FAR_{1,6}, FAR_{2,6}, FAR_{3,7}, FAR_{4,6}$,	Marine operations – Diving Support	7.50
Helicopter	$FAR_{0,1}, FAR_{1,7}, FAR_{2,7}, FAR_{3,8}, FAR_{4,7}$	Cruise	97
Pipeline cut and lift activities	$FAR_{2,4}, FAR_{3,2}$	Marine operations – Crane barges/vessels	5.50
Pipeline removal using reverse S-lay and cutting on the vessel deck	$FAR_{3,4}$	Marine operations – Crane barges/vessels	5.10 + 4.10 = 9.20
Offshore support activities	$FAR_{3,5}$	Marine operations – Supply	18.10

Table 13
The number of personnel onboard $P_{i,j}$ for each vessel in different decommissioning options (person).

Activities	Notation	Value
JUV- pipeline preparation and cleaning	$P_{1,0}, P_{2,0}, P_{3,0}, P_{4,0}$	76 (Fairfield Energy, 2021)
DSV- mobilisation, transit, and removal activities	$P_{1,1}, P_{1,2}, P_{1,3}, P_{2,1}, P_{2,3}, P_{3,1}, P_{3,3}, P_{4,1}, P_{4,4}$	76 (Fairfield Energy, 2021)
RDV- rock-dumping	$P_{1,4}, P_{1,5}, P_{2,5}, P_{3,6}, P_{4,5}$	20 (Fairfield Energy, 2021)
ROVSV- pipeline survey	$P_{0,0}, P_{1,6}, P_{2,6}, P_{3,5}, P_{3,7}, P_{4,3}, P_{4,6}$	44 (XODUS, 2023)
TSV- trenching activities	$P_{2,2}, P_{3,2}, P_{4,2}$	50 (XODUS, 2023)
CSV- cut and lift activities	$P_{2,4}$	50[a]
Helicopter	$P_{0,1}, P_{1,7}, P_{2,7}, P_{3,8}, P_{4,7}$	10[a]
PLV activities	$P_{3,4}$	76 (XODUS, 2023)

[a] Assumed in this study.

connects the Brent Charlie and Cormorant Alpha platforms. The pipeline is the largest pipeline in the Brent field (Shell UK Limited, 2020a) and was installed in 1978 using the S-lay method and partially trenched along its length. Fig. 3 illustrates the overall configuration of the PL001/N0501 pipeline in the Brent field with spool pieces at the platform ends. PL001/N0501 is a rigid pipeline consisting of 12,819 tonnes of steel, 11,983 tonnes of concrete, and 728 tonnes of coating materials (Shell UK Limited, 2020a). According to the multi-beam echo sounder survey results reported in the Brent TD (Shell UK Limited, 2020b), approximately 70% of the pipeline length is trenched with the top of the pipeline at seabed level or up to 0.6 m below the seabed level. This needs to be remediated during the decommissioning operations. It is assumed that there are 10 mattresses across the pipeline with 4 mattresses placed at the platform ends. The Brent TD (Shell UK Limited, 2020b) has performed a CA for this pipeline by considering the 5 different decommissioning options as explained in Section 2.1. In this study, the different options for the PL001/N0501 pipeline are assessed in terms of economic, environmental, and safety criteria using the proposed formulations and the obtained results are compared to those reported in the Brent TD (Shell UK Limited, 2020b).

The detailed durations, costs, energy usages, and emissions calculated from the proposed approach are given in Tables B1-B5 in Appendix B. To provide a brief comparison, Table 14 compares the results obtained in this study to those reported in the Brent TD (Shell UK Limited, 2020b) in terms of costs, energy usages, emissions, and safety risks. It is observed that the proposed approach provides estimates with less than 10% differences across some of the sub-criteria. Regarding the cost values, it can be seen from Table 14 that the cost differences are less than 10% for options 0 and 1, while it is more than 10% for other options. The differences in the cost values may arise from assumptions made for different parameters, such as the vessel/equipment leasing rates, duration parameters, and weather delays.

When it comes to the energy usage and emission amounts in Table 14, the results provided by the proposed approach are more consistent with those reported by the Brent TD (Shell UK Limited, 2020b), as the differences are below 10%. Both energy and emission differences are even smaller, being <5% for options 1 and 2, which verifies the efficacy of the proposed approach. The differences in the energy usage and emission estimations could result primarily from the fuel consumption and emissions factors assumed for the different vessels/equipment as well as material reproduction and recycling processes. However, it should be noted that the estimations for the activity durations can also cause differences in the energy and emissions values.

The safety risk results obtained from the proposed formulations are close to those reported in the Brent TD (Shell UK Limited, 2020a). From Tables 14, it is observed that the differences between the obtained PLL values are ≤5% for options 2, 3, and 4. Although the differences in the PLL values for options 0 and 1 are slightly higher, the numerical PLL values still provide a good level of accuracy considering the uncertainties in available data. The differences in PLL values may be caused by the assumptions made in this study for the number of personnel onboard involved in each activity and the duration parameters.

Figs. 4–7 compare the costs, energy usages, emissions, and safety risks associated with the operations in each decommissioning option, respectively. In addition, Fig. 8 presents the breakdown charts for the costs, energy usages, emissions, and safety risks in each option. As can be seen from Fig. 4, the full removal options, i.e., options 2 and 3, have the highest costs and the option of leave in place with minimum intervention has the lowest cost as might be expected. The reverse installation alongside the cut and lift operation are the major contributors to the costs of the full removal options. From an environmental viewpoint, Figs. 5 and 6 suggest that the energy usages and emissions related to the material replacement for the leave in place options are significant and can be even higher than the energy usage and emissions expected to be caused by the full removal options. This highlights the necessity of considering the wider emissions impact of material replacement for the leave in place options. Fig. 7 provides some interesting insights from the safety viewpoint. The full removal options, i.e., options 2 and 3, have the highest safety risks to offshore personnel due to the extent of the operations they include, while the leave in place options cause minimum safety risks as it was expected. The reverse installation alongside the cut

