Risk-Based Cost-Effectiveness Analysis of Waste Handling Practices in the Arctic Drilling Operation

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As oil and gas companies in the Arctic attempt to maximize the value of each project and optimize their portfolio of investment opportunities, it has become vital to evaluate drilling waste handling practices for their cost-effectiveness in order to support strategic decisions. Identifying cost-effective waste handling practices, which have a minimal environmental footprint, however, is one of the biggest challenges for Arctic offshore industries. The cost and potential risks of drilling waste handling practices in the Arctic offshore operation will differ vastly, depending on the operating environment such as the ice conditions and negative sea temperature. However, in the majority of the available cost-effectiveness and risk analysis literature, the influence of the operating environment on the cost and risk profile has received less attention. Hence, the aim of this paper is to propose a methodology for risk-based cost-effectiveness analysis (RB–CEA) of drilling waste handling practices by considering the complex and fast-changing nature of the Arctic. The central thrust of this paper is to highlight the fact that comparing different alternatives based on the cost elements alone is misleading. The proposed methodology uses risk assessment as a key component for the cost-effectiveness analysis (CEA). The application of the proposed methodology is demonstrated by a case study of the drilling waste handling practices of an oil field in the Barents Sea. The case study results demonstrate that the operating environment causes costs to be between 1.18 and 1.52 times greater, depending on the type of practices and operating season, in the Arctic offshore compared with the North Sea. Further, the risk of undesirable events is between 1.48 and 2.60 times greater during waste handling activities under Arctic operational conditions.
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1 Introduction

As the offshore industry expands into the Arctic and sub-Arctic areas, the oil and gas exploration activities generate all kinds of waste, varying from contaminated runoff water to material packaging; however, the majority of the waste is associated with the drilling cuttings from drilling activities [1,2]. To maximize the value of each project and optimize their portfolio of investment opportunities, oil and gas companies operating in the region are attempting to properly identify suitable methods for handling the drilling waste. Current industry practice for managing and disposing of drilling waste is broadly classified into three major categories: (i) offshore discharge—treating and discharging the drilling waste to the ocean (sea), (ii) offshore re-injection—re-injecting the drilling waste offshore both in a dedicated re-injection well and/or in a dry (dead) well, and (iii) skip-and-ship—hauling the drilling waste back to shore for further treatment and disposal [3].

In the past, offshore disposal was a popular method of waste management practice in many parts of the world [4]. Thereafter, as many countries' environmental awareness has grown, any oil-based mud from offshore must be hauled back to onshore for disposal or be injected underground at the well site [3]. However, most water-based muds (WBMs) and cuttings continue to be discharged to the ocean in many areas. At present, as drilling operations become more demanding and move into environmentally sensitive areas such as the Arctic region, the requirements for managing offshore drilling waste are becoming stricter [3]. Hence, methods to dispose of drilling wastes depend on the local options available, the nature of the waste, and prevailing regulations, as well as stringent waste-discharge guidelines [5].

The ranges of possible waste management solutions, the technological advances, and the new concepts in Arctic drilling pose their own peculiar demands and affect the waste management decision-making process [6–8]. When looking for a safe and sustainable solution to waste management problems associated with the drilling and completion of oil wells in the Arctic offshore, cost and prevailing legislation are the two main issues that need to be considered [9,10]. Hence, to support strategic decisions, it has become vital to evaluate drilling waste handling practices for their cost-effectiveness [8,11,12]. CEA refers to "the consideration of decision alternatives in which both their costs and consequences are taken into account in a systematic way" [13]. Typically, CEA focuses on the costs of achieving the goals of the waste handling activities and the most efficient way of achieving them [11]. It seeks to identify and place "dollars" on the costs of each of the waste handling practices. Then, it relates these costs to specific measures of system effectiveness.

To identify cost-effective and efficient waste handling practices for Arctic offshore drilling, it has been argued that two questions are fundamental [9,12]. First, which drilling waste handling practice is estimated to be cost-effective and environmentally sustainable, based on the prevailing evidence? Second, should further research be carried out in order to minimize the level of

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uncertainty related to the decision? To answer these questions and determine the cost-effectiveness of the waste handling practices, a number of studies have been carried out; see, e.g., Refs. [12–16]. For instance, for better understanding of the overall life cycle cost, Gentil et al. [12] proposed a model for assessing the total cost over the lifetime of the waste handling practices. Further, Kazanowski [14] discussed a standardized approach for carrying out a CEA of various waste handling practices.

Furthermore, to provide a basis for comparing alternative ways of achieving a certain benefit, aid safety design and offer a fair basis for evaluating alternative drilling waste handling practices, a number of quantitative risk assessment models have been developed; see, e.g., Refs. [17–22]. For instance, Khakzad et al. [20] demonstrated the application of bow-tie and Bayesian network methods in conducting quantitative risk analyses of drilling operations. Guo et al. [18] presented a monitoring and diagnostic analysis for managing uncertainties and risks related to a drill cuttings re-injection process for a project offshore of Sakhalin Island. Abimbola et al. [17] proposed a dynamic safety assessment approach based on bow-tie analysis and a real-time barriers' failure probability assessment of offshore drilling operations.

However, in most of the available cost-effectiveness and risk analysis literature discussed above, either cost or risk factor is the only factor considered; and there is a lack of consideration of the impact of the operating environment on the cost and risk profile. This is considered as a significant drawback, especially in a complex operational environment such as the Arctic region. This is particularly important in the Arctic offshore operation because of its slow, nonlinear, and potentially irreversible ecological and physical process. The Arctic region has a harsh, sensitive, and challenging environment, in which it is difficult to operate. The region is characterized by varying forms and amounts of icing, very strong winds, and polar lows, all of which can affect the cost- and risk profile of drilling waste handling practices. For instance, the offshore industry in the region is experiencing longer lead times due to frozen drilling cuttings being stuck in skips while waiting to get emptied onshore for further treatment [6]. This means that the longer the lead-time, the higher the cost of the waste handling practice will become. In addition, due to the environment, which is sensitive to disruption on one hand, but harsh and unforgiving on the other, any mishap during the waste handling process can take longer to heal and cost more to remediate in the region [2,18,23].

Based on the above discussion, it is an important requirement to consider the impact of the operating environment when identifying those cost-effective drilling waste handling practices with a low level of risk for oil and gas companies operating under Arctic conditions. In this paper, a new RB–CEA methodology is proposed, which considers the complex and fast-changing nature of the Arctic. This paper seeks to identify the drilling waste handling practice that is expected to provide the highest level of benefit for a given level of cost, and which has a minimal impact on health, safety and environment (HSE).

The rest of the paper is organized as follows: Section 2 presents the proposed RB–CEA methodology. Section 3 describes an illustrative case study and sensitivity analysis to demonstrate the application of the proposed methodology. Section 4 provides the conclusion.

2 Proposed RB–CEA Methodology

The proposed methodology is an integrated set of risk and CEA, principles, and general procedural guidelines. Figure 1 illustrates specific steps that help the risk and cost analyst to find the most suitable alternative waste handling practices for Arctic offshore drilling operations based on the expected risk and the cost element.

2.1 Stage 1: Define the Drilling Waste Handling Practices.

As mentioned previously, in the Arctic region, waste handling methods are generally dependent on the local practices available, the nature of the waste, and the prevailing regulations [5]. Hence, in the first stage, methods to dispose of the drilling waste, by considering the operating environment of the region, should be defined and analyzed. These include analyzing and assessing both offshore and onshore waste handling practices, such as offshore discharge and offshore re-injection, and onshore practices, such as landfill and composting. For instance, Fig. 2 illustrates a typical procedure prior to offshore discharge.

