Risk Assessment Methods for Comparative Assessment of Options for Decommissioning of Subsea Installations

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Abstract: Several options are possible for the decommissioning of subsea installations, varying from the extremes cases of total removal and leave in situ, and passing by various possibilities of partial removal. Comparative assessment is now well established as a method for determining the preferred option among a list of several possible options. It involves a decision based on several criteria, the most common ones being: safety, environmental, technical feasibility, societal and cost. Risk assessment is an important part of a comparative assessment because several sub-criteria are assessed as risks. In this paper, we argue that in comparative assessment one does not need to produce "absolute" risk values but only "relative" risk values which help to differentiate the decommissioning options. Furthermore, we argue that IRPA is not an adequate risk indicator for decommissioning options, and that the PLL indicator be used to measure the *expected number of fatalities during the realization of the option*. A thorough specification of the possible risks involved in the decommissioning of subsea installations and corresponding indicators are presented. This includes risks related to safety of people and environmental risks. Some practical examples are given to illustrate the concepts.

Keywords: Subsea Decommissioning, Comparative Assessment, Risk Assessment, Risk Indicators.

1. INTRODUCTION

Several options are possible for the decommissioning of subsea installations, varying from the extremes cases of total removal and leave in situ, and passing by various possibilities of partial removal. Comparative assessment is now well established as a method for determining the preferred option among a list of several possible options. It involves a decision based on several criteria, the most common ones being: safety, environmental, technical feasibility, societal and cost. Typically, each of those criteria are subdivided in sub-criteria. In all cases, risk assessment is an important part of a comparative assessment because several sub-criteria (mostly related to safety of people but not only) are assessed as risks, meaning that risk indicators are used as a measure of performance of each decommissioning option with respect to the referred sub-criteria.

An important document in this area is the Guidance Notes on Decommissioning [1], originally published by the UK Department of Energy and Climate Change (DECC) in 2013. DECC has now been substituted by BEIS (Department for Business, Energy and Industrial Strategy) which has very recently released a new draft version of the Guidance Notes which contains an appendix dedicated to comparative assessment [2]. The BEIS Guidance Notes [2] explicitly suggests the use of PLL and IRPA as risk indicators to be used in comparative assessment of decommissioning options; it also indicates that *absolute* risk values be obtained and compared to risk tolerability criteria suggested by the UK HSE [2].

2. OBJECTIVES

In this paper, we argue that in comparative assessment one does not need to produce "absolute" risk values but only "relative" risk values which help to differentiate the decommissioning options from the viewpoint of risk. Furthermore, we also argue that IRPA is not an adequate risk indicator for

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decommissioning options, and in fact, not even the traditional evaluation of PLL as the expected number of fatalities per year should be used in the case of comparative assessment of decommissioning options.

Decommissioning activities are not long-term activities such as is the case of process plants of offshore platforms which are supposed to operate 24 hours a day for 25-30 years; instead they are mostly short-term operations that may last some months to a couple of years. Furthermore, different decommissioning options may have tasks which require very different number of person-hours to be completed. Therefore, the risk indicators used in comparative assessment must reflect such conditions, which is not the case of traditional PLL and IRPA. These are both based on long-term average frequencies, expressed on an annual basis, and therefore not apt to reflect the durations of different tasks of each decommissioning option.

It is here suggested that the PLL indicator be used to measure the *expected number of fatalities during the realization of the option*. In this sense, for the occupational risks it must appropriately take into account the number of person-hours required to accomplish the tasks of each option; for the case of major risks which are characterized by an event frequency (for example, the risk of collision of a passing ship with decom ships), the PLL for the option has to assess the probability that such an event happen during the time predicted for the execution of the option (its duration). Even for the case of the risks to fishermen from long term degraded installations left in situ (the so-called legacy risk), the probability over the appropriate time interval must be used.

Another discussion involves the most adequate way to express the risks to the environment from the decommissioning activities, including the legacy risk. A peculiarity of subsea decommissioning in Brazil is the impact of subsea decommissioning activities on the dissemination of invasive species, in particular, the sun-coral which has been introduced to Brazilian waters in recent years [3] - [4]. Because of the very high visibility of this issue, a special comparison sub-criterion has been introduced (see Table 2) but this issue is not further discussed in this paper.

A thorough specification of the possible risks involved in the decommissioning of subsea installations is presented in this paper, the corresponding risk indicators are identified and appropriate risk assessment methods for comparative assessment are suggested for the evaluations. This includes risks related to safety of people and environmental risks.