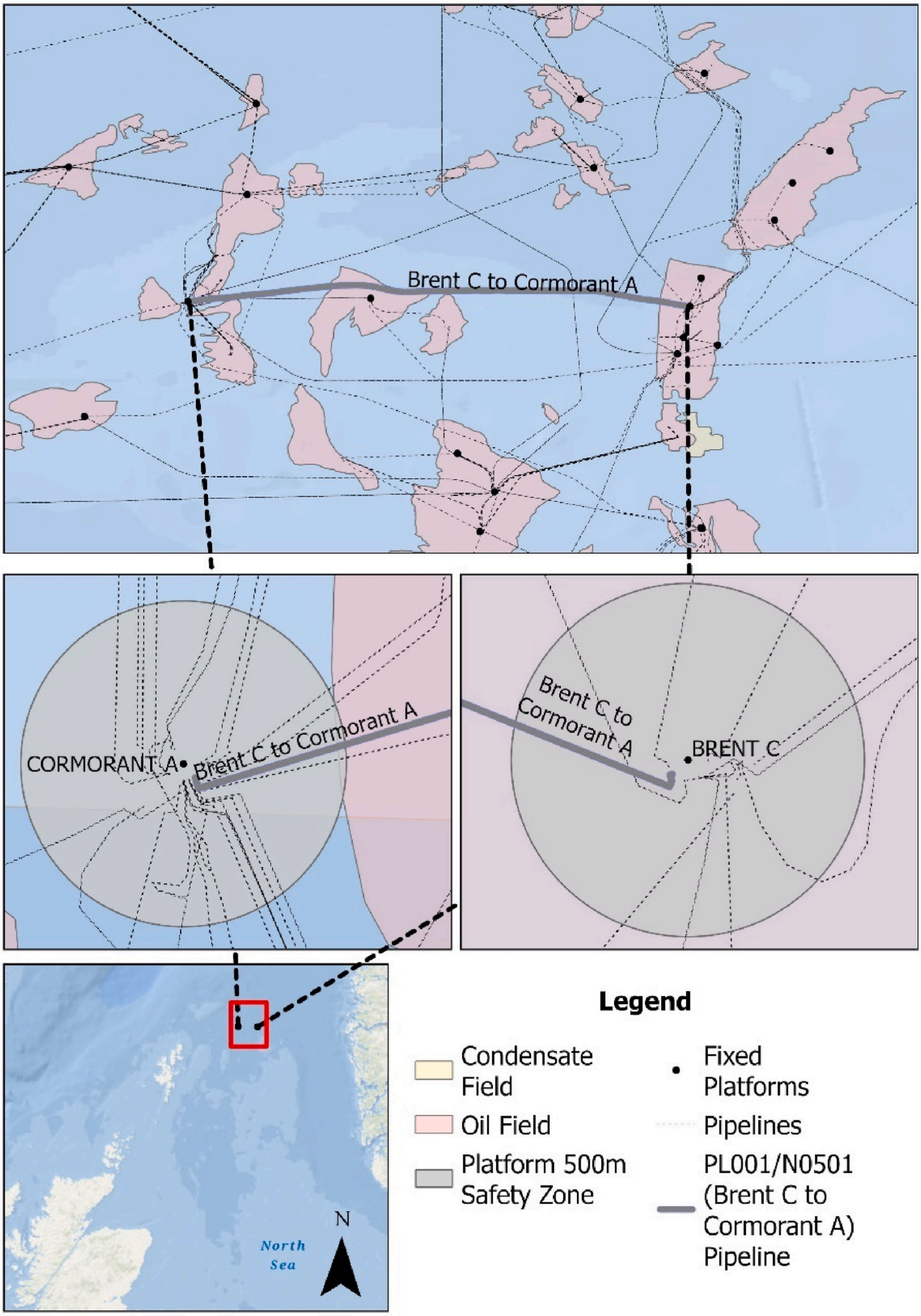

Fig. 3. Location and configuration of the PL001/N0501 pipeline in the Brent field.

Table 14

Comparison of the results obtained from the proposed approach to those reported by the Brent field TD (Shell UK Limited, 2020b) for the PL001/N0501 pipeline.

Options	Source	Cost (£ million)	Difference (%)	Energy (GJ)	Difference (%)	CO_2 Emissions (tonnes)	Difference (%)	Safety risk[a] (PLL)	Difference (%)
Option 0: Leave in place with minimum intervention	Brent field TD (Shell UK Limited, 2020b)	0.76	**9.9%**	409,373	**6.2%**	32,362	**9.3%**	0.0011	<u>14.3%</u>
	This study	0.69		434,672		35,379		0.000943	
Option 1: Leave in place with minor intervention	Brent field TD (Shell UK Limited, 2020b)	11.83	**9.2%**	491,006	**2.2%**	37,320	**3.3%**	0.0043	**8.4%**
	This study	10.74		479,960		38,533		0.004661	
Option 2: Full Removal- Cut & Lift	Brent field TD (Shell UK Limited, 2020b)	76.73	<u>18.1%</u>	467,517	**2.18%**	31,916	**2.6%**	0.0299	**4.5%**
	This study	62.81		477,706		31,100		0.028569	
Option 3: Full Removal- Reverse Installation	Brent field TD (Shell UK Limited, 2020b)	89.57	<u>19.9%</u>	421,140	**1.1%**	28,945	**7.2%**	0.0408	**0.5%**
	This study	71.75		416,676		26,855		0.040603	
Option 4: Partial trench and backfill with isolated rock-dump	Brent field TD (Shell UK Limited, 2020b)	9.49	<u>17.6%</u>	461,192	**2.9%**	35,837	**6.5%**	0.0051	**4.8%**
	This study	7.82		474,480		38,152		0.005344	

Note: the difference values in bold show good accuracy and the underlined values indicate higher differences.

[a] Safety risk to offshore project personnel.

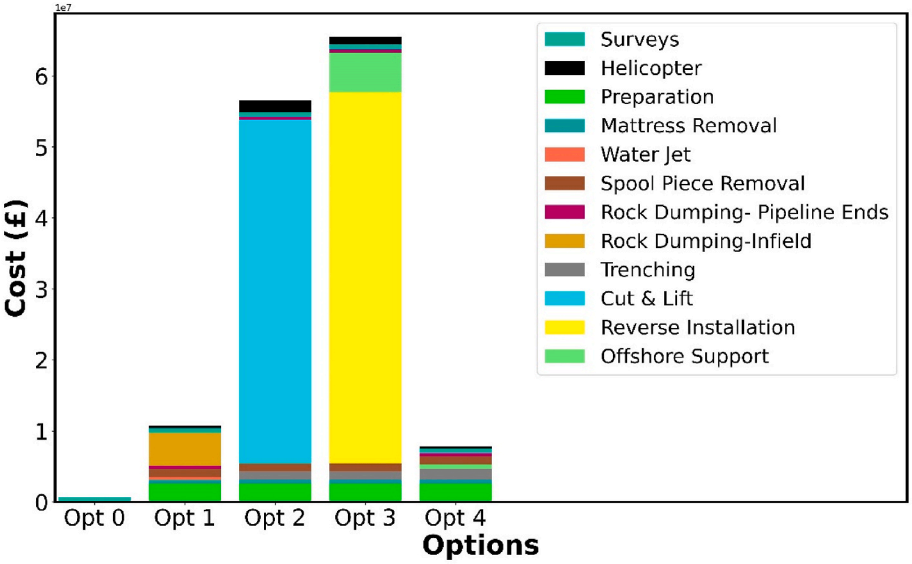

Fig. 4. Comparison of the costs related to the different decommissioning options for the PL001/N0501 pipeline in the Brent field.

and lift as well as offshore support operations have the highest PLL values and are expected to cause the highest level of safety risks.

5.1. Sensitivity of bottom-up formulations

As can be seen in Section 3, the bottom-up formulations for the costs, energy usages, emissions, and safety risks presented in this study are linear functions of input data variables. The data uncertainties can cause significant changes in the results. The uncertainties in input data can affect the outputs from the multi-criteria decision analysis (Gitinavard et al., 2018). Due to a lack of available probabilistic data for each input variable, it is difficult to analyse the sensitivity of the proposed bottom-up formulations to the uncertainties associated with the input variables. However, to show how the results of multi-criteria analysis can be affected by the data uncertainties, the sensitivities of costs, energy usage, emissions, and safety risk to the changes in the pipeline deburial/trenching rate r_T are shown in Fig. 9. As can be seen from Fig. 9, the performance of each decommissioning option can be changed dramatically by the variations in trenching rate parameter. For example, option 4 is more favourable than options 1 and 2 in terms of energy usage for the lower trenching rates, whereas options 1 and 2 exhibit better energy performance for higher trenching rates. Hence, the uncertainties in input variables can significantly affect the multi-criteria decision analysis results. The availability of probabilistic data could potentially pave the way towards more comprehensive statistical sensitivity analyses of the proposed multi-criteria bottom-up formulations.