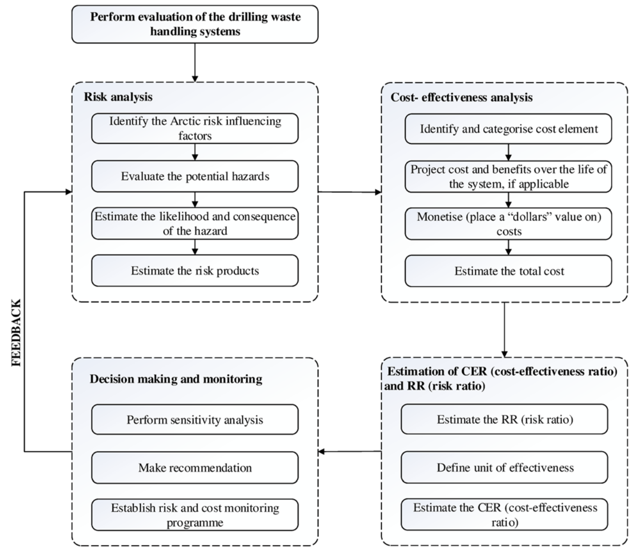


Fig. 1 The proposed RB–CEA methodology for the Arctic offshore drilling waste handling practices

2.2 Stage 2: Risk Analysis.

The key purpose of risk analysis is to support management in rational decision-making. Hence, the aim of this step is to identify and quantify the impact of the peculiar Arctic risk influencing factors (RIFs) on the drilling waste handling practices. RIFs are the factors that potentially affect the barriers and barrier performance [24]. As discussed previously, in the Arctic offshore, the predominant RIFs are the climatic and environmental conditions, such as snowstorms, atmospheric and sea spray icing conditions. These factors depend on various variables and they also interact with each other. Their interaction is very complex and has a cumulative negative synergy effect on the drilling waste handling practices and the personnel working in that specific environment. In combination, these factors will determine the performance of the drilling waste handling practices or the suitability of new drilling waste handling technologies in the region.

This risk analysis step attempts to estimate the frequency of undesirable events and the magnitude of their consequences by different methods. The risk in the context of this paper is the risk in monetary terms that arises due to the adverse effects of the peculiar Arctic RIFs, such as solids-control system failures and equipment damage. In general, the classical risk product (RP), which is the expected negative outcome of undesirable event, i, can be expressed as follows:

$$\mathrm{RP}_{\mathrm{UE}_i}(C_{\mathrm{UE}_i}, P_{\mathrm{UE}_i}) = E[C_{\mathrm{UE}_i}] \times P_{\mathrm{UE}_i} \quad (1)$$

where

- $\mathrm{RP}_{\mathrm{UE}_i}(C_{\mathrm{UE}_i}, P_{\mathrm{UE}_i})$ is the monetized expected cost. The unit of risk is in \$(USD) per time unit (e.g., year);
- P_{UE_i} is the probability or frequency of occurrence of undesirable event, i;
- $E[C_{\mathrm{UE}_i}]$ is the expected consequences (i.e., the financial impact) due to the occurrence of undesirable event, i.

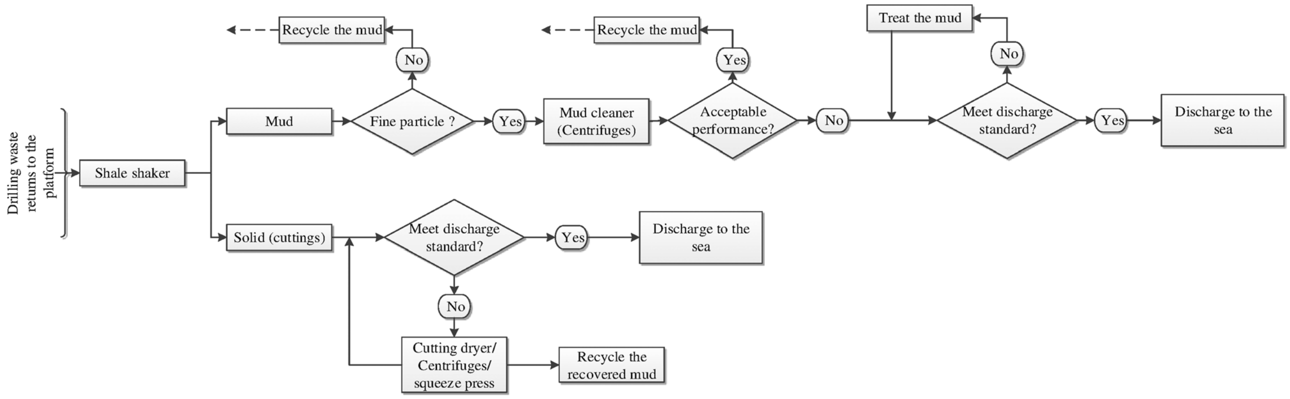


Fig. 2 Generic offshore discharge flowline

In the Arctic offshore waste handling operations, especially in the Barents Sea—the Norwegian part of the Arctic—there is less experience and less valid historical data regarding system failure rate and its associated consequence [25,26]. This is due to the limited industrial activities in the region to date. The lack of sufficient reliable data and information about operating and environmental conditions of the Arctic could increase the uncertainty associated with risk analysis [26]. Moreover, waste handling activities in the Arctic region may face unforeseen challenges, which could also increase the uncertainty and the risk involved [27,28]. The shortage of valid data could, for instance, be associated with the lack of a robust weather forecasting infrastructure, weather modeling, and inadequate forecasting techniques for the Arctic [29,30].

Hence, in the case of lack of valid historical data, expert judgment plays a crucial role during potential hazard and risk analysis [2,6]. Expert judgment is important for identifying and assessing all influencing factors, which can affect the waste handling system performance and safety of the system. In other words, expert judgment is practically always needed to complete the quantification of the risk analysis [25]. Moreover, one brings in experts to provide these judgments because they have developed the mental tools needed to make sound evaluations [31]. These mental tools include: "knowledge of what evidence can be brought to bear on the question, the abilities to weigh the validity of various pieces of evidence and to interpret the relative importance of various facts or assertions, and to craft a view from an ensemble of information that may be inherently limited or self-conflicted" [31]. However, in risk analysis these judgments can entail uncertainty. Further, the experience of the "qualified" risk analyst can also be a decisive factor in determining the subjective probabilities and consequences of the undesirable events. Hence, to understand how the uncertainties are involved in the risk assessment process such that they can be taken into consideration as a decision support, elicited probability distributions need to be calibrated. In addition, performance-based weighting can help to reduce the bias and uncertainty distributions over the parameters.

Based on the above discussion, in the proposed methodology, the expert judgments are considered as an important source of information to quantify the risk of undesirable events. Probabilities or frequencies of undesirable events are thus primarily obtained from the judgments by experienced risk analysts. The financial loss (consequence) of the undesirable events includes several factors, such as cost of extended waste handling system (solids-control system) downtime ($), cost of idle work force ($), clean-up cost ($), and HSE cost ($).

2.3 Stage 3: CEA. When identifying and categorizing the costs and benefits of waste handling practices in the Arctic operating environment, a reasonable effort has to be made to identify those costs that will have the most significant implications on the strategic decision [32,33]. Hence, at this stage, the direct or primary costs and benefits as well as indirect or secondary costs and benefits should be identified and analyzed. In general, the CEA process involves: (i) determining which cost variables affect the cost-effectiveness of the chosen drilling waste handling solution. This includes determining and analyzing: (a) internal cost factors, which arise because of company decisions and goals; the company largely manages these cost factors and, if necessary, they can be changed and (b) external cost factors, which are not controlled by the company but will influence the overall cost and the decisions. (ii) Determining inherent risk factors for the chosen drilling waste handling practices and the company tolerance for them. (iii) Determining the functional interdependence between the cost and risk variables and the degree to which each of these variables can be controlled.

2.4 Stage 4: Risk Ratio (RR) and Cost-Effectiveness Ratio (CER). The next step in the proposed methodology is to estimate the RR and CER for each of the alternative waste handling practices. This will help to determine which waste handling practice costs less per unit of treated (disposed of) drilling waste and possesses the minimum negative HSE impact.

2.4.1 RR: Measure of Relative Effect of the Arctic Operating Environment. RR is used to express the measure of relative effect the operating environment of the Arctic region has compared to that of a reference-operating region, for example, the North Sea. It is the ratio of the risk of an undesirable event in both the Arctic and the reference region. This ratio shows how the RP will be changed (increased or decreased) based on the effect of the operating environment. The initial idea for the RR formulations comes from the calculation of RR, which is used in clinical experiments [34] for the estimation of the clinical importance of a given treatment.

Suppose our data comprise a series of observations, in which an undesirable event has occurred or not, and we wish to compare the probability of such events with the consequence under Arctic and reference-operating conditions. For the two operating environments with probabilities, P_{AR_i} and P_{REF_i}, and consequences, C_{AR_i} and C_{REF_i}, the RR_W of a particular drilling waste handling practice W is given as

$$\mathrm{RR}_W = \frac{\sum_{i=1}^{n} E[C_{\mathrm{AR}_i}]P_{\mathrm{AR}_i}}{\sum_{i=1}^{n} E[C_{\mathrm{REF}_i}]P_{\mathrm{REF}_i}} \quad (2)$$

where

- $E[C_{\mathrm{AR}_i}]$ and $E[C_{\mathrm{REF}_i}]$ are the expected consequences of undesirable events in the Arctic and reference-operating region, respectively.