3. ABBREVIATIONS AND DEFINITIONS

The complete list of all abbreviations used in this paper is shown in Table 1.

Table 1 - Abbreviations used in the paper

Abbreviation	Meaning
AIR	Average Individual Risk
CA	Comparative Assessment
CNAE	Brazilian National Classification of Economic Activities (“Classificação Nacional de Atividades Econômicas” - in Portuguese)
ESV	Expected spilled volume
FAR	Fatal Accident Rate
IBGE	Brazilian Institute of Geography and Statistics
IRPA	Individual Risk Per Annum
MCDA	Multi-Criteria Decision Analysis

NPH	Number of Person-Hours
PLL	Potential Loss of Life
QRA	Quantitative Risk Assessment

4. COMPARATIVE ASSESSMENT OF OPTIONS FOR DECOMMISSIONING OF SUBSEA INSTALLATIONS

4.1. Overview

It is well known that the activities involved in decommissioning of subsea installations generate effects of different categories, such as environmental damage and possible injuries and fatalities of workers, among several others. Different technical options may be available for the accomplishment of the decommissioning of a given subsea installation, varying between the two extremes cases of removing everything or leaving everything in situ. Hence it is necessary to choose the preferred option to be implemented in each decommissioning plan.

A Comparative Assessment (CA) of the options must then be performed which needs to consider the different category and degree of consequences from each option comprising a range of various assessment criteria, encompassing from safety and environment to others such as technical feasibility and cost of each alternative. Therefore, the choice of the preferred option within a comparative assessment falls within the realm of the discipline of Multi-Criteria Decision Analysis - MCDA. Following Pohekar and Ramachandran [5], MCDA methods can be defined as structured frameworks that deal with the process of making decisions in the presence of multiple objectives. In this sense, all existing comparative assessment methods in use in the oil and gas decommissioning area are variations of MCDA application to the preferred decommissioning option decision problem. It is important to make it clear that this paper is not about the methods of MCDA but it deals only with the application of risk assessment methods to the MCDA method used in CA of decommissioning options. There are many comprehensive texts on MCDA with a variety of approaches and depths of the subject. An introductory text that gives an excellent overview of the approaches used in governmental decisions is that of Reference [6].

4.2. Criteria and Sub-criteria in Comparative Assessment

As indicated before, the effects of the decommissioning options can be felt over a range of different categories of consequences. Five criteria have been proposed in the BEIS Guidance Notes [2] published by the competent authority in the UK and those have been used in practically all comparative assessments made to date for the decommissioning of oil and gas installations in the North Sea (available from https://www.gov.uk/guidance/oil-and-gas-decommissioning-of-offshore-installations-and-pipelines). The five criteria proposed by the UK regulators are:

1. Safety,
2. Environmental,
3. Technical Feasibility,
4. Societal, and
5. Economic.

In principle, if a performance measure, p_i, is assigned to each of the above five criteria leading to an aggregated performance measure for each option, then the preferred decommissioning option will be the one with the highest aggregated performance measure (assuming that the performance measures indicate the direction of the preference). An important aspect of the aggregation process is the assignment of relative weights, w_i, to the different criteria, reflecting the relative values of the different criteria to the decision maker. A simple aggregation process that has been used in most decommissioning plans to date is the assessment of the aggregate performance of each option as the weighted average value of the performance of the option for each of the five criteria, that is:

$$PO j=i=15 wi \times pi(O j) \quad (1)$$

where:

PO_j is the performance (aggregated value) of Option j,

w_i is the relative weight of the i^{th} criterion (w_i is between 0 and 1 and the sum of the weights of the criteria is equal to 1), and

$p_i(O_j)$ is the performance value of Option j with respect to the i^{th} criterion.

To facilitate the development of the comparative assessment, sub-criteria can be used for each of the criterion. In this case, the weights of each criterion is sub-divided among its corresponding sub-criteria, and Eq.(1) can then be re-written as:

$$PO j=i=15 wi \times k=1 Ki wi,k \times pi,k(O j) \quad (2)$$

where:

K_i is the number of sub-criteria of the i^{th} criterion,

$w_{i,k}$ is the relative weight of the j^{th} sub-criterion of the i^{th} criterion ($w_{i,k}$ is between 0 and 1 and the sum of the weights of the sub-criteria of each criterion is equal to 1), and

$p_{i,k}(O_j)$ is the performance value of Option j with respect to the k^{th} sub-criterion of the i^{th} criterion.