6. Visualising decision-making in an immersive environment

The proposed bottom-up formulations may be employed to inform the decision-making process by industry companies and stakeholders in the UKCS. When making decisions in a complex environment such as the UKCS, it is necessary to consider not just the area or asset of interest, but

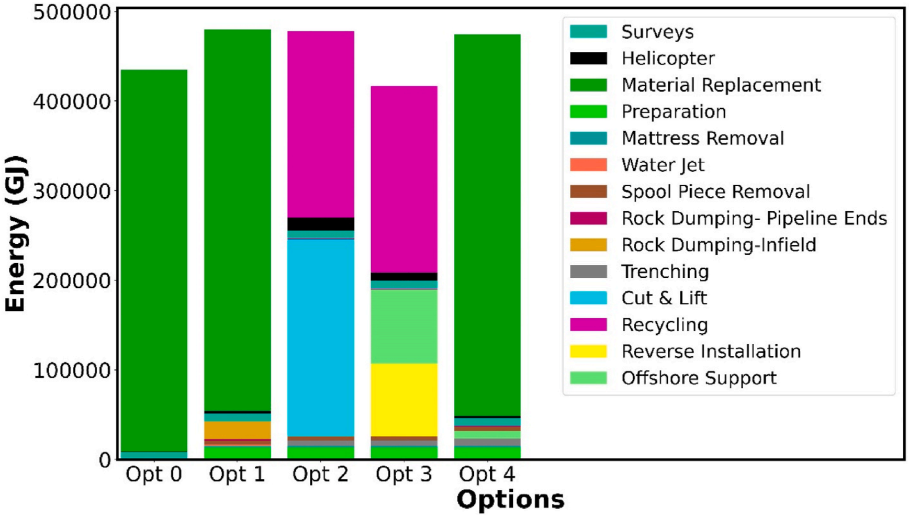

Fig. 5. Comparison of the energy used by the different decommissioning options for the PL001/N0501 pipeline in the Brent field.

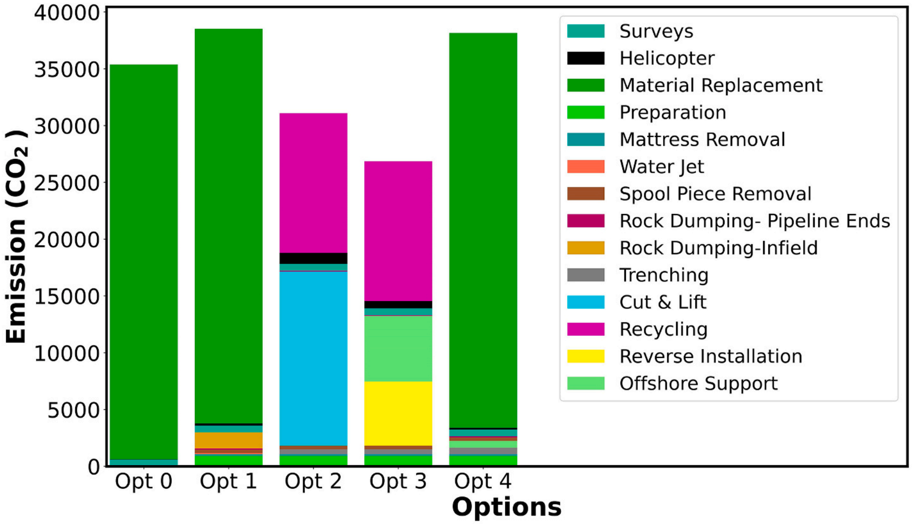

Fig. 6. Comparison of the carbon emissions caused by the different decommissioning options for the PL001/N0501 pipeline in the Brent field.

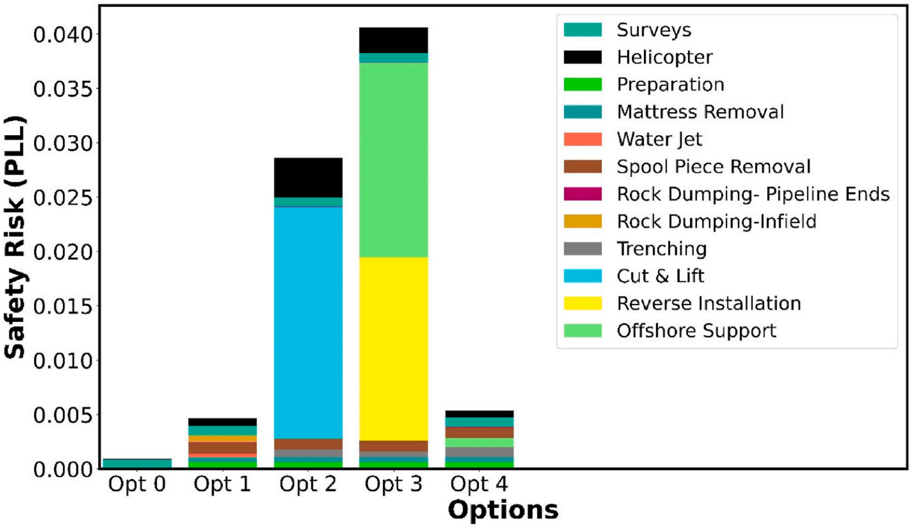

Fig. 7. Comparison of the safety risks related to the different decommissioning options for the PL001/N0501 pipeline in the Brent field.