- P_{AR_i} and P_{REF_i} are the probabilities of undesirable events in the Arctic and reference-operating environments, respectively.
- i indicates the undesirable events, $i = 1, \ldots, n$.

The RRs are useful to describe the multiplication of the risk that occurs due to the operating environment of the Arctic region. For instance, an RR of 2.5 for a specific drilling waste handling practice implies that the operating environment of the Arctic increases the risk of events by $100 \times (\mathrm{RR}_W - 1)\% = 150\%$. Similarly, an RR of 0.5 is interpreted as the probability of a risk event in the Arctic region being half of that in the reference area. The numerical value of the estimated RR must always be between 0 and $(1/\mathrm{RP}_{\mathrm{REF}})$.

Further, it is convenient to work with the natural logarithm of the RR so that it takes on the values of the whole range between $-\infty$ and $+\infty$. Hence, log(RR) can be expressed as:

$$\log(\mathrm{RR}_W) = \theta = \log\left(\sum_i^n E[C_{\mathrm{AR}_i}]P_{\mathrm{AR}_i}\right) - \log\left(\sum_i^n E[C_{\mathrm{REF}_i}]P_{\mathrm{REF}_i}\right) \quad (3)$$

To assist the interpretation of $\log(\mathrm{RR}_W)$ and, for small values of $\theta = \log(\mathrm{RR}_W)$, θ can be approximated as follows:

$$\theta \approx \log(1+\theta) \quad (4)$$

For instance, $\log(\mathrm{RR}_W) = 0.2$ corresponds roughly to $\mathrm{RR}_W = 1.22$ or 22% risk increase (the exact figure is $\mathrm{RR}_W = 1.2214$). Thus, in general, $100 \times \log(\mathrm{RR}_W)$ is approximately the percentage change (increased or decreased) in risk.

2.4.2 Stage 4.2: CER. The CER is a ratio in which the denominator is the unit of effectiveness and the numerator is the present value of the cost of a particular waste handling practice. Units of effectiveness are a measure of any quantifiable outcome central to the drilling waste management objectives. In drilling waste management, the total volume of drilling waste treated (disposed of) would be the most important outcome and would be an obvious unit of effectiveness. The result can then be interpreted as $per unit ton of drilling waste treated (disposed of). Mathematically, CER for a specific waste handling practice in the Arctic operating environment, based on Cellini and Kee [35], can be described as

$$\mathrm{CER}_{\mathrm{AR}_W} = \frac{\mathrm{PVC}_{\mathrm{AR}_T}}{U_{\mathrm{AR}_W}} \quad (5)$$

where

- U_{AR_W} is the unit of effectiveness of waste handling practice W.
- $\mathrm{PVC}_{\mathrm{AR}_T}$ is the present value of cost of waste handling practice W, and is given by

$$\mathrm{PVC}_{\mathrm{AR}_T} = \mathrm{TC}_{\mathrm{AR}1} + \frac{\mathrm{TC}_{\mathrm{AR}2}}{(1+r)^1} + \frac{\mathrm{TC}_{\mathrm{AR}3}}{(1+r)^2} + \ldots. + \frac{\mathrm{TC}_{\mathrm{AR}t}}{(1+r)^{t-1}} = \sum_{t-1}^{T} \frac{\mathrm{TC}_{\mathrm{AR}t}}{(1+r)^{t-1}} \quad (6)$$

where

- $\mathrm{TC}_{\mathrm{AR}_t}$ is the annualized total cost of waste handling practice, W.
- t indicates the year from 1 to T (the last year of the analysis).
- r is the discount rate, which is meant to reflect society's impatience or preference for consumption today over consumption in the future.

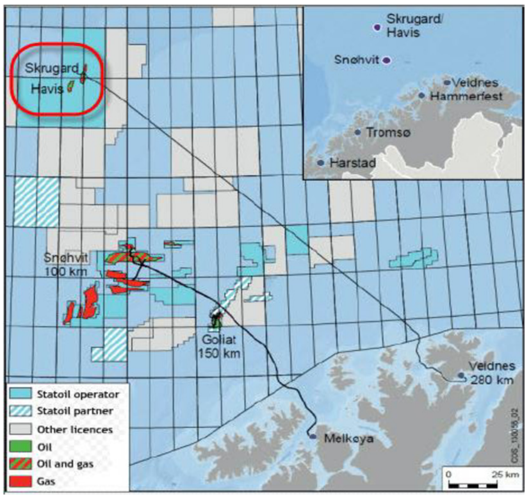
Cost-effectiveness ratio results are very sensitive to the choice of the discount rate, and thus an appropriate choice of the discount rate is critical; there is ongoing and considerable debate as to the appropriate rate; see, e.g., Stern [36], Lopez [37], and Cellini and Kee [35]. In this paper, the classical discount rate of 3% suggested by Cellini and Kee [35] is considered for computational convenience.

2.5 Stage 5: Sensitivity Analysis and Recommendation. In the last stage, a sensitivity analysis should be carried out and a recommendation should be drawn: (i) *Sensitivity analysis*—its purpose is to identify the key cost variables and their potential impact in terms of changes in the annualized total cost and present value cost. Partial and extreme cases are the two common sensitivity analyses. The partial approach varies one assumption (or one parameter or number) at a time, holding all else constant [35]. On the contrary, extreme case sensitivity analysis varies all of the uncertain parameters simultaneously, picking the values for each parameter that yields either the best- or worst-case scenario [35]. (ii) *Recommendation*—the recommendation should comply with stringent drilling waste-discharge guidelines, such as zero "hazardous" discharge requirements, and compliance with the requirement of best environmental practice as well as best available techniques (BATs) [5]. For instance, for offshore drilling activities in the Norwegian part of the Barents Sea, the Norwegian regulators insist that the drilling waste shall not be discharged to the ocean (sea) if the content of formation oil, other oil, or base fluid in organic drilling fluid exceeds 10 g per kilo of dry mass [38]. Moreover, in cases where BAT is not sufficient, new technologies qualified for cold areas should be developed. That means the systems should be specialized or tailor-made for cold areas. One such technology could be the application of a winterization procedure in the Arctic offshore facilities. Further, more reliable system can be designed incorporating nontraditional arrangements and unconventional technologies, by considering the Arctic operational condition.

Afterward, the approved recommendation should be monitored by establishing the risk- and cost-monitoring program. That means the monitoring program has to include the follow-up of the performance of the chosen practices and the overall waste handling process, emphasizing what does work, what does not work, and what continues to work. Further, there should be a feedback loop where the recommendations should help to review the risk analysis process and the choice of the alternatives. This loop helps to detect any changes in the operating environment and their effect on the risk profile and cost element.

3 An Illustrative Case Study

The proposed RB–CEA methodology will be illustrated via the evaluation of the drilling waste management practices for the Johan Castberg oil field development project. The Johan Castberg field (formerly Skrugard and Havis) is an oil field development project in the Barents Sea (part of the Norwegian Arctic) located about 200 km from the nearest Ingøya Island, in Finnmark, northern Norway [39]. The development scheme for Johan Castberg is under continuous update by Statoil—the operator of the oil field. The development plan includes installation of a floating production unit or floating production storage and offloading unit with a 280 km long pipeline to shore and an onshore oil terminal at Veidnes, outside Honningsvåg, in Finnmark, northern Norway [39]. However, there are significant cost differences between a concept based on offshore oil offloading and a concept based on bringing the oil to shore in a pipeline. Hence, Statoil and its partners are involved in a continuous process to optimize the opportunities in the area and the timing of the project activities [39]. Figure 3 illustrates the field location and key field data.



Key Field Data	
Status:	Under update (Planned project)
Operator:	Statoil AS
Year of discovery:	2011
Planned start-year of production:	2018
Location:	Barents Sea
Water depth:	370 m
Main development plan:	FPSO/FPU
Total investment:	USD 14.5 Billion

Fig. 3 Johan Castberg oil field Statoil [39]

The bottom line principle in the Barents Sea is that the oil and gas exploration activities shall be at least as safe as they are in the North Sea [40]. In this case study, the North Sea is thus considered as a reference region. The case study emphasized the measurement of the relative effect of the Arctic operating environment when the decision maker tries to identify the most cost-effective commercially available waste handling practices with minimum level of HSE risks for oil and gas companies operating in the Arctic. Further, the other main focus of the case study is to evaluate the applicability and suitability of the *available* waste handling systems, *without considering winterization*, for Arctic operations.