In the BEIS Guidance Notes [2], criteria and corresponding sub-criteria are presented as suggestions. In fact, a large variety of sub-criteria have been used in the comparative assessments submitted in support of the choices of decommissioning options proposed by the oil operators. A typical set of sub-criteria is proposed in Table 2 under study for possible use in subsea decommissioning in Brazil.

Table 2 - Example of Criteria and Sub-criteria

Criteria	Sub-criteria	Performance assessment indicators
Safety	Risk to offshore personnel	PLL
	Risk to other users of the sea	PLL
	Risk to onshore personnel	PLL
	Risk to the onshore public	PLL
Environmental	Operational offshore impacts	Qualitative matrix (score from 1 to 16)
	Operational onshore impacts	Qualitative matrix (score from 1 to 16)
	Risk of oil spill	ESV (m^3 – see Section 7)
	GHG emission	Tons of CO2
	Dissemination of invasive species	Qualitative matrix (score from 1 to 16)
	Impact of legacy	Percentage of total material left in place
Technical	Risk of major project failures	Probability of project cost overrun
Societal	Impact on fisheries	Variation of gain with fisheries ($)
	Employment	Variation of number of employments
	Other societal impacts	Qualitative matrix (score from 1 to 16)
Economic	Cost	Currency ($)

As can be seen from Table 2, the performance indicators of each sub-criteria shown in column 3 may have a variety of units and therefore cannot be aggregated as such. It is first necessary to transform them into a common form. This can be done by converting all of them to a 0 to 1 scale, which is obtained by normalizing each one to the interval between the corresponding minimum and the maximum values. Furthermore, it is necessary to represent all of them in a way that indicates a coherent variation from the worst to the best option. Since the best option is the one with the highest aggregated score, then some of the indicators may have to be normalized in an inverted sense. For instance, in terms of safety of people, the best option is the one with the lowest PLL value. In this case, the option with the highest PLL value will be assigned a 0 and the option with the lowest PLL will be assigned a 1. Options with intermediate PLLs will be proportionally scaled as indicated in Eq.(3):

$$PLLint-norm=1-PLLint-PLLminPLLmax-P\ \ Lmin \qquad (3)$$

Since the four sub-criteria for the Safety criterion have the same units (PLL) and each one represents a piece of the total risk to people, it is important that they be measured on the same scale. One way to do that is by considering the normalization to the overall minimum and maximum values among the PLL for all four sub-criteria, as indicated in Figure 1.

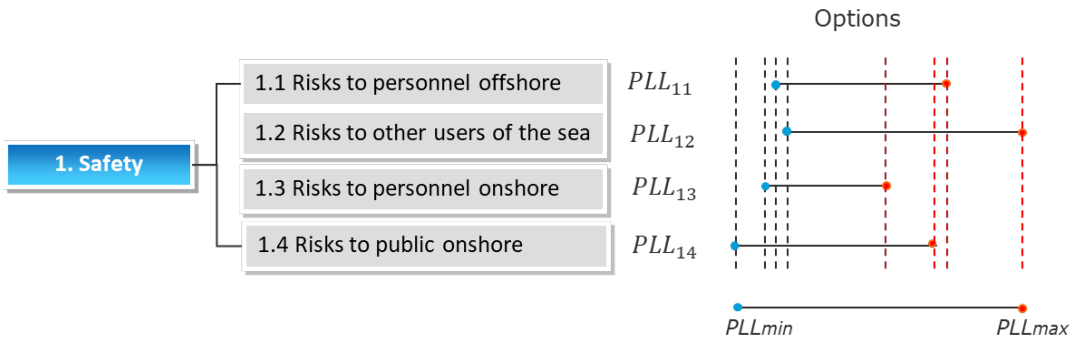

Figure 1 - Normalization scheme for the four safety sub-criteria

In this case, the PLL values for the four sub-criteria could be added, forming a single performance measure for the Safety criterion (which could be called "Risks to People"), and only then normalized considering the new minimum and maximum values. The resulting preference order for the decommissioning options would be the same as that obtained with the above procedure. But if each one was separately normalized to each specific minimum and maximum values, the preference order could be different. If the decision-maker would like to consider that the risks to the public are more important than the risks to the workers, then she could simply increase the weight of the sub-criteria of risks to the public (1.2 and 1.4 in Figure 1).