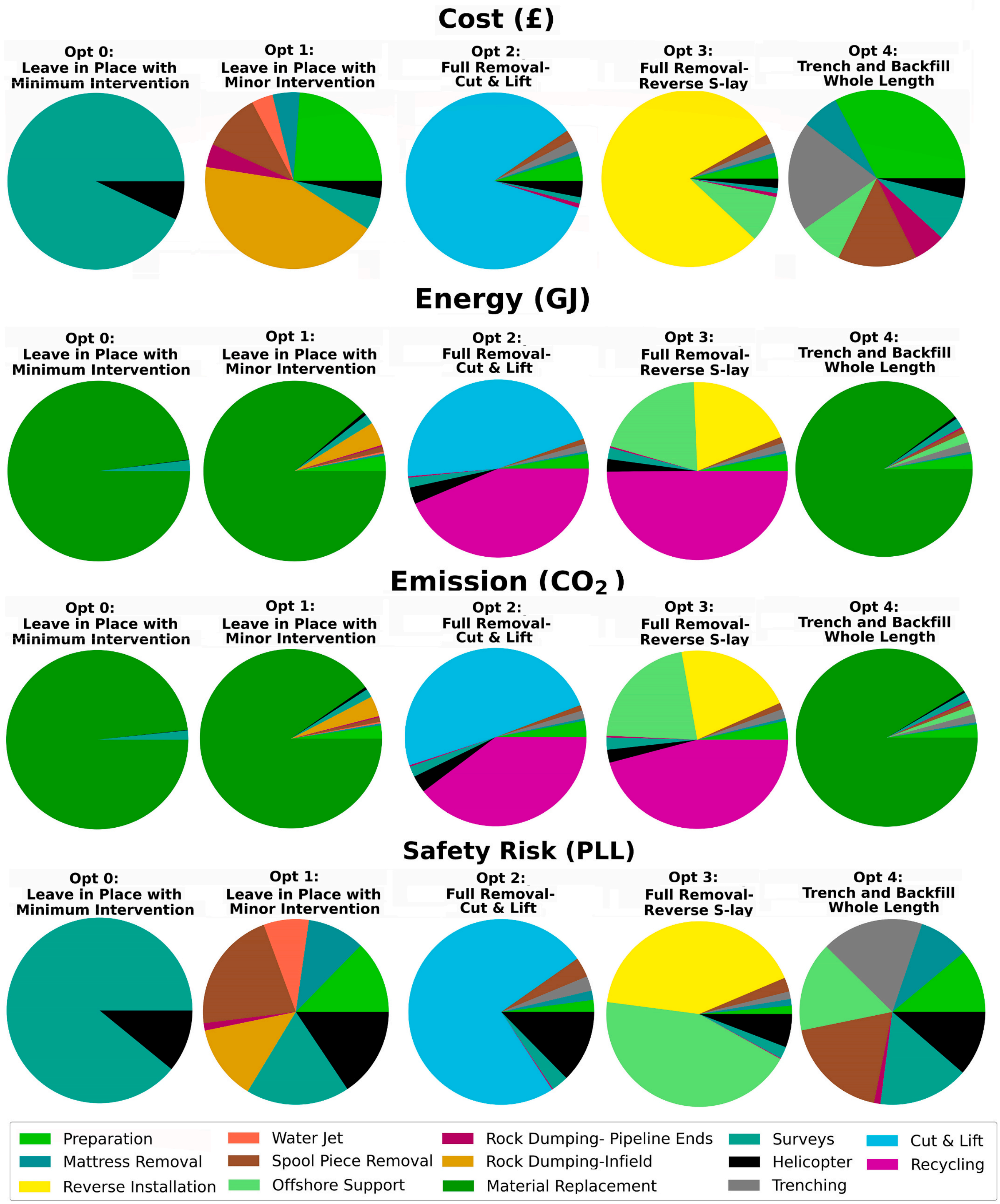

Fig. 8. Cost, energy usage, emissions, and safety risk breakdowns in the different decommissioning options for the PL001/N0501 pipeline in the Brent field.

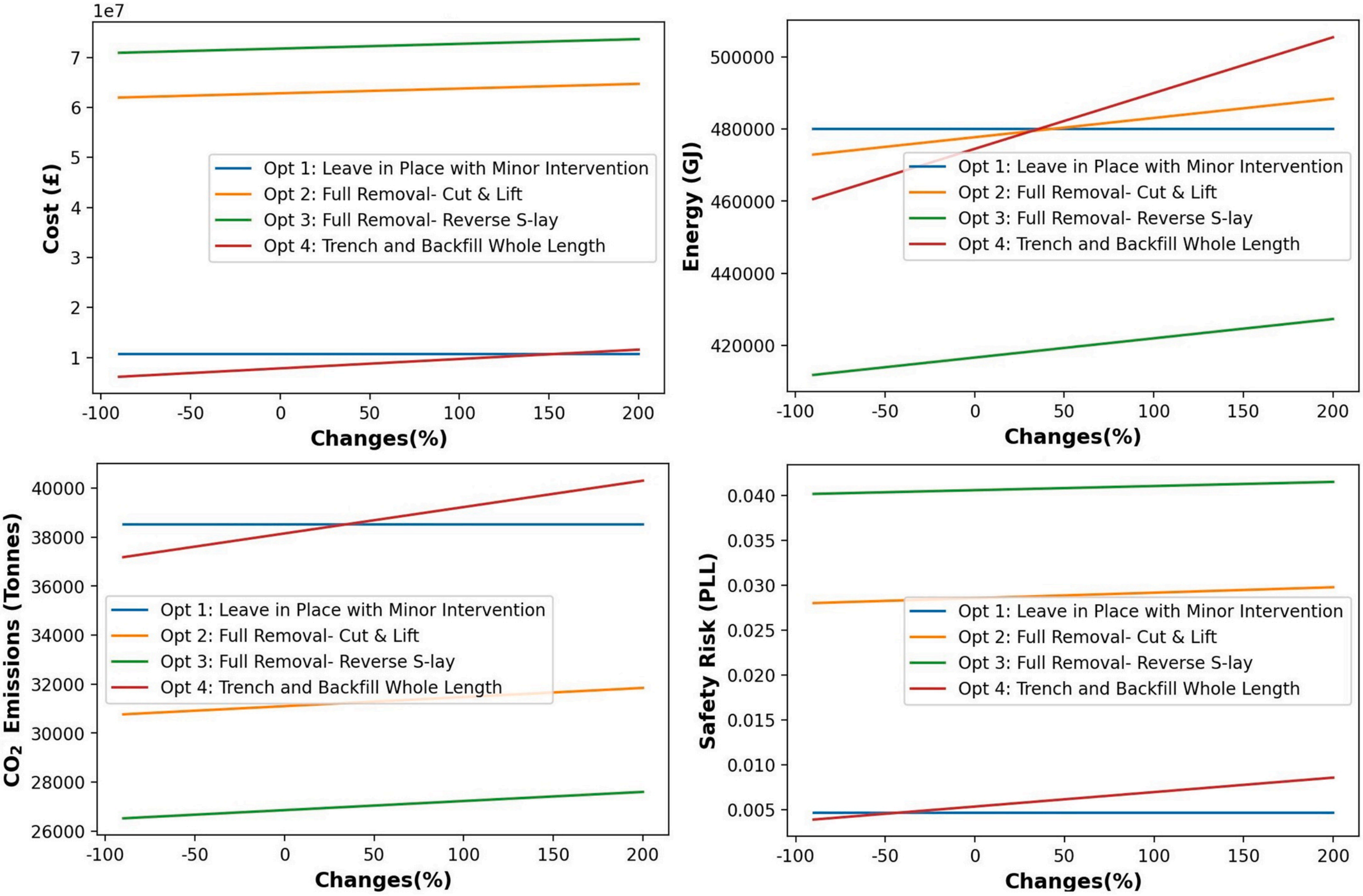

Fig. 9. Sensitivities of the costs, energy usages, emissions, and safety risks to the changes in the deburial/trenching rate parameter r_T

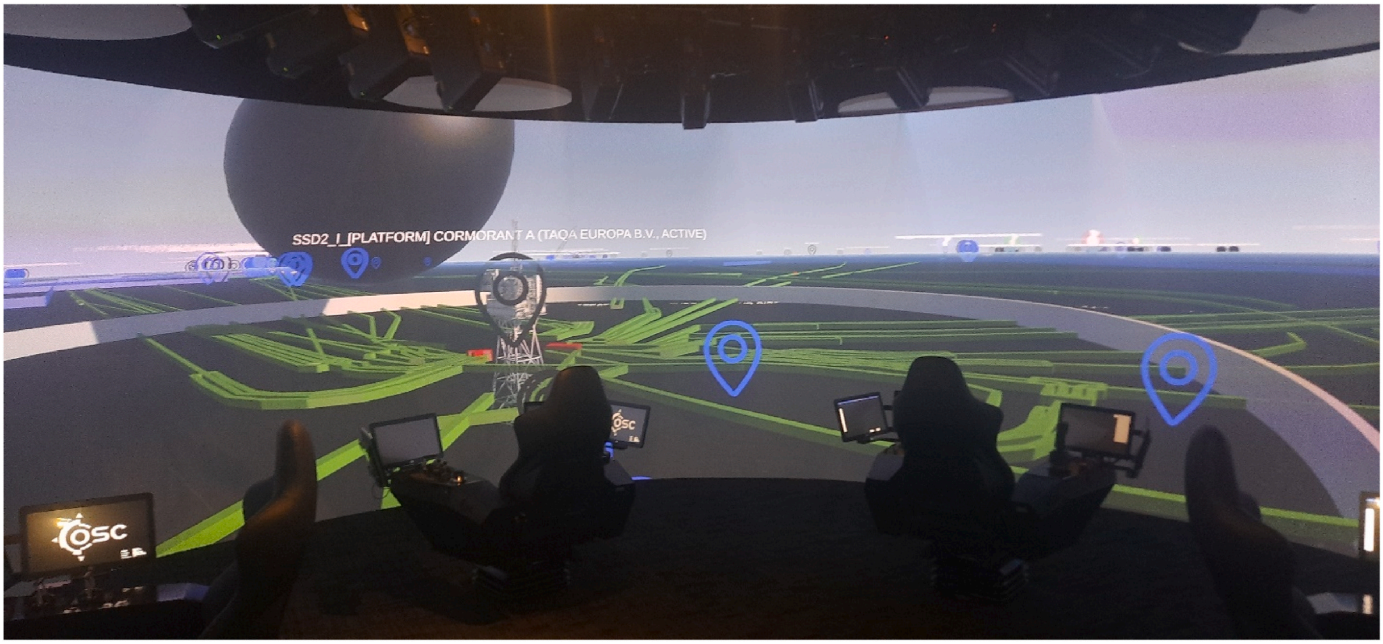

Fig. 10. View of the marine simulator dome showing the area around Cormorant A. Grey circle shown is the safety zone around Cormorant A, green lines are pipelines, red lines are freespans, black pin marks the platform, and blue pins mark subsurface infrastructure. The large black sphere represents CO$_2$ emissions for Cormorant A in 2020 (37,874.51 tonnes). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