3.1 Define the Drilling Waste Handling Practices. For the Johan Castberg development project, the operator plans to drill 38 wells in total, including 22 production wells, 12 water injection wells, and four gas injection wells [39]. As part of the development solution, and to propose the ideal drilling waste handling solutions, this paper evaluates the risk and examines the cost-effectiveness of the commercially available practices in the region. These include estimating the cost and predicting the risk of: (i) offshore discharge, (ii) offshore re-injection, and (iii) skip-and-ship.

Table 1 presents a summary of the well sections, section length, rate of penetration (ROP), volume of the generated drilling waste (fluids and cuttings), and the washout (an enlarged section of the wellbore caused by removal of formation grains during drilling and/or circulation). The well data is taken from a Statoil [39] report. The water-based drilling fluid system would be applied; and for the top hole sections, the fluid systems consist entirely of the pose little or no risk to the environment (PLONOR) list of green chemicals. The only yellow chemical to be used in the drilling fluid system is the glycol-based substance GEM GP, on the two bottom sections (sections 12¼" and 8½"). The assumed densities are 2.3 and 1.2 for cuttings and fluid, respectively. Theoretically, the volume of drilling cutting can be estimated by

Theoretical hole volume

$$(m^3) = \pi\left(\frac{D}{2}\right)^2 L \quad (7)$$

where D is a well diameter (m) and L is a section length (m).

It is assumed that all the wells have the same configurations and that the proposed practices should cope with the expected rate of drilling waste generation, which is generated at an average 120 m/day ROP. However, in the case of re-injection, based on past experience, the rate of drilling waste generation will most often be higher than the rate of injection, during the two top sections (section 36" and 17½"). Thus, in such cases, other practices will be utilized in addition to the re-injection.

3.2 Risk Analysis. The basic assumptions in this risk analysis are: a year-round operational window and there is no winterization or enclosure of the waste handling systems to protect the vulnerable areas. As mentioned previously, in the Arctic offshore waste handling operations, especially in the Barents Sea, there is a lack of historical system failure rate data. Hence, judgments provided by those people with expertise in identifying potential hazards and risks of undesirable events are utilized at various stages of this risk analysis in order to perform effective risk identification and quantification. Their expertise is used to analyze historical

Table 1 Total volume of the generated drilling waste per well

				Drilling waste						
				Fluid		Cutting			Total waste	
Section	Section length (m)	ROP (m/day)	Drilling time (day)	(m^3)	(MT)	(m^3)	(MT)	Washout (%)	(m^3)	(MT)
36"	63	150	0.42	227	522.1	41	49.20	10	272.10	576.22
17 ½"	395	150	2.63	666	1531.8	61	73.20	10	733.10	1612.32
12 ¼"	280	120	2.33	105	241.5	84	100.80	5	193.20	347.34
8 ½"	575	75	7.67	129	296.7	21	25.20	5	151.05	323.16
Total			13.05	1127	2592.1	207	248.40		1349.45	2859.04

information, define and analyze potential hazards, and evaluate the consequence of undesirable events.

Selecting the experts: The experts have been selected based on the criteria suggested by Ortiz et al. [41], which state that experts collectively should represent a wide variety of background and experience. The experts are selected based on their publication record, their direct involvement, and consulting as well as managing research projects in the related areas. The selected experts are two types of experts—academics and professionals with hands-on experience, having expertise in risk analysis, waste handling and management, drilling and reliability engineering, meteorology, cold-climate technology, and offshore engineering, with 5 to 15 years of experience in their respective fields.

Posing questions to the experts: At this stage, the questionnaires are prepared by describing the potential hazards and undesirable events. The potential hazards are suggested for use as guidance, and consequence (potential loss) categories are also provided. The consequence rating categories and the questionnaire used for eliciting information from experts are presented in the Appendix (Tables 13 and 14). Thereafter, the selected experts are informed about the operational environment in the reference area, i.e., the North Sea and the target area, i.e., the Barents Sea.

Suppose that we have UE_N number of undesirable events. The experts were asked to provide their degree-of-belief probabilities and consequences rating of each undesirable event. Then, the probabilities of the undesirable events are denoted as $P_{i_{0.05}}$, which is designated as the lower value; $P_{i_{0.50}}$, which is interpreted as the median value; and $P_{i_{0.95}}$, which is interpreted as the 95% percentile value (the expert conservative judgment about the undesirable event i). In addition, the experts are also asked to give their best judgment about the lower $C_{i_{0.05}}$, median, $C_{i_{0.50}}$, and the conservative, $C_{i_{0.95}}$ consequences ratings for each of the undesirable events. Table 2 shows a sample of the experts' judgments (both the median and conservative probabilities as well as the consequence ratings) for a system installed in the Arctic, their working experience in years, and normalized and non-normalized performance-based weight for each expert.

The quality of the expert judgments: Since degree-of-belief probabilities are personal and vary from expert to expert and from time to time, there is no "true" probability that one might use as a measure of the accuracy of a single elicited probability [31]. To illustrate the kinds of distortion that are possible in the specification of weighted distributions for the degree-of-belief probabilities, six experts were asked to specify 5% (lower), 50% (median), and 95% (upper) values for the solids-control system failure probabilities. These parameters included the probability of failure of the shale shakers and screw conveyors; storage containers, buffer and recovery tanks; filtering and slope water treatment unit failure; and cutting drier unit failure. Figure 4 depicts the cumulative findings of the interexpert variation, expressed for brevity of presentation in terms of a typical solids-control system failure's parameters.

The results show that expert 1 can be regarded as overconfident and biased; expert 3 is well calibrated but uninformative; the other experts can be regarded as well calibrated and informative. Hence, the desirability of some form of calibration for experts is apparent. In general, calibration refers to the "faithfulness of probabilities in that events that are assigned a probability p should occur with a relative frequency of p" [31]. In order to address the goodness of the probabilities, the following two properties are desirable [31]:

(i) Degree-of-belief probabilities should be informative and
(ii) degree-of-belief probabilities should authentically represent uncertainty.

Further, Chang et al. [42] suggested convergence, as a means of validating judgment results. Convergence, in general, can be achieved by asking the same basic question in several different ways [42]. Hence, to check the fulfilment of the above two properties and assess the quality of experts' judgments, the elicited probability distributions have been calibrated. Thereafter, the calibration score and information score are used to determine the non-normalized performance-based weight for expert i. In this risk analysis, experts are scored on the basis of answers to the questions for which the answer is only known to the analyst. According to Cooke [43], the non-normalized performance-based weight for expert i, k_{nnw_i} is proportional to calibration score times information score, and it can be expressed mathematically as follows:

$$k_{\mathrm{nnw}_i} \propto C(E_i) \times I(E_i) \tag{8}$$

where k_{nnw_i} is the non-normalized performance-based weight for expert i, $C(E_i)$ represents the calibration score for expert i, and $I(E_i)$ represents the information score for expert i.

The estimated non-normalized and normalized performance-based weights for each expert i are summarized in Table 2.

Aggregating the expert judgments: In order to aggregate the experts' judgments, the following expert aggregation method is used:

$$P_{\mathrm{UE}}(\mathrm{UE}) = \sum_{i=1}^{n} k_{\mathrm{nw}_i} P_{\mathrm{UE}i}(\mathrm{UE}_i) \tag{9}$$

where $P_{\mathrm{UE}}(\mathrm{UE})$ is the aggregated expert judgment probability of undesirable event, k_{nw_i} is the normalized performance-based weight for expert i and is given as

$$k_{\mathrm{nw}_i} = \frac{k_{\mathrm{nnw}_i}}{\sum_{i=1}^{n} k_{\mathrm{nnw}_i}} \tag{10}$$

Thereafter, for each drilling waste handling option, the aggregated values, by considering the normalized experts' performance-based weight, are estimated and discussed below.

Offshore discharge: After coming to the platform, drilling waste has to pass through a series of pretreatments, such as chemical, mechanical, thermal, or biological processes before discharge to the ocean (sea). To evaluate the peculiar operational risks of the offshore discharge practice, it is then important to map the predominant risks related to the susceptible areas. Thus, these areas are identified, and potential hazards and undesirable events are postulated and presented in Table 3. Further, the median and 95% percentile aggregated probabilities and the expected consequence value, for both Arctic (AR) and North Sea (NS), are depicted in Table 4.

Offshore re-injection: The re-injection technology involves grinding or processing the solids (cuttings) into small particles, mixing them with water or some other liquid to make a slurry, and injecting the slurry into an underground formation at pressures high enough to fracture the rock [3]. For the offshore re-injection risk analysis, the main assumption is that a dedicated well is used for the waste disposal and that the geologic conditions in the drilling area are favorable for the slurry re-injection. The potential hazards and undesirable events for both offshore re-injection and skip-and-ship practices are presented in the Appendix (Table 15). Table 5 presents the median and 95% percentile aggregated probabilities and the expected consequence value for both AR and NS.