5. RISK ASSESSMENT INDICATORS RELEVANT TO COMPARATIVE ASSESSMENT OF SUBSEA DECOMMISSIONING

5.1. Introduction

As indicated in Section 1.1, The BEIS Guidance Notes [2] explicitly suggests the use of PLL and IRPA as risk indicators to be used in comparative assessment of decommissioning options; it also indicates that *absolute* risk values be obtained and compared to risk tolerability criteria suggested by the UK HSE (max 10^{-3}/yr for individual risk of fatality of workers) [2]. In the present section we discuss the suggestion of using PLL and IRPA in CAs and in the next (Section 6) we argue that it is not necessary that absolute risk values be used in CAs.

5.2. Traditional Definitions of PLL and IRPA Used in QRAs

PLL and IRPA are risk indicators which have been used for a long time in QRAs of onshore and offshore process installations.

Conceptually, the PLL has been defined as "the predicted long-term average number of fatalities in a system or an activity, usually per year" (see Rausand [7]). It has also been referred to as "the average societal (or group) risk" (see CCPS **Error! Reference source not found.**) and "the Average Rate of Death" (see Lees **Error! Reference source not found.**). In the latter reference, it is defined as "the average number of fatalities that might be expected per unit time from all possible incidents". Quantitatively, the PLL for a group of exposed people (which can be the workers of a plant or the exposed members of the population surrounding the plant) from a hazardous plant with *N* accident scenarios can be obtained by Eq.(4):

$$PLL=i=1N fi\times Ci \qquad (4)$$

where:

f_i is the average frequency of the i^{th} accident scenario, and

C_i is the number of fatalities in the i^{th} accident scenario.

A formal definition of individual risk has been given by the IChemE [11] as the frequency at which an individual may be expected to sustain a given level of harm from the realization of specified hazards. The term Individual Risk Per Annum (IRPA) is often used as an individual risk of fatality expressed on a yearly basis. This term has also been referred as the average individual risk (AIR) [12]. In simple terms, IRPA and PLL are related by the following relationship: IRPA= PLL/(number of exposed people).

Therefore, both IRPA and PLL refer to long-term frequencies of accidents in a process installation that is designed to operate over long periods involving 30 to 50 years of operation and their applications in such cases do make sense. On the other hand, as above defined they are not adequate for applications to decommissioning activities as will be shown in the subsequent section.

5.3. The Main Characteristics of Subsea Decommissioning Options: Their Durations

Contrary to the situation of process installations, decommissioning options are of a short-duration nature, varying on average from one month to one or two years. Furthermore, in many cases, they can be decomposed in even shorter activities and tasks which themselves are the sources of risks to the decommissioning workforce. Hence, it does not make sense to apply risk indicators, such as IRPA and PLL, which are defined as long-term averages of long duration and mostly steady-state hazardous conditions. For instance, evaluating the PLL in a QRA implies the use of weather data which is averaged over a period of a couple of years to try to capture temporal variations in the geographical area where the installation is located. The same calculation in a short-term decommissioning activity in a defined time-window may only need to consider the weather patterns that are typical of the season (or seasons) during which the activity is scheduled to take place.

Mostly importantly, the objective of a Comparative Assessment is to uncover the variation of risk among the proposed decommissioning options. One of the most important discriminating characteristics of the various options is the duration of each one. Consider a simple situation of three subsea decommissioning options applied to a subsea pipeline: 1st option: leave the whole pipeline in situ, 2nd option: remove part and leave part of the pipeline in situ, and 3rd option: remove everything. It is easy to see that the durations of the options vary from practically zero for the first option to a long period (let us say, one year) for the third, with an intermediate duration for the second option. If the decommissioning activities for the second and third options give rise to the same type of hazards, the main risk differentiator among them will be their respective durations. This difference would not be captured if only long-term average indicators such as the traditional PLL and IRPA were used.

6. APPROPRIATE RISK INDICATORS FOR DECOMMISSIONING ACTIVITIES

6.1. Redefining the PLL

Instead of defining the PLL as the long-term average rate of fatality per year, it will be defined here as: “the average number of fatalities resulting from the (finite duration) activity. Using this definition, we are able to capture the effect of the duration of each activity on its risk. For the quantitative risk evaluation, Eq.(4) is then substituted by Eq.(5):

$$PLL=i=1NPi\times Ci \qquad (5)$$

where:

P_i is the probability of occurrence of the i^{th} accident scenario within the duration of the activity, and

C_i is the corresponding number of fatalities in the i^{th} accident scenario.