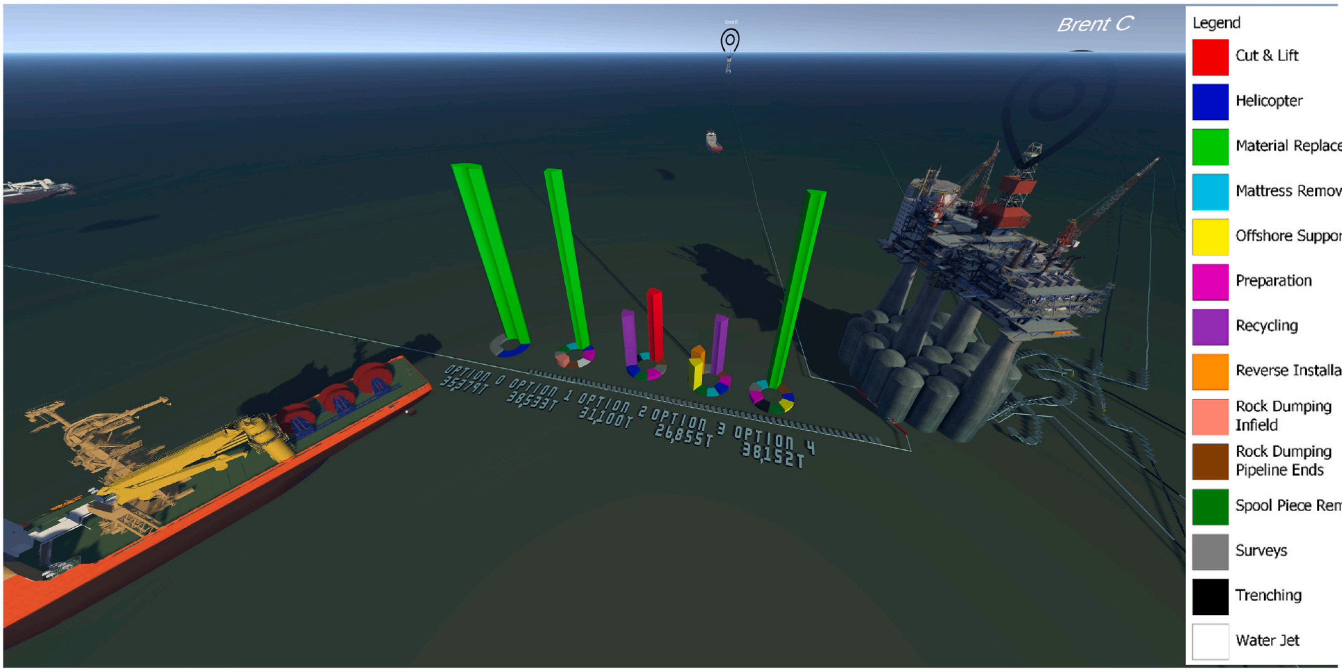

Fig. 11. Visualisation of emissions resulting from the different decommissioning options for PL001/N0501 within the simulator.

all nearby assets and infrastructure, and other interactions, including commercial and environmental. This involves investigating many disparate data streams and creating a unified model of the environment for the proposed activity. One way of achieving this which provides a user-friendly way of interrogating this model is by deploying it in an immersive environment. To test this, the marine simulator at the National Decommissioning Centre,[1] which was installed by the Offshore Simulator Centre,[2] was utilised. This offers a full weather and physics 3D simulation of a marine environment. The physics capabilities of this simulator are largely out of the scope of this work, but have been explored in (Terrero-Gonzalez et al., 2024), (Martinez et al., 2023). As part of this, the infrastructure is modelled using a variety of vessels, assets, and structures from a built-in library, or by adding new models. The output of this is a 3D scene which can be explored readily from within a 300°, 9-m diameter immersive dome, shown in Fig. 10. The simulator consists of 22 servers (8 to run the 16 projectors, 8 to run the 4 control chairs, and 6 to run the physics engine). The chairs in the dome can be assigned to control equipment (such as vessels, cranes, and ROVs) to simulate scenarios involving operating these simultaneously.

The marine simulator utilises a proprietary commercial software package created by the Offshore Simulator Centre, which utilises AGX Dynamics[3] to provide its physics simulations. The data visualisations are included as part of the Augment City[4] software package, again provided by Offshore Simulator Centre as part of the simulator. To provide an immersive decision-making environment for stakeholders, outputs of the proposed bottom-up multi-criteria formulations were converted into a suitable format for visualising within the marine simulator, specifically CSV files to display as bar charts. The PL001/N0501 pipeline was also modelled, along with other nearby pipelines, the subsea infrastructure (including concrete mattresses), and the nearby platforms. Depending on the scenario selected by the user, the simulator shows the cost, energy usage, emission, and safety risk results based on the input data. For illustrative purposes, Fig. 11 shows the emissions resulting from each option visualised within the simulator at a section of PL001 pipeline adjacent to Brent Charlie. It is worth mentioning the emissions represented in Fig. 11 are identical to those presented in Fig. 6. The simulator also allows us to visualise the results for other criteria in a similar way. It should be noted that the platform shown in Fig. 11 is representative, and not a model specifically of Brent Charlie.

One of the key benefits of the developed decision-making environment is that it provides an interactive way to not only show the results to stakeholders in the context of specific asset's environment, but also to drive discussion of the data presented, potentially identifying new options and scenarios. This provides real context for the challenges involved in carrying out decommissioning operations and allows identification of issues early with the potential to reduce risks and costs. The developed decision-making environment allows stakeholders to explore problems in a more visually engaging manner than being presented with lengthy reports, as they can navigate in 3D through the physical layout of the environment with all relevant data for the proposed options overlaid. Additionally, this decision-making environment has the potential to model other offshore operations that could take place in this environment, which could provide further support for the decision-making process.

7. Conclusions

This study proposed a set of bottom-up formulations to support the multi-criteria decision analysis process within the CA of O&G decommissioning projects in the NSR. Bottom-up formulations were developed for the economic, environmental, and safety assessment of different pipeline decommissioning options based on the available data and information from the O&G industry. The approach adopts current guidelines in the O&G industry and considers a range of parameters to provide estimations for the costs, energy usages, emissions, and safety risks. These parameters include, but are not limited to, site-specific data, operational durations, vessel/equipment leasing rates, vessel/equipment fuel consumption and emission factors, material recycling/replacement emissions, and probabilistic safety risk parameters. The qualities of assumed data input for the mentioned parameters play a key role in the performance of the proposed approach. The study provided a review of currently available data and information from the O&G

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[1] NDC Simulator - https://www.ukndc.com/research/facilities/simulator/.