Skip-and-ship: During skip-and-ship practice, cuttings are collected and transferred to a suitable location for loading within the drilling platform. Then, the drill waste is loaded (transferred) into skips via a steerable chute. Afterward, full skips have to be hauled back to shore using a dedicated collection vessel or a standard platform supply vessel (PSV). Hence, the analysis of the risk should then cover the estimation of the RP of: (i) collecting and processing the drilling waste offshore and (ii) transporting or hauling the drilling waste to shore. A PSV with ice class ICE-1A and De-ice notation has been considered for the logistics of the drilling waste and year-round operation in the Arctic offshore environment. Table 6 summarizes the estimated RPs of offshore

Table 2 A sample of experts' judgments elicited for shale shaker failure in the arctic

Expert i		1	2	3	4	5	6
Experience (years)		7	5	12	10	15	9
Background		Acad.	Acad.	Pro.	Pro.	Pro.	Pro.
Performance-based weights	Non-normalized	0.467	0.333	0.800	0.667	1.000	0.600
	Normalized	0.121	0.086	0.207	0.172	0.259	0.155
$P_{i0.50}/P_{i0.95}$		0.953/0.994	0.926/0.966	0.951/0.992	0.901/0.940	0.923/0.963	0.851/0.888
$C_{i0.50}/C_{i0.95}$		1/3	2/3	2/4	1/3	2/5	1/3

Acad.—academic and Pro.—professional.

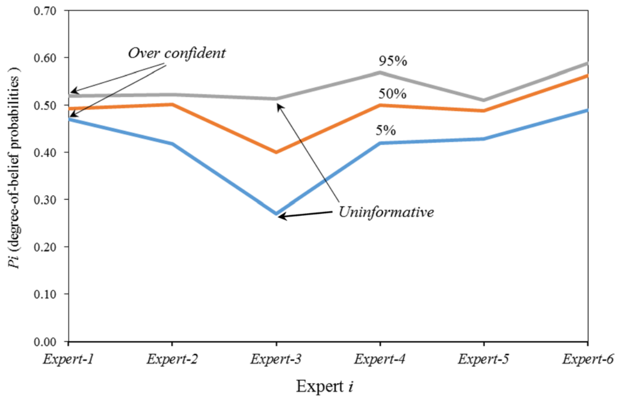


Fig. 4 Interexpert variation in 5%, 50%, and 95% estimates of undesirable events in the North Sea offshore drilling waste handling operation

operation and any failure mode or undesirable events related to the assumed PSV.

3.3 CEA. Ex-ante CEA is applied to assess the expected cost of the given waste handling alternatives and to estimate the relative effect of the Arctic on the total cost compared with the North Sea. The cost-related data have been collected using different sources via meetings and discussion with drilling waste treatment plant operators; owners of waste containers, container trucks, and super-sucker trucks; and suppliers of offshore services. The following steps were followed to estimate the cost elements for each waste handling option. The steps will be discussed by considering the skip-and-ship option as an example.

Logistics and shipping: The total volume of drilling waste that needs to be processed, treated, and disposed of is estimated to be 2859.04 MT per well, which is equal to 1349.45 m^3 per well. In general, wherever possible the drilling waste from the 36'' and 17½'' hole sections should be drilled with WBM consisting entirely of the PLONOR list of green chemicals and the waste discharged offshore. To manage the cuttings from the two lower hole sections, the number of skips required is estimated. The average skip volume capacity is considered to be 4 m^3. Thus, for the 344 m^3 of waste (the summation of the total waste for the 12¼'' and 8½'' hole sections), the required number of skips is 86. However, due to the potential of uneven packing of the drilling waste, the number of skips will most often increase by 1.5 times the estimated total number of skips. Hence, the number of required skips will be 129 for the two lower hole sections. Typical PSVs have the capacity for 100 skips, which may not be enough to handle the entire 12¼'' and 8½'' hole sections. In this case, turnaround times must be considered, as well as the possible requirement for a second vessel to cover the changeover period. In some cases, due to statutory legislation, offshore discharge for the two upper hole sections can be hindered. In such cases, in order to proceed with the drilling operation, the cuttings should be hauled back to shore for disposal. In this case, the number of skips required will be higher, equal to 507 per well (for a total volume of 1349.45 m^3 drilling waste).

Weather effects: The loading of mud skips or containers onto the transport ship by the use of cranes is a slow process, and severe weather can significantly affect the waste handling process. In general, loading and lifting operations will stop, when wind speed exceeds 40 knots, or possibly 30 knots for floating installations [45]. In addition, for full cuttings skips, a limit of 3.5 m critical wave height is recommended as a guideline. For instance, for North Sea skip-and-ship operations, the annual average time that the 40 kt and 30 kt wind speeds exceeded is only 2.2% and 12% of the time, respectively, Ref. [45]. However, the 3.5 m wave height limit is exceeded more often. Table 7 depicts the seasonal variation of the percentage of the time the significant wave height exceeds 3.5 m.

Based on these seasonal variations of wind speed and wave height, an estimation of likely downtime has been carried out. By considering the expected downtime, the estimated average drilling time is 13 rig days per well in the North Sea (reference-operating environment). Moreover, in addition to the "expected" downtime in the North Sea, for Arctic skip-and-ship operation, it is advisable to consider the downtime periods due to extended delays caused by the harsh operating condition of the region. For instance, as mentioned above, during winters the skip-and-ship operation in the Arctic experiences long lead times due to drilling cuttings being frozen, stuck in skips while waiting to get emptied onshore for further treatment [6]. Further, in some areas of the Arctic region, between 65 and 70% extra costs incurred during drilling

Table 3 The potential hazards and undesirable events for offshore discharge practice

ID	Potential hazards	Undesirable events
UE1	Negative air temperature and ice accretion	Shale shakers and screw conveyors failure
UE2	Atmospheric icing and negative air temperature	Storage containers, buffer, and recovery tanks failure
UE3	Icicles, atmospheric icing, and negative air temperature	Vacuum unit failure
UE4	Rime, glaze, snow, and icicles	Filtering and slope water treatment unit failure
UE5	Negative air temperature, rime, glaze, and snow	Cutting drier unit failure
UE6	Atmospheric icing and negative air temperature	Centrifuges failure
UE7	Low temperature, rime, glaze, and snow	Cutting blower pump failure
UE8	Freezing temperature and ice accretion	Flexible hose failure

UE: undesirable events.

Table 4 The estimated RPs for offshore discharge practice

	North sea (NS)			Arctic (AR)		
ID	$P_{i0.50}/P_{i0.95}$	$E[C_{i0.50}]/E[C_{i0.95}]$	$RP_{i0.50}/RP_{i0.95}$	$P_{i0.50}/P_{i0.95}$	$E[C_{i0.50}]/E[C_{i0.95}]$	$RP_{i0.50}/RP_{i0.95}$
UE1	0.537/0.560	300,000/5,000,000	161,100/2,800,000	0.918/0.958	300,000/10,000,000	275,400/9,580,000
UE2	0.502/0.524	50,000/2,000,000	25,100/1,048,000	0.890/0.928	50,000/2,000,000	44,500/1,856,000
UE3	0.492/0.513	50,000/2,000,000	24,600/1,026,000	0.891/0.930	300,000/5,000,000	267,300/4,650,000
UE4	0.545/0.569	50,000/2,000,000	27,250/1,138,000	0.938/0.978	50,000/2,000,000	46,900/1,956,000
UE5	0.489/0.511	300,000/5,000,000	146,700/2,555,000	0.901/0.940	300,000/5,000,000	270,300/4,700,000
UE6	0.564/0.588	50,000/2,000,000	28,200/1,176,000	0.881/0.919	50,000/5,000,000	44,050/4,595,000
UE7	0.548/0.572	300,000/5,000,000	164,400/2,860,000	0.896/0.935	300,000/10,000,000	268,800/9,350,000
UE8	0.513/0.535	50,000/2,000,000	25,650/1,070,000	0.911/0.950	300,000/5,000,000	273,300/4,750,000
Summation of RP		$\sum_i^n E[C_{NS_i}]P_{NS_i}$	603,000/13,673,000		$\sum_i^n E[C_{AR_i}]P_{AR_i}$	1,490,550/41,437,000
	$\log(\sum_i^n E[C_{NS_i}]P_{NS_i})$		5.78/7.14		$\log(\sum_i^n E[C_{AR_i}]P_{AR_i})$	6.17/7.62