Therefore, the risk of each specific decommissioning activity will be expressed, not as a function of the long-term average frequencies of the hazardous events, but in terms of the probability that the hazard event will occur within the expected duration of the activity. Considering that the accident scenario i occurs with a constant rate r_i at any instant of time during the expected duration, D_i , of the activity, the probability of occurrence of scenario i during the realization of the activity can be evaluated by Eq.(6):

$$P_i = 1 - e^{-r_i \times D_i} \quad (6)$$

If the product of the accidental scenario rate r_i and the duration D_i is lower than 0.1, the accidental scenario probability can be approximated by Eq.(7):

$$P_i = r_i \times D_i \quad (7)$$

It can be argued that the duration of an activity can be made smaller by employing a bigger number of people, which would apparently have the effect of lowering the risk of the activity. But that is not really true, because doing the activity at a faster pace would not only cause an increase of the accident rate (r_i), but also an increase of the consequences of each accident scenario (more people would be in the area of the accident). These effects would then cause the risk to increase, thus compensating for the reduction of the duration of the activity. Therefore, calculating the PLL as redefined here [Eq.(5)] is an adequate way of comparing the risks of the various decommissioning options. In fact, the PLL of an activity as evaluated here depends basically on the number of person-hours (NPH) used to develop the activity.

Since IRPA and PLL are not independent, it does not make sense to use both risk indicators as comparison factors for the decommissioning options. Since PLL is a measure of group risk, it gives a better indication of the risk of each decommissioning option, it is the preferred risk indicator and it has been used in most of the comparative assessments made to date.

6.2. The Issue of Compliance with Risk Acceptability Requirements

In Annex A ("A Guide to Comparative Assessment") of the BEIS Guidance Notes [2] it is indicated that:

- "In assessing and comparing the safety risks of different options the general principles of risk management used within the industry should be applied".
- "The use of quantitative risk assessment (QRA) techniques should be employed. Typical mechanisms include using Potential Loss of Life (PLL), Individual Risk Per Annum (IRPA) and Fatal Accident Rate (FAR) criteria".
- "Comparison should be made with the risk levels generally supported by the Health & Safety Executive who define the maximum tolerable level of individual risk of fatality as 1 in 1000 per year, and for the broadly acceptable level of individual risk to be set in the range of 1 in 100,000 to 1 in 1 million per year".
- "The risks should also be set in context by drawing comparison with the risks that were judged to be acceptable during the installation and development phase and the risks that exist in other industries."

We think that there is a bit of confusion in the presentation of the above suggestions. While they are valid in the case of safety management of decommissioning activities, they are really not very meaningful as guidance for the development of comparative assessment of decommissioning options. After one specific decommissioning option has been selected as the preferred one, then safety management principles would be implemented to make sure that risks to people (workers and the public) are in compliance with the requirement of the competent authorities. Of course, if any of the competing options is suspected of having an unacceptable risk, then it could be fully risk assessed to confirm or not the suspicion. Then it could be discarded in case of a positive answer or else additional safety measures could be implemented to reduce the risks. It is important to note that the HSE risk acceptability requirements are set only for individual risks and not for group risks (PLL), and high individual risks are easier to reduce than high group or societal risks. For instance, suppose a certain diving activity is performed by a single diver and it results in a high individual risk value to the diver. This individual risk can then be lowered simply by employing two or three divers instead of just one to do the referred task. By doing that, each diver would be exposed to less diving time, resulting in a lower individual risk value for each of the divers.

In any case, care must be taken for a proper risk acceptability judgement to be made: as indicated in the previous section, decommissioning activities are short-term ones, while the HSE acceptability criteria are set in terms of long-term average frequencies which are appropriate to process plant operations.

6.3. Using Relative rather than Absolute Risk Values in Comparative Assessments

Since the objective of a Comparative Assessment is to rank the decommissioning options in terms of their preference orders according to a set of criteria, it is sufficient that the performance measures with respect to each criterion be assessed in a relative form. In terms of risk, this means that it is only necessary that relative risks of the various options be assessed. For instance, consider the case of the decommissioning of a subsea pipeline. The same pipeline flushing activity is to be performed all the decommissioning options (leave the whole pipeline in situ, remove part of it, or remove all of it), and therefore, the risks involved in such activity do not have to be evaluated as part of the risk assessment of each of the option for the comparative assessment. Only the activities that result in different risk values for the different options need to be assessed, either because they involve different tasks or because they involve different durations of the same tasks. Therefore, at the comparative assessment development phase, only relative risks among the various options need to be assessed and this means that the values that are obtained this way cannot be used for compliance with legal requirements.