[2] OSC - https://osc.no/.

[3] Algoryx - https://www.algoryx.se/agx-dynamics/.

[4] Augment City - https://augmentcity.no/.

industry and adapted appropriate values for the different parameters.

To verify the effectiveness of the proposed formulations, the longest oil export pipeline in the Brent field, PL001/N0501, was selected as a case study under five decommissioning options. The results showed that the full removal options have the highest decommissioning costs and safety risks to the offshore personnel. It was observed that the energy usages and emissions related to the replacement of lost materials for the leave in place options can be even higher than the energy usages and emissions expected to be caused by the full removal options. From an accuracy viewpoint, the numerical results from the proposed approach revealed good consistency with those reported by the Brent TD. In most cases, the comparisons suggested that the proposed approach provides estimates with less than 10% differences for the costs, energy usages, emissions, and safety risks. The average differences between the estimates obtained in this study and those reported by Brent TD are less than 3%, 6%, and 7% for the energy usages, emissions, and safety risks, respectively. However, the differences for the cost values are a bit higher, with average difference of about 15%. The differences in the results may arise from a range of assumptions made for the different parameters, such as vessel/equipment leasing rates, duration parameters, fuel and emission factors, number of people involved in each activity, and weather delays. The advantage of the proposed bottom-up approach is its flexibility that provides the possibility of model expansion/modification for new data, technologies, or projects. The proposed bottom-up formulations can be used within decision frameworks to inform the decision-making process for the O&G pipeline decommissioning.

The proposed bottom-up approach offers a range of benefits for stakeholders involved in the decision-making process for O&G pipeline decommissioning. The approach, in which detailed data are modelled, enhances the accuracy of multi-impact analysis. This will make it easier for stakeholders to identify major contributors to the cost, emissions, energy usage, and safety risk figures. This will not only allow better scrutiny of the methodology, scenarios, and results, but also share learning and improve cross stakeholder engagement and understanding. Due to the bottom-up nature of the approach, the formulations can also be employed by decision makers to identify potential technology improvement opportunities and better resource allocation in O&G pipeline decommissioning projects.

The proposed multi-criteria bottom-up formulations were implemented within a marine simulator to provide an immersive decision-making environment which can provide visualisation of the consequences of decisions made by stakeholders on the economy, environment, and safety in an interactive way. This provides a user-friendly environment for stakeholders to inform the decision-making process and guide the discussions around the sustainability of decommissioning projects in the UKCS.

The approach also has some uncertainty and applicability limitations. The proposed bottom-up formulations are functions of a set of input data variables which can affect significantly the accuracy of the results. The results from the sensitivity analysis revealed that the uncertainties in input variables can affect significantly the outcome of the multi-criteria decision analysis. Moreover, the proposed formulations are developed based on the data and information available in the North Sea region. Therefore, its applicability to the pipeline decommissioning projects in other regions needs to be investigated based on the local data and practice. Future works can focus on the model boundary expansions, new data acquisition, and probabilistic sensitivity analysis of the proposed approach to the input data variables to provide more accurate estimations for the O&G pipeline decommissioning projects. The long-term financial liabilities related to the decommissioning activities is another important aspect of decision-making process. Although the costs related to the post-decommissioning surveys are considered within the proposed formulations, a more detailed economic analysis is needed to estimate long-term financial liabilities of the operators.

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CRediT authorship contribution statement

Shahin Jalili: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Georgios Leontidis:** Writing – review & editing, Project administration, Data curation, Conceptualization. **Samuel R. Cauvin:** Writing – review & editing, Visualization. **Kate Gormley:** Writing – review & editing, Visualization. **Malcolm Stone:** Writing – review & editing, Project administration. **Richard Neilson:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. List of parameters

Table A. 1
List of parameters

Parameter	Unit	Definition
C_i^{V}	£	The cost of *i* th
$c_{i,j}$	£	The cost of the *j* th operation at option *i*
n_i^{o}	number	The number of operations at option *i*
$t_{i,j}$	day	The duration of operation *j* at the *i* th option
$C_{\mathrm{D}}^{\mathrm{JUV}}$	£	The day rate of the JUV
$t_{\mathrm{m,P}}^{\mathrm{JUV}}$	day	The JUV mobilisation duration for the pipeline cleaning and preparation
$t_{\mathrm{tr,P}}^{\mathrm{JUV}}$	day	The JUV transit duration between the port and site for pipeline cleaning and preparation
$t_{\mathrm{P}}^{\mathrm{JUV}}$	day	The operational duration of pipeline cleaning and preparation using JUV
$C_{\mathrm{D}}^{\mathrm{DSV}}$	£	The day rate of the DSV

(*continued on next page*)

Table A. 1 (*continued*)