Table 5 The estimated RPs for offshore re-injection practice

	North sea (NS)			Arctic (AR)		
ID	$P_{i0.50}/P_{i0.95}$	$E[C_{i0.50}]/E[C_{i0.95}]$	$RP_{i0.50}/RP_{i0.95}$	$P_{i0.50}/P_{i0.95}$	$E[C_{i0.50}]/E[C_{i0.95}]$	$RP_{i0.50}/RP_{i0.95}$
UE1	0.537/0.560	300,000/5,000,000	161,100/2,801,349	0.918/0.958	300,000/10,000,000	275,400/9,577,797
UE2	0.511/0.533	50,000/2,000,000	25,550/1,066,286	0.874/0.911	300,000/2,000,000	262,066/1,822,813
UE3	0.498/0.520	300,000/2,000,000	149,400/1,039,159	0.851/0.888	300,000/2,000,000	255,399/1,776,441
UE4	0.513/0.535	50,000/5,000,000	25,650/2,676,149	0.877/0.915	300,000/5,000,000	263,092/4,574,869
UE5	0.502/0.524	50,000/2,000,000	25,100/1,047,506	0.858/0.895	300,000/5,000,000	257,450/4,476,773
UE6	0.578/0.603	300,000/2,000,000	173,400/1,206,093	0.911/0.950	300,000/5,000,000	273,300/4,752,382
UE7	0.148/0.154	2,000,000/5,000,000	296,000/772,066	0.253/0.464	5,000,000/10,000,000	1,265,028/4,640,000
UE8	0.130/0.136	300,000/5,000,000	39,000/678,166	0.222/0.442	300,000/10,000,000	66,670/4,420,000
UE9	0.150/0.156	300,000/5,000,000	45,000/782,499	0.256/0.498	2,000,000/5,000,000	512,849/2,490,000
UE10	0.124/0.129	300,000/10,000,000	37,200/1,293,733	0.212/0.421	2,000,000/10,000,000	423,955/4,210,000
Summation of RP		$\sum_i^n E[C_{NS_i}]P_{NS_i}$	977,400/13,363,009		$\sum_i^n E[C_{AR_i}]P_{AR_i}$	3,855,209/42,741,075
	$\log(\sum_i^n E[C_{NS_i}]P_{NS_i})$		5.99/7.13	$\log(\sum_i^n E[C_{AR_i}]P_{AR_i})$		6.59/7.63

Table 6 The estimated RPs for skip-and-ship practice

	North sea (NS)			Arctic (AR)		
ID	$P_{i0.50}/P_{i0.95}$	$E[C_{i0.50}]/E[C_{0.95}]$	$RP_{i0.50}/RP_{i0.95}$	$P_{i0.50}/P_{i0.95}$	$E[C_{i0.50}]/E[C_{0.95}]$	$RP_{i0.50}/RP_{i0.95}$
UE1	0.510/0.532	300,000/2,000,000	153,000/1,064,199	0.872/0.910	2,000,000/5,000,000	1,743,687/4,548,116
UE2	0.055/0.057	5,000,000/10,000,000	275,000/573,833	0.094/0.098	5,000,000/10,000,000	470,112/980,966
UE3	0.532/0.555	300,000/2,000,000	159,600/1,110,106	0.909/0.949	300,000/5,000,000	272,836/4,744,309
UE4	0.250/0.261	2,000,000/5,000,000	500,000/1,304,166	0.427/0.446	2,000,000/10,000,000	854,748/4,458,937
UE5	0.532/0.555	2,000,000/5,000,000	1,064,000/2,775,266	0.909/0.949	5,000,000/10,000,000	4,547,263/9,488,618
Summation of RP		$\sum_i^n E[C_{NS_i}]P_{NS_i}$	2,151,600/6,827,571		$\sum_i^n E[C_{AR_i}]P_{AR_i}$	7,888,646/24,220,946
	$\log(\sum_i^n E[C_{NS_i}]P_{NS_i})$		6.33/6.83		$\log(\sum_i^n E[C_{AR_i}]P_{AR_i})$	6.90/7.38
Additional RP—to consider the risks during collection and transferring of the drilling waste offshore $\log(\sum_i^n E[C_{NS_i}]P_{NS_i})$			5.78/7.14	$\log(\sum_i^n E[C_{AR_i}]P_{AR_i})$		6.17/7.62
Total RP			12.11/13.97			13.07/15.00

Table 7 Seasonal variations in the percentage of the time the significant wave height exceeds 3.5 m in the North Sea, adapted from Ref. [45]

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
% of wave height $\geq$3.5 m	55	44	44	19	7	3	1	3	20	33	42	53

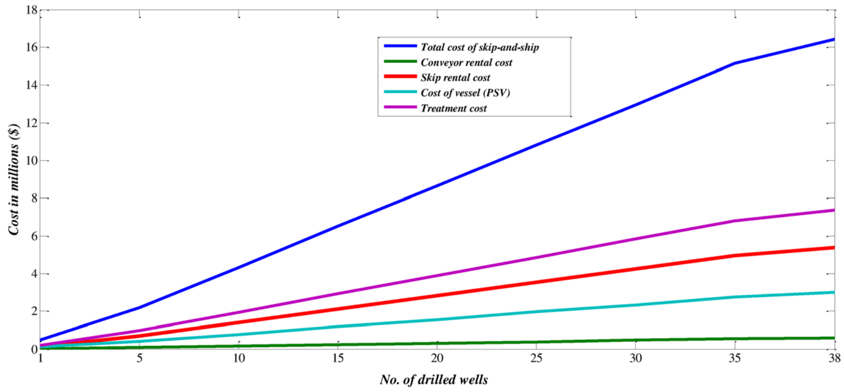


Fig. 5 Cost elements for skip-and-ship operation in the Arctic

waste handling activities are weather related [46]. Hence, from past experience and based on expert judgment, the average drilling time in the Arctic operating conditions is considered to be 1.7 times higher than that of the North Sea. Hence, for the cost estimation, the drilling time is considered to be 22 rig days per well in the Arctic region and 13 rig days per well in the North Sea. The total drilling operation period thus will be 836 days for 38 wells for the Arctic operation.

Cost breakdown analysis: The dock charges, installation costs, costs related to nonconformances, operation costs per day, skip

Table 8 Cost elements per well drilled ($ as of 2012)

Cost elements			No. of items	Operating period (days) NS	Operating period (days) AR	Unit cost ($)	Total cost ($) NS	Total cost ($) AR
Offshore discharge	Cost of design and engineering: compliance testing cost, cost of discharge modeling, field monitoring programs' cost, etc.					25,000.00	25,000.00	25,000.00
	Solid control equipment cost Installation of shale shaker, mud cleaners or centrifuges		1			35,000.00	35,000.00	35,000.00
	Desander and desilters		3			5,000.00	15,000.00	15,000.00
	Mud tank		1			65,000.00	65,000.00	65,000.00
	Mud agitator		6			7,000.00	42,000.00	42,000.00
	Generator		2			60,000.00	120,000.00	120,000.00
	Base cost: staffing per day		4	13	22	450.00	23,400.00	39,600.00
	Total cost of offshore discharge per well ($)						325,400.00	341,600.00
Offshore re-injection	Cost of design and engineering: cost of dedicated re-injection well and installation costs		1				40,000,000.00	45,000,000.00
	Equipment cost Cost of slurrification system	Operational	1	13	22	1,800.00	23,400.00	39,600.00
		Stand by	1	13	22	1,250.00	16,250.00	27,500.00
	Cost of data monitoring package		1	13	22	900.00	11,700.00	19,800.00
	Cost of mud holding tank		1	13	22	500.00	6,500.00	11,000.00
	Cost of injection pump skid		1	13	22	3,700.00	48,100.00	81,400.00
	Operation cost: cost of power consumption		1	13	22	1,450.00	18,850.00	31,900.00
	Total cost of offshore re-injection per well ($)						40,124,800.00	45,211,200.00
Skip and ship	From shaker to the boat							
	Personnel		4	13	22	420.00	21,840.00	36,960.00
	Skip (container) rent		507	13	22	20.00	131,820.00	223,080.00
	Equipment cost (conveyor rental)	Operational	1	13	22	250.00	3,250.00	5,500.00
		Stand by	1	13	22	160.00	2,080.00	3,520.00
	Transport: costs of vessels including supply boat		1	1	2	30,000.00	30,000.00	60,000.00
	Treatment costs: waste treatment on land-based treatment plant		1349.45			100.00	134,945.00	134,945.00
	Base cost: staffing, rent of a skipper, etc.		1	13	22	140.00	1,820.00	3,080.00
	Total cost of skip-and-ship per well ($)						325,755.00	467,085.00