7. APPLICATION TO THE ENVIRONMENTAL RISK OF SPILLS

A comprehensive analysis of the environmental risk of oil/fuel spills is one of the requirements for licensing of oil drilling and exploration in Brazil, and in several other areas of the world. As in a QRA, the assessment of this environmental risk requires the evaluation of two factors: the frequencies of the oil spill accident scenarios and the corresponding consequences to the environmental resources. The consequence assessment involves several calculations including the amount released in each scenario, the modelling of the oil dispersion in the sea and the effect of oil impact on each designated environmental resource. The environmental risk of oil/fuel spills can be one of the sub-criteria of the environmental criterion in a comparative assessment of decommissioning options. The spills originate from accidents involving the various ships used in the decommissioning activities, with each option presenting a different degree of risk. In such cases, the only significant variables that differ among the various options are the frequency and the amount of oil/fuel spilled in each scenario. All other factors (location, environmental resource, metocean data, distances) are the same for all options. Therefore, the performance indicator for the environmental risk of oil spills can simply be the average volume of oil predicted to be spilled for each option. This is named the Expected Spilled Volume (ESV), and calculated for each decommissioning option by the following equation:

$$ESV=i=1NPi\times Vi \qquad (8)$$

where:

P_i is the probability of occurrence of the i^{th} oil/fuel spill accident scenario, and

V_i is the volume of oil spilled in the i^{th} oil/fuel spill accident scenario.

The advantage of using such a surrogate oil spill risk indicator in the comparative assessment is the greater simplicity of its calculations compared to those of a full environmental risk of oil spills. Once the decommissioning option is chosen, then a full environmental risk assessment may be conducted and, if the risk is found to be unacceptable (a very unexpected case in terms of oil spill risk during decommissioning), then risk reduction measures must be applied to bring the risks under compliance.

8. RISKS TO WORKERS AND RISKS TO THE PUBLIC

8.1. General Risk Assessment Scheme

As indicated in Table 2, both the risks to the workers and to the public from decommissioning activities have to be assessed in a CA. The general scheme for conducting the quantitative risk assessment for safety of people is illustrated in the flow diagram of Figure 2 which indicates two separate pathways to the risk evaluation. The first one refers to the occupational risks and the second one to the major hazards risks. In fact, only the workers (offshore or onshore) may be exposed to both types of risk. The other-users-of-the-sea and the onshore public are only exposed to the major hazards risks since they are not directly involved in the decommissioning activities.

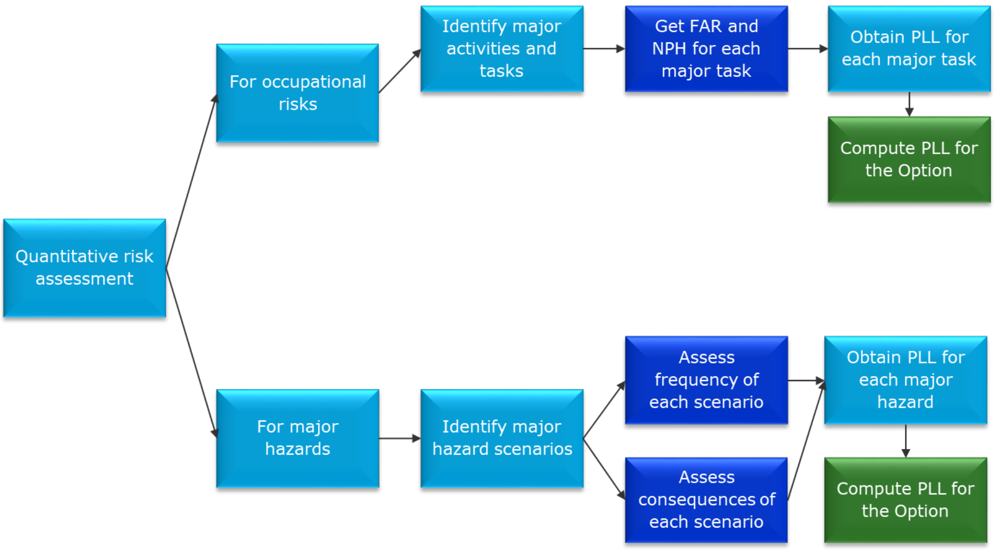

Figure 2 - General flow scheme for quantitative risk assessment of decommissioning activities