Parameter	Unit	Definition
$t_{\mathrm{m,MR}}^{\mathrm{DSV}}$	day	The DSV mobilisation duration for the mattress removal operation
$t_{\mathrm{tr,MR}}^{\mathrm{DSV}}$	day	The DSV transit duration for the mattress removal operation
α_{w}	–	WoW parameter
$t_{\mathrm{MR}}^{\mathrm{DSV}}$	day	The operation duration of mattress removal using DSV
$t_{\mathrm{m,EX}}^{\mathrm{DSV}}$	day	The DSV mobilisation duration for the deburial operation of the pipeline ends
$t_{\mathrm{tr,EX}}^{\mathrm{DSV}}$	day	The DSV transit duration for the deburial operation of the pipeline ends
$t_{\mathrm{EX}}^{\mathrm{DSV}}$	day	The operational duration of pipeline ends deburial using DSV
$t_{\mathrm{m,SP}}^{\mathrm{DSV}}$	day	The DSV mobilisation duration for the spool piece removal operation
$t_{\mathrm{tr,SP}}^{\mathrm{DSV}}$	day	The DSV transit duration for the spool piece removal operation
$t_{\mathrm{SP}}^{\mathrm{DSV}}$	day	The spool piece removal operational duration using DSV
$C_{\mathrm{D}}^{\mathrm{RDV}}$	£	The day rate of the RDV
$t_{\mathrm{m,RDSP}}^{\mathrm{RDV}}$	day	The RDV mobilisation duration for the rock-dumping operation at spool piece locations
$t_{\mathrm{tr,RDSP}}^{\mathrm{RDV}}$	day	The RDV transit duration for the rock-dumping operation at spool piece locations
$t_{\mathrm{RDSP}}^{\mathrm{RDV}}$	day	The duration of the rock-dumping operation at spool piece locations using RDV
$t_{\mathrm{m,S}}^{\mathrm{ROVSV}}$	day	The ROVSV mobilisation duration for the pre- and post-decommissioning survey operations
$t_{\mathrm{tr,S}}^{\mathrm{ROVSV}}$	day	The ROVSV transit duration from and to site for the pre- and post-decommissioning survey operations
$t_{\mathrm{S}}^{\mathrm{ROVSV}}$	day	The ROVSV operational duration for the pre- and post-decommissioning survey operations
$C_{\mathrm{D}}^{\mathrm{H}}$	£	The day rate of Helicopter for a round trip between offshore site and shore
$r_{\mathrm{m,P}}^{\mathrm{JUV}}$	day/km	Mobilisation/demobilisation rate for the pipeline preparation and clearance using an JUV
L	km	Pipeline length
$r_{\mathrm{m,SP}}^{\mathrm{DSV}}$	day/km	Mobilisation/demobilisation rate of the DSV for spool piece removal operation
$r_{\mathrm{m,S}}^{\mathrm{ROVSV}}$	day/km	The mobilisation/demobilisation rate of ROVOSV for the pre- and post-decommissioning survey operation
r_{p}	day/km	Pipeline preparation and cleaning rate using an JUV
r_{m}	day/unit	Mattress removal rate
n_{Me}	Units	the number of mattresses at the pipeline ends, which is assumed as two mattresses at each end
r_{EX}	day/unit	The rate of pipeline end deburial using the water jet technique
r_{SP}	day/unit	Spool piece removal rate
n_{SP}	units	The number of spool pieces
r_{RDSP}	day/unit	The rock dumping rate for the spool piece locations at platform ends
r_{S}	day/unit	The pre- and post-decommissioning survey rate for leave in situ pipelines
n_{M}	units	The total number of mattresses on the pipeline
$t_{\mathrm{m,RDEX}}^{\mathrm{RDV}}$	day	Mobilisation/demobilisation rate of the RDV for rock-dumping operation on the exposed parts of the pipeline
$t_{\mathrm{tr,RDEX}}^{\mathrm{RDV}}$	day	The RDV transit duration for the rock-dumping operation on the exposed parts of the pipeline
$t_{\mathrm{RDEX}}^{\mathrm{RDV}}$	day	The RDV operational duration for the rock-dumping operation on the exposed parts of the pipeline
r_{RDEX}	day/unit	The rock-dumping rate on the exposed parts of the pipeline using RDV
L_{ex}	km	The total exposed length of the pipeline
$C_{\mathrm{D}}^{\mathrm{TSV}}$	£	The day rate of TSV
$t_{\mathrm{m,T}}^{\mathrm{TSV}}$	day	The TSV mobilisation duration for the trenching operation
$t_{\mathrm{tr,T}}^{\mathrm{TSV}}$	day	The TSV transit duration for the trenching operation
$t_{\mathrm{T}}^{\mathrm{TSV}}$	day	The trenching operational duration using TSV
$t_{\mathrm{m,L}}^{\mathrm{CSV}}$	day	The CSV mobilisation duration for the cut and lift operation
$t_{\mathrm{tr,L}}^{\mathrm{CSV}}$	day	The CSV transit duration for the trenching operation
$t_{\mathrm{L}}^{\mathrm{CSV}}$	day	The duration of cut and lift operation using CSV
r_{T}	day/km	The deburial/trenching rate of the pipeline using TSV or CSV
r_{L}	day/km	Cut and lift rate of the pipelines using CSV
$C_{\mathrm{D}}^{\mathrm{PLV}}$	£	The day rate of PLV
$t_{\mathrm{m,RI}}^{\mathrm{PLV}}$	day	The PLV mobilisation duration for the revere installation-based removal and cut on the deck operation
$t_{\mathrm{tr,RI}}^{\mathrm{PLV}}$	day	The PLV transit duration for the reverse installation-based removal operation
$t_{\mathrm{RI}}^{\mathrm{PLV}}$	day	The duration of reverse installation-based removal and cut on deck operation using PLV
$C_{\mathrm{D}}^{\mathrm{ROVSV}}$	£	The day rate of ROVSV
r_{R}	day/km	The pipeline removal rate using the reverse installation method
r_{TB}	day/km	The trench and backfill rate of the pipeline using TSV
F_i	tonnes	Fuel consumption in the *i* th option
$f_{i,j}$	tonnes	Fuel consumption by the *j* th operation at the option *i*
$\mathscr{E}_i$	tonnes of CO_2	Emissions produced by the *i* th option
$\mathscr{E}_i^{\mathrm{rp}}$	tonnes of CO_2	Emissions generated by the material recycling/production at the option *i*
$\varepsilon_{i,j}$	tonnes of CO_2	Emissions produced by the *j* th operation at the option *i*
ε_{f}	tonnes of CO_2/tonnes of fuel	Emission factor
E_i	GJ	Energy usage in the *i* th option
$e_{i,j}$	GJ	Energy usage by the *j* th operation at the option *i*
e_{f}	GJ/tonnes of fuel	Energy factor
E_i^{rp}	GJ	Energy usage by the material recycling/production at the option *i*
$f_{\mathrm{m}}^{\mathrm{JUV}}$	tonnes/day	Fuel consumption of JUV in mobilisation
$f_{\mathrm{tr}}^{\mathrm{JUV}}$	tonnes/day	Fuel consumption of JUV in transit
$f_{\mathrm{o}}^{\mathrm{JUV}}$	tonnes/day	Fuel consumption of JUV in operational
$f_{\mathrm{m}}^{\mathrm{DSV}}$	tonnes/day	Fuel consumption of DSV in mobilisation
$f_{\mathrm{tr}}^{\mathrm{DSV}}$	tonnes/day	Fuel consumption of DSV in transit
$f_{\mathrm{o}}^{\mathrm{DSV}}$	tonnes/day	Fuel consumption of DSV in operational
$f_{\mathrm{w}}^{\mathrm{DSV}}$	tonnes/day	Fuel consumption of DSV in waiting

(*continued on next page*)

Table A. 1 (*continued*)

Parameter	Unit	Definition
$f_{\mathrm{m}}^{\mathrm{RDV}}$	tonnes/day	Fuel consumption of RDV in mobilisation
$f_{\mathrm{tr}}^{\mathrm{RDV}}$	tonnes/day	Fuel consumption of RDV in transit
$f_{\mathrm{o}}^{\mathrm{RDV}}$	tonnes/day	Fuel consumption of RDV in operational
$f_{\mathrm{w}}^{\mathrm{RDV}}$	tonnes/day	Fuel consumption of RDV in waiting
$f_{\mathrm{m}}^{\mathrm{ROVSV}}$	tonnes/day	Fuel consumption of ROVSV in mobilisation
$f_{\mathrm{tr}}^{\mathrm{ROVSV}}$	tonnes/day	Fuel consumption of ROVSV in transit
$f_{\mathrm{o}}^{\mathrm{ROVSV}}$	tonnes/day	Fuel consumption of ROVSV in operational
$f_{\mathrm{w}}^{\mathrm{ROVSV}}$	tonnes/day	Fuel consumption of ROVSV in waiting
f^{H}	tonnes/day	Fuel consumption of helicopter
w_{s}	tonnes	Steel weight
w_{c}	tonnes	Concrete weight
w_{co}	tonnes	Coating weight
ε_{s}	tonnes of CO_2/tonnes	Production emissions per tonne of steel
ε_{c}	tonnes of CO_2/tonnes	Production emissions per tonne of concrete
$\varepsilon_{\mathrm{co}}$	tonnes of CO_2/tonnes	Production emissions per tonne of coating material
e_{s}	GJ/tonnes	Production energy usage per tonne of steel
e_{c}	GJ/tonnes	Production energy usage per tonne of concrete
e_{co}	GJ/tonnes	Production energy usage per tonne of coating material
$\varepsilon_{\mathrm{rs}}$	tonnes of CO_2/tonnes	Recycling emissions per tonne of steel
$\varepsilon_{\mathrm{rc}}$	tonnes of CO_2/tonnes	Recycling emissions per tonne of concrete
$\varepsilon_{\mathrm{rco}}$	tonnes of CO_2/tonnes	Recycling emissions per tonne of coating material
e_{rs}	GJ/tonnes	Recycling energy usage per tonne of steel
e_{rc}	GJ/tonnes	Recycling energy usage tonne of concrete
e_{rco}	GJ/tonnes	Recycling energy usage tonne of coating material
PLL_i	PLL	PLL for the *i* th option
$pll_{i,j}$	PLL	PLL for the *j* th operation of the *i* th option
$P_{i,j}$	Person	Number of personnel on board in the *j* th operation of the *i* th option
$FAR_{i,j}$	Fatalities/10^8 exposure hours	Fatal Accident Rate (FAR) for the *j* th operation of the *i* th option