Table 9 Total cost of waste handling practices ($ as of 2012)

No. of wells	Discharge to ocean		Re-injection		Skip-and-ship	
	NS	AR	NS	AR	NS	AR
1	325,400	341,600	40,124,800	45,211,200	325,755	467,085
5	442,400	539,600	40,657,800	46,113,200	1,598,775	2,245,425
10	559,400	737,600	41,190,800	47,015,200	3,227,550	4,520,850
15	676,400	935,600	41,723,800	47,917,200	4,826,325	6,766,275
20	793,400	1,133,600	42,256,800	48,819,200	6,425,100	9,011,700
25	910,400	1,331,600	42,789,800	49,721,200	8,053,875	11,287,125
30	1,027,400	1,529,600	43,322,800	50,623,200	9,652,650	13,532,550
35	1,144,400	1,727,600	43,855,800	51,525,200	11,511,425	15,777,975
38	1,214,600	1,846,400	44,175,600	52,066,400	12,228,690	17,149,230

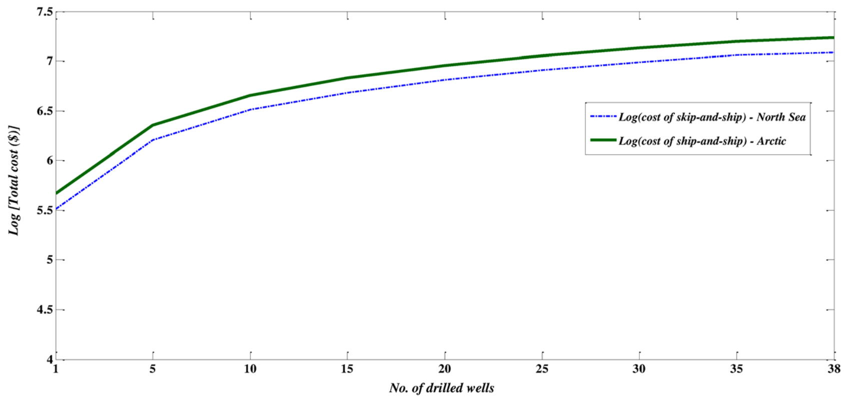


Fig. 6 A semilogarithmic plot of the total cost of skip-and-ship in North Sea and Arctic versus number of wells. Notice that while the horizontal (No. of drilled wells) axis is linear, with the number of drilled wells evenly spaced, the vertical (total cost of skip-and-ship) axis is logarithmic with the evenly spaced division being labeled with log [cost of skip-and-ship]

rental (per skip per day), cost of vessel, and treatment cost for unit ton/kilo of drilling waste have been estimated. The cost breakdown analysis for the skip-and-ship practice for Arctic operation is illustrated in Fig. 5. Further, Table 8 presents the resulting cost elements, as of year 2012, per well drilled—for offshore discharge, offshore re-injection, and skip-and-ship.

The result shows that the cost of re-injection in a dedicated well is higher than that of the two other practices for both regions. Comparing the cost of offshore discharging practice with skip-and-ship, for both the North Sea and the Arctic region, the cost appears to be comparable when the volume of waste is low. However, as the volume of the waste increases, the skip-and-ship practice shows cost increment. Further, the effect of the operating environment of the Arctic region on the cost element becomes more significant as the volume of the waste increases. Table 9 demonstrates that these adverse effects cause between 1.18 and 1.52 times higher costs in the Arctic compared with the North Sea. In addition, a semilogarithmic plot of the total cost of skip-and-ship in North Sea and Arctic versus number of wells presented in Fig. 6.

3.4 CER and RR. The CERs for offshore discharge, offshore re-injection, and skip-and-ship practices are estimated and the

Table 10 Estimated CERs

Options	Total waste volume (ton)	r (%)	PVC ($)		CER ($ per unit ton)	
			NS	AR	NS	AR
Offshore discharge	108,453.52	3	1,196,911.65	1,819,510.68	11.04	16.78
Offshore re-injection	162,680.28	3	43,532,266.02	51,308,151.46	267.59	315.39
Skip-and-ship	108,453.52	3	12,198,417.82	17,490,746.07	112.48	161.27

Table 11 Estimated median and 95% percentile RRs

Options	$\log\left(\sum_i^n E[C_{\mathrm{NS}_{0.50}}]P_{\mathrm{NS}_{0.50}}\right)$	$\log\left(\sum_i^n E[C_{\mathrm{AR}_{0.50}}]P_{\mathrm{AR}_{0.50}}\right)$	$\mathrm{RR}_{0.50}$	$\log\left(\sum_i^n E[C_{\mathrm{NS}_{0.95}}]P_{\mathrm{NS}_{0.95}}\right)$	$\log\left(\sum_i^n E[C_{\mathrm{AR}_{0.95}}]P_{\mathrm{AR}_{0.95}}\right)$	$\mathrm{RR}_{0.95}$
Offshore discharge	5.78	6.17	1.48	7.14	7.22	1.08
Offshore re-injection	5.99	6.59	1.82	7.13	7.63	1.65
Skip-and-ship	12.11	13.07	2.61	13.97	15.00	2.80

Table 12 Partial case sensitivity analysis result

Waste disposal practice		Drilling time (days) Per well / total			Effect of change of the drilling time ($)
	Per well	17	22	27	
	total	646	836	1026	
Total cost ($)	Offshore discharge	1,495,400	1,846,400	2,197,400	±$351,000
	Offshore re-injection	50,508,400	52,066,400	53,624,400	±$1,558,000
	Skip-and-ship	14,798,930	17,149,230	19,499,530	±$2,350,300

The total costs in the table represent the total cost of the 38 wells.

results are depicted in Table 10. When estimating the present value of cost (PVC), 3% discount rate (r) and T (the last year of the analysis) equals 2 years are considered. In addition, the case of offshore re-injection, the total waste volume has been multiplied by the factor 1.5 in order to consider the addition of water or some other liquid to make slurry before re-injection.

The CER result shows that offshore re-injection practice is significantly more expensive than offshore discharge and skip-and-ship practices. Further, it can be deduced that the cost of discharging the waste offshore is ten times less than the skip-and-ship practice and almost 20 times less than the offshore re-injection practice, in the case of Arctic drilling waste handling operations. The CER estimation demonstrates that offshore discharge practice is the cheapest one for Arctic offshore drilling waste handling operations, in comparison to the other two practices, based on the considered assumptions.

Moreover, the RRs are estimated for each practice and the results are presented in Table 11. The results demonstrate that the operating environment of the Arctic region increases the risk of undesirable events by 1.48 times during the offshore discharge practices when compared to the North Sea. This negative impact rises to 1.82 and 2.60 times in the case of offshore re-injection and skip-and-ship practices, respectively.

3.5 Sensitivity Analysis, Recommendation, and Winterization Measure. Sensitivity analysis: In this case study, for computational convenience, a partial sensitivity analysis has been applied. The sensitivity of the total cost for three different drilling time scenarios (17, 22, and 27 days/well) has been considered. The result of the partial sensitivity analysis for different waste handling practices for Arctic offshore operation is depicted in Table 12.

The sensitivity analysis result demonstrates that 5 days fewer/more drilling time per well has a significant cost variation for all considered waste disposal practices. In the case of skip-and-ship, the cost variation is higher than for the other two practices. In general, from the above sensitivity analysis results, it can be deduced that the CEA is most sensitive to the drilling time.

Make a recommendation: The practice of offshore discharge possesses the lowest CER and RR, thus it is the recommended practice for the Johan Castberg oil field development project. This recommendation is based on the above-discussed assumptions. Further, in the Arctic, it is expected that operating conditions will vary within a short period, thus a well-defined risk- and cost-monitoring process needs to be integrated with the discharge process to check the frequently changing requirements. Moreover, the operator has to comply with the Norwegian law of protection against pollution and waste (the Pollution Control Act, Chap. 2, Sec. 4 and Chap. 3, Sec. 11) and the requirements for risk management during petroleum exploration (Petroleum Safety Authority Management Regulations, Secs. 3–6). Complying with the regulations can reduce future liability costs.

If, for instance, the offshore discharge practice were not viable due to statutory legislation, in such a case, the traditional CEA would suggest that the skip-and-ship practice be implemented, since the total cost and the CER are less than those of the re-injection practice. However, as the RR results demonstrate, the increase in the risk of undesirable events in the skip-and-ship practice is almost twice that of re-injection. This shows that comparing different alternatives based on the cost elements alone is misleading. The effect of such a suggestion, i.e., without considering the risk of undesirable events, can be significant, especially in the Arctic offshore operation. Hence, evaluation of the potential hazards and the risk of undesirable events should always be integrated with CEA for better drilling waste management decisions.