Although a major hazards accident that kills a worker is also considered an occupational accident in legal terms, in this paper they are treated separately because the methods used in each case to assess the risk values are different. Nevertheless, in both cases, the risk indicator is the PLL. Hence, the overall PLL for the workers is determined by summing the PLL values obtained from both pathways (occupational + major hazards) and that for the non-workers (other-user-of-the-sea and onshore public) is obtained from the major hazards assessment pathway, as indicated in Eqs.(9) and (10), respectively:

$$PLLworkers = PLLOccup + PLL(MH) \quad (9)$$

$$PLLnon\text{-}workers = PLL(MH) \quad (10)$$

The methods for the assessment of PLL to the workers and the public are presented in the following subsections.

8.2. Assessing Occupational Risks to the Workers

For each decommissioning option the occupational risks due to decommissioning activities can be evaluated using the following steps (illustrated in the upper pathway of Figure 2:

1. Identify the major work activities (first step of a Job Safety Analysis) to be conducted for the decommissioning option under analysis:

   $$Ak, \quad k=1 \ldots K \tag{11}$$

   where K is the total number of activities of the decommissioning option.

   Offshore operations include the use of equipment for dismantling, lifting, transporting and recovering parts of the subsea installation. Onshore operations include dismantling, transporting and reprocessing. Activities or major tasks, for example to lift a subsea manifold and take it to shore may include:

   - Mobilization of vessels to site
   - Anchoring of vessels
   - Cutting of manifold piles using Remotely Operated Vehicle (ROV)
   - Use of crane on vessels to lift the subsea manifold to a barge
   - Use of multi-support vessel on stand-by
   - Use of barge on stand-by
   - Transport of materials by barge to shore
   - Helicopter flights
   - Waiting on weather for a number of vessels
   - Demobilization of vessels

2. Determine the technology and resources required to perform the activities. For each activity define the number of required number of person-hours (NPH_k) that will be used to complete the activity.

3. For each activity or work task obtain the corresponding Fatal Accident Rate (FAR) value (see below).

4. For each activity evaluate the Expected Potential Loss of Life Per Activity (PLL_k) using the FAR value for the activity and the predicted number of person-hours (NPH_k) necessary to complete the activity (can be obtained by the product of the duration of the activity D_k and the number of persons required to complete the activity N_k within the duration).

   $$PLLk = FARk \times NPHk\ 108 \quad k=1 \ldots K \tag{12}$$

5. Obtain the occupational Potential Loss of Life for the decommissioning option, *PLL(occup)* by summing the PLL_k of over all activities of the option:

   $$PLL(occup) = k=1KPLLk \tag{13}$$

The above procedure must be repeated for all decommissioning options in the CA.

The Fatal Accident Rate (FAR) value is defined as the number of fatalities in a specific activity for each 100 million hours worked in the specific activity. FAR values for major activities involved in the decommissioning of offshore installations in the North Sea can be obtained in Ref.[13]. Most of the CAs performed in support of decommissioning activities in the North Sea use FAR values taken from this reference.

In Brazil, the Brazilian Institute of Social Welfare ("Instituto Nacional do Seguro Social") publishes values of the "mortality rate" [14] for most occupational activities listed in CNAE registry [15] (developed by the Brazilian IBGE). The mortality rate of an activity is defined as the annual number of fatalities per 100.000 workers involved in the activity. Considering that each employee works approximately 2000h per year, then the number of worked-hours of 100.000 workers in one year is equal to 200 million hours, which corresponds to twice the number of worked-hours used to obtain the FAR. Therefore, given the mortality rate of an activity, its corresponding FAR is half the value of the mortality rate. Therefore, one way to assess the occupational PLL of a decommissioning activity in Brazil is to obtain its mortality rate value and then calculate its FAR value. Once the FAR value is known for the activity, the occupational PLL can be obtained by using it together with the predicted number of person-hours (NPH) for the realization of the activity in Eq.(12).

8.3. Assessing Risks of Major Hazards to the Workers and the Public

A non-exhaustive list of major hazards that may be included in a major hazards risk assessment of subsea decommissioning activities is given below, firstly for offshore activities and secondly to onshore activities.