Appendix B. Detailed results obtained from the proposed approach

Table B. 1
The costs, energy usages, emissions, and safety risks for the option 0

Operations	Vessel	$t_{i,j}$ (days)	Cost (£)	Fuel (tonnes)	Energy (GJ)	CO_2 Emission (tonnes)	$FAR_{i,j}$	$P_{i,j}$	Exposure (person-hours)	Safety Risk (PLL)
Surveys	ROVSV	10.61	636,314	186.6	8470.4	591.4	7.5	44	11,199.1	0.000844
Helicopter	N/A	0.44	48,784	8.74	415.96	27.70	97.0	10	106.1	0.000103
Material Replacement	N/A	N/A	N/A	N/A	425,785.9	34,760.1	N/A	N/A	N/A	N/A
Total	N/A	11.05	685,098	195.31	434,672	35,379	N/A	N/A	11,305	0.000943

Table B. 2
The costs, energy usages, emissions, and safety risks for the option 1

Operations	Vessel	$t_{i,j}$ (days)	Cost (£)	Fuel (tonnes)	Energy (GJ)	CO_2 Emission (tonnes)	$FAR_{i,j}$	$P_{i,j}$	Exposure (person-hours)	Safety Risk (PLL)
Preparation	JUV	17.08	2,561,700	289.4	13,138.9	917.4	1.9	76	31,150.3	0.000592
Mattress Removal	DSV	3.42	533,000	43.8	1,990.0	139.0	7.5	76	6,232.0	0.000467
Water Jet	DSV	2.69	419,406	33.1	1,503.9	105.0	7.5	76	4,903.8	0.000368
Spool Piece Removal	DSV	7.27	1,134,120	100.5	4,562.7	318.6	7.5	76	13,260.5	0.000995
Rock Dumping- Pipeline Ends	RDV	3.04	455,700	27.6	1,251.7	87.4	4.1	20	1,458.2	0.000060
Rock Dumping-Infield	RDV	31.03	4,653,773	447.4	20,310.9	1,418.2	4.1	20	14,892.1	0.000611
Surveys	ROVSV	10.61	636,314	186.6	8,470.4	591.4	7.5	44	11,199.1	0.000840
Helicopter	N/A	3.13	345,559	61.9	2,946.4	196.2	97	10	751.2	0.000729
Material Replacement	N/A	N/A	N/A	N/A	425,785.9	34,760.1	N/A	N/A	N/A	N/A
Total	N/A	78.25	10,739,571	1190.3	479,960.9	38,533.3	N/A	N/A	83,847.2	0.004661

Table B. 3
The costs, energy usages, emissions, and safety risks for the option 2

Operations	Vessel	$t_{i,j}$ (days)	Cost (£)	Fuel (tonnes)	Energy (GJ)	CO_2 Emission (tonnes)	$FAR_{i,j}$	$P_{i,j}$	Exposure (person-hours)	Safety Risk (PLL)
Preparation	JUV	17.1	2,561,700	289.4	13,138.9	917.4	1.9	76	31,150.3	0.000592
Mattress Removal	DSV	3.4	533,000	43.8	1,990.0	139.0	7.5	76	6,232.0	0.000467
Trenching	TSV	8.1	1,215,450	140.4	6,372.7	445.0	7.5	50	9,723.6	0.000729
Spool Piece Removal	DSV	7.3	1,134,120	100.5	4,562.7	318.6	7.5	76	13,260.5	0.000995
Cut & Lift	CSV	322.4	48,361,125	4,834.1	219,468.7	15,324.1	5.5	50	386,889.0	0.021279
Rock Dumping- Pipeline Ends	RDV	3.0	455,700	27.6	1,251.7	87.4	4.1	20	1,458.2	0.000060
Surveys	ROVSV	10.6	636,314	186.6	8,470.4	591.4	7.5	44	11,199.1	0.000840
Helicopter	N/A	15.5	1,710,825	306.5	14,587.5	971.5	97	10	3,719.2	0.003608
Recycling	N/A	N/A	6,200,500	N/A	207,862.9	12,306.2	N/A	N/A	N/A	N/A
Total	N/A	387.4	62,808,733	5,928.8	477,705.6	31,100.6	N/A	N/A	463,631.9	0.028569

Table B. 4
The costs, energy usages, emissions, and safety risks for the option 3

Operations	Vessel	$t_{i,j}$ (days)	Cost (£)	Fuel (tonnes)	Energy (GJ)	CO_2 Emission (tonnes)	$FAR_{i,j}$	$P_{i,j}$	Exposure (person-hours)	Safety Risk (PLL)
Preparation	JUV	17.1	2,561,700	289.4	13,138.9	917.4	1.9	76	31,150.3	0.000592
Mattress Removal	DSV	3.4	533,000	43.8	1,990.0	139.0	7.5	76	6,232.0	0.000467
Trenching	TSV	8.1	1,215,450	140.4	6,372.7	445.0	5.5	50	9,723.6	0.000535
Spool Piece Removal	DSV	7.3	1,134,120	100.5	4,562.7	318.6	7.5	76	13,260.5	0.000995
Reverse Installation	PLV	100.5	52,283,400	1,779.7	80,799.7	5,641.7	9.2	76	183,394.1	0.016872
Offshore Support	ROVSV	93.5	5,612,700	1,821.0	82,672.3	5,772.5	18.1	44	98,783.5	0.017880
Rock Dumping- Pipeline Ends	RDV	3.0	455,700	27.6	1,251.7	87.4	4.1	20	1,458.2	0.000060
Surveys	ROVSV	10.6	636,314	186.6	8,470.4	591.4	7.5	44	11,199.1	0.000840
Helicopter	N/A	10.2	1,120,564	200.7	9,554.6	636.3	97	10	2,436.0	0.002363
Recycling	N/A	0.0	6,200,500	0.0	207,862.9	12,306.2	N/A	N/A	N/A	N/A
Total	N/A	253.8	71,753,448	4,589.7	416,676.0	26,855.5	N/A	N/A	357,637.3	0.040603

Table B. 5
The costs, energy usages, emissions, and safety risks for the option 4

Operations	Vessel	$t_{i,j}$ (days)	Cost (£)	Fuel (tonnes)	Energy (GJ)	Emission (CO_2)	$FAR_{i,j}$	$P_{i,j}$	Exposure (person-hours)	Safety Risk (PLL)
Preparation	JUV	17.1	2,561,700	289.4	13,138.9	917.4	1.9	76	31,150.3	0.000592
Mattress Removal	DSV	3.4	533,000	43.8	1,990.0	139.0	7.5	76	6,232.0	0.000467
Trenching	TSV	10.5	1,581,630	185.3	8,413.2	587.4	7.5	50	12,653.0	0.000949
Offshore Support	ROVSV	10.5	632,652	185.4	8,415.8	587.6	7.5	44	11,134.7	0.000835
Spool Piece Removal	DSV	7.3	1,134,120	100.5	4,562.7	318.6	7.5	76	13,260.5	0.000995
Rock Dumping- Pipeline Ends	RDV	3.0	455,700	27.6	1,251.7	87.4	4.1	20	1,458.2	0.000060
Surveys	ROVSV	10.6	636,314	186.6	8,470.4	591.4	7.5	44	11,199.1	0.000840
Helicopter	N/A	2.6	287,483	51.5	2,451.3	163.2	97	10	625.0	0.000606
Material Replacement	N/A	N/A	N/A	N/A	425,785.9	34,760.1	N/A	N/A	N/A	N/A
Total	N/A	65.1	7,822,599	1,070.1	474,480.0	38,152.2	N/A	N/A	87,712.8	0.005344

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