Winterization measure: The concept of risk management includes proper knowledge and understanding of the pro-active and re-active risk reduction measures. Winterization or enclosure of the waste handling systems to protect vulnerable areas is considered as the main risk and ice incident impact reduction measure for onsite risk assessment procedures. Winterization measures include [47]: protecting the solids-control system functions, which are considered important to safety, and implementing procedures for safe operation and personnel welfare. These measures are very effective in reducing the likelihood of occurrence of the undesirable events. However, their effectiveness is insignificant once the risk presents itself [47]. On the other hand, ice management can be any method that protects the waste handling systems and structures against ice accretion, and it can also be a process of removal of the ice from the structure. The typical ice management measures, such as de-icing, anti-icing, and winterization help to limit the accretion of the ice on the waste handling systems and remove the ice from the equipment. For instance, the most common anti-icing measures are [48]: coatings, design, heat, electrical, ice detection, and windows.

In this study, however, the influence of winterization measures on the final risk and cost profile is not considered. The reason is that, as mentioned above, the main focus of the case study is to check whether the available waste handling practices, which are employed in less harsh region, are applicable in Arctic offshore operation or not. The result shows that the need to employ risk and ice management practices, such as winterization measures during the operational phase of an offshore waste handling activity is an important aspect that must be considered in the Arctic offshore.

4 Conclusion

This work introduced a methodology for RB–CEA of drilling waste handling practices based on losses from undesirable events, by considering the effect of the extreme cold operational conditions. The methodology is particularly important in the Arctic operating environment since there is less experience and data in the region. The proposed methodology considered risk assessment as a key component for the CEA, and it involves the following steps: (i) risk analysis (to assess the impact of the peculiar Arctic RIFs); (ii) CEA (to estimate the relative effect of the Arctic operating environment on the total cost compared with the reference region); (iii) estimation of RR and CER (to measure how the cost profile and the RP changes (increased or decreased) based on the effect of the operating environment); and (iv) sensitivity analysis (to identify the key cost variables).

The findings are as follows:

- The proposed methodology is beneficial as it outlines a set of steps that assists the risk and cost analyst to find the most suitable alternative waste handling practice that is cost-effective with the minimum level of risk, by considering the Arctic operating environment.

- The risk analysis results showed that the risk of undesirable events, due to the negative effect of the adverse operating condition of the Arctic, during offshore drilling waste handling activities, is between 1.48 and 2.60 times greater than that of the North Sea.
- The effect of the operating environment of the Arctic region on the cost element results is between 1.18 and 1.52 times greater costs for the Arctic when compared to the North Sea.
- The sensitivity analysis illustrated that the total cost per unit ton of drilling waste disposed is dependent on the key assumption, which in our case is drilling time per well. Hence, it is particularly effective to clearly identify and explain the assumptions during the risk and CEA.

Our intent is not to provide generalized advice on whether drilling should take place or not, since these prescriptions will be particular to and heterogeneous across the Arctic region. Rather, the intent is to highlight the fact that it is misleading to compare different alternatives based on the cost elements alone. Our conclusion is that proper risk assessment as a key part of CEA will result in more efficient waste handling operations and improved environmental protection. A shortage of historical probability of occurrence data, for different risk of events, was an issue during the illustrative case study analysis, due to the lack of operational experience in the Arctic. Therefore, the results should not be taken at face value; they should be interpreted in light of the current state of knowledge about operating experience in the Arctic. Moreover, the resulting risk values from the illustrative case study analysis should be updated as new data/evidence becomes available, preferably in the form of field (hard) data reflecting the actual operational experience in this Arctic region and therefore gradually supplanting the opinions elicited from experts. All these elements, however, do not invalidate the results from the illustrative case study analysis. Furthermore, to document the faithfulness of the probabilities given by the experts, calibration, which is a measure of the quality of probability distributions given by experts, is vital. In addition, performance-based weighting can help to reduce the bias and uncertainty distributions over the parameters.

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APPENDIX

Table 13 The questionnaire used to collect subjective probabilities and consequence ratings

Company profile												
Field of expertise												
Years of experience												
Type of waste handling practice												
		North sea (NS)						Arctic (AR)				
		Probability			Consequence rating			Probability			Consequence rating	
Potential hazards	UE	$P_{i0.05}$	$P_{i0.50}$	$P_{i0.95}$	$C_{i0.05}$	$C_{i0.50}$	$C_{i0.95}$	$P_{i0.05}$	$P_{i0.50}$	$P_{i0.95}$	$C_{i0.05}$	$C_{i0.50}$	$C_{i0.95}$
Negative air temperature and ice accretion												
Atmospheric icing and negative air temperature												
Icicles, atmospheric icing, and negative air temperature												
Rime, glaze, snow, and icicles												
Negative air temperature, rime, glaze, and snow												
Atmospheric icing and negative air temperature												
Low temperature, rime, glaze, and snow												
Freezing temperature and ice accretion												

[a]*UE*—represents undesirable events.
[b]Consider the following waste handling practices: (i) offshore discharge—treating and discharging the drilling waste to the ocean (sea); (ii) offshore re-injection—re-injecting the drilling waste offshore both in a dedicated re-injection well and/or in a dry (dead) well; and (iii) skip-and-ship—hauling the drilling waste back to shore for further treatment and disposal.
[c]The reference area, is North Sea and the target area, is Barents Sea.
[d]Consider Johan Castberg (formerly Skrugard and Havis) field development project as a case. Location of the field is in the Barents Sea—part of the Norwegian Arctic, about 200 km from the nearest Ingøya Island, in Finnmark, northern Norway.
[e]The suggested potential hazards can be used as a guidance; however, you are free to include other potential hazards.
[f]Refer to consequence categories, when you estimate the rate of occurrence and the associated loss (see Table 14). $P_{i0.05}$ is interpreted as the lower value; $P_{i0.50}$ is interpreted as the median value (the expert best judgment about the undesirable event *i*); and $P_{i0.95}$ is interpreted as 95% percentile value (the expert conservative judgment).
[g]Thank you very much for your participation in this interview.

Table 14 Consequence categories

Rating	Description	Financial impact ($)	
		Minimum	Maximum
1	Negligible, insignificant consequences	≤50,000	300,000
2	Slight, minor consequences	300,000	2,000,000
3	Moderate, hinders the waste handling process	2,000,000	5,000,000
4	Major, causes high or significant impact	5,000,000	10,000,000
5	Catastrophic, very high or severe damage	10,000,000	≥10,000,000

Table 15 The potential hazards and undesirable events for offshore re-injection and skip-and-ship

	ID	Potential hazard	UE
Offshore re-injection	UE1	Negative air temperature and ice accretion	Shale shakers failure
	UE2	Atmospheric icing and negative air temperature	Auger or conveyor system failure
	UE3	Icicles, negative air temperature, and atmospheric icing	Grinding mill (tank) failure
	UE4	Rime, glaze, snow, and icicles	Conditioned tank failure
	UE5	Negative air temperature, rime, glaze, and snow	Holding tank failure
	UE6	Atmospheric icing and negative air temperature	Injection pumps failure
	UE7	Wellbore instability	Contamination of the sea (if close to the wellhead) or shallow aquifers
	UE8	Fracture growth	Contamination of shallow fresh water aquifers
	UE9	Communication of the induced fracture with existing wells in the field	Environmental contamination of the sea, due to leakage in one of the casings near surface or at the wellhead [44]
	UE10	Presence of local faults/fractures close to the injection/disposal zone	Induced local tectonic movements, due to reactivation of the conduits [44]
Skip-and-ship	UE1	Fog, blowing snow, darkness	Operator error; fatal crane incident; untreated drilling waste discharge
	UE2	Ice floes contact	Propulsion failure; untreated drilling waste spill; HSE damage; loss of vessel; serious marine incident; and significant economic loss
	UE3	Rime, glaze, snow, and icicle formation on the railings, decks, gangs, stairs, and superstructure	Equipment damage; increased energy consumption; and difficulty during maintenance operation
	UE4	Polar low accompanied by sea spray icing, and snowstorms	Blackout because of freezing of the ship; loss of stability (in case of heavy load ice accretion in short time); personnel injuries; and increased heat requirement
	UE5	Negative air temperature and ice formation on windows, searchlights, and navigation lights	No indication of sailing direction, size of the ship, and no sign whether or not the ship is anchored; reduced or no visibility for mariners; and possibility of collision

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