Offshore:

- Ship sinking or capsizing (back load, bad weather, structural failure, etc.) while in location or in transit
- Fires and explosions in decommissioning ships
- Accidental release of hazardous toxic material (H_2S, others)
- Collision between decommissioning ships in location
- Collision between decommissioning ships in transit and fixed structures (offshore platforms, FPSOs)
- Collision between decommissioning ships and passing vessels (fishing/commercial/relief tankers/others)
- Collision of helicopter with decommissioning ships
- Decommissioning vessel hit by rising riser buoy
- Dropped heavy object on operating pipelines
- Contamination of workers with NORM
- Decommissioning vessel grounding
- Ship accidents at harbor
- Fishing ships sinking or capsizing due to trawling snag on subsea equipment left in situ
- Inspection vessels accidents during periodic monitoring of subsea equipment left in situ

Onshore:

- Fires and explosions in decommissioning yard
- Accidental release of hazardous toxic material (H_2S, others) in decommissioning yard
- Fires and accidents during refueling (releases of diesel/gas/gasoline)
- Contamination of workers with NORM
- Road accidents between decommissioning vehicles and other vehicles or fixed structure

For each decommissioning option, the assessment of major hazards safety risks to workers and to the public (others users of the sea and to the public onshore) can be evaluated according to the following steps (illustrated in the bottom pathway of Figure 2):

1. Perform a Preliminary Hazard Analysis (PHA) per activity to identify all major hazards and accident scenarios during decommissioning option activities.

2. For each identified accident scenario, evaluate its occurrence frequency, exposure period during which the hazard is present (duration of the activity) and its consequences to the exposed people:

$$\{ ri, Di, Ci \} \quad i=1 \ldots N \tag{1}$$

   where N is the option total number of accidental scenarios due to major hazards, r_i is the rate of occurrence (assumed to be constant) of the major hazard accident scenario i, D_i is the period during which the accidental scenario can occur (duration of the activity) and C_i is the expected number of fatalities given the occurrence of scenario i. Specific quantitative risk assessment studies may need to be conducted, such as ship collision risk analysis, dropped object analysis, leave-in-situ legacy risk analysis, and others, to determine the frequency and consequences of the major hazards. For leave-in-situ legacy risk to other users of the sea (such as fishermen sinking due to snagging on installations/equipment left in-situ, D_i is the future period of time during which the subsea equipment left in situ may represent a hazard to the other users of the sea (this will depend on the degradation patterns of the material left in-situ).

3. For each option, evaluate the Expected Potential Loss of Life (PLL) of each major hazard accident scenario to personnel offshore and onshore, to other users of the sea and to the public onshore (risks not included in the activities covered by the FAR values). The PLL of each accident scenario can be calculated by Eqs.(5 – 7).

4. Obtain the Potential Loss of Life for the option due to major hazards accident scenarios by summing the PLL of each accidental scenario PLL_i over all major hazards accident scenarios of the option.

9. FINAL COMMENTS

In this paper, we make a general presentation of the quantitative risk assessment methods used in comparative assessment of the various options for the decommissioning of offshore oil installations with special emphasis to subsea ones. A thorough specification of the possible risks involved in the decommissioning of such installations is presented, the corresponding risk indicators are identified and appropriate risk assessment methods for comparative assessment are suggested for the evaluations. This includes risks related to safety of people and environmental risks.

It is argued here that in comparative assessment one does not need to produce “absolute” risk values but only “relative” risk values which help to differentiate the decommissioning options from the viewpoint of risk. We think that it is much more sensible that the issue of compliance with risk acceptability limits be undertaken after the comparative assessment of the options is concluded and one specific decommissioning option is chosen as the preferred one. Then the full risk assessment of that option may be completed and additional risk reduction measures be implemented if necessary.

Since decommissioning activities are mostly short-term operations that may last some months to a one or two years, it is shown that IRPA is not an appropriate risk indicator to be used in CAs of decommissioning options. Not even the traditional definition of PLL as the expected number of fatalities per year should be used in the case of comparative assessment of decommissioning options. A different definition of PLL as the expected number of fatalities predicted to occur during the realization of each option, which considers the number of person-hours needed to complete each activity (used for the evaluation of the PLL for occupational risks) or the duration of the activity (exposure) for the case of the evaluation of the PLL for the scenarios involving major hazards.

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