Economical Optimal Reserve Strength for a jacket structure

Gerhard Ersdal, Petroleum Safety Authority Norway[1]
Oliver Kübler, Swiss Federal Institute of Technology, ETH, Switzerland
Professor Michael H Faber, Swiss Federal Institute of Technology, ETH, Switzerland
Professor John D Sørensen, Aalborg University, Denmark
Dr Sverre Haver, Statoil, Norway
Professor Ivar Langen, Stavanger University, Norway

Abstract

This paper evaluates the optimal reserve strength (RSR) of a jacket structure based on a model taking into account the cost of design, fabrication and installation of the jacket structure and the possible cost of failure. The failure probability resulting from this economical optimal reserve strength is compared with acceptance criteria given in regulations and viewed upon in the light of the principle that the probability of fatality for the individual workers should not be significantly increased as a result of working in the offshore industry.

The cost of the jacket structure includes an estimate of building cost and the cost of increasing the strength of the jacket to higher reserve strength. The cost of failure is taking into account consequences of material losses and loss of lives.

The sensitivity of the economically optimal reserve strength to the different types of uncertainty included in the optimization is studied. This includes a study with only aleatory uncertainties included, a study with aleatory and epistemic uncertainties included, and various models considering also different types of additional failure modes like wave in deck and possible single member failure.

The present study shows that, with the legislative requirements imposed on offshore operators in the North Sea today, the optimal design of fixed jacket structures is governed by the minimum safety level implicit in the regulation and standards. This can be regarded as representing a maximum acceptable risk of fatalities. The economical (life cycle benefit) optimal failure probabilities can result in an increased fatality risk for the individual worker. However, this may lead to an increased expected total benefit.

Introduction

As economical margins for field developments have been reduced as a result of smaller fields, improved safety requirements from regulators combined with higher revenue requirements by the owners, extended theoretical work towards optimality and acceptance criteria for the design and operation of offshore facilities have been performed, e.g ref Stahl (1998), Skjong and Ronold (1998), Vinnem (1996), Pinna et al. (2001), Kübler and Faber (2002). Decision on structural strength parameters (load and resistance factors, reserve strength ratio, etc.) may be optimised on the basis of past practice and cost benefit considerations together with the legislative requirements to the safety of personnel.

To the knowledge of the authors, the full use of the possibilities with optimised design of offshore installations has not been implemented in any practical design. However, structural reliability analysis and evaluations of optimal safety levels have been used in code development (Sørensen et al 1994). Optimisation based on economical cost benefit analysis has, in Norwegian field developments, only been allowed used on unmanned installations with insignificant environmental consequences in case of failure.

In optimising the safety of a risk exposed system, all failure modes and uncertainties associated to these failure modes should in principle be addressed. As this in practical design is an impossible task, the following fundamental principle should be applied: The risk

[1] Petroleum Safety Authority Norway is the former Safety Division of the Norwegian Petroleum Directorate

model is sufficient accurate when any improvement to the risk model to make it more accurate should not lead to a change in the conclusions made (Aven, 2003). Evaluations of the optimal reserve strength ratio (RSR) of jacket structures are typically performed without looking at the possibility of member failures and the possibility of wave in deck loading. This paper will address these two possible additional failure modes to make the risk model more accurate, and to evaluate the effect on the conclusion.

Also, the effect of varying the epistemic uncertainty (statistical and model uncertainties related to e.g. shape parameter, wave load, capacity) is evaluated. This will exemplify the sensitivity to the subjective expert judgement for the probability distributions used to describe the uncertainties of factors.

The following cases have been evaluated in this paper: 1) The optimal RSR without wave in deck loads and without possible member failure is evaluated. This can be viewed as what we initially would believe is the correct description of failure probability. 2) The effect of epistemic uncertainty is evaluated by removing the assumed epistemic uncertainties in the calculations (spread is removed, and the distribution is fitted with varying the bias). 3) Introduction of new failure modes in order to evaluate the change in optimal RSR. The following changes are applied: a) Possible member failure reducing the structural capacity is included. The failure may be a result of fatigue, overload, corrosion, or gross errors[2]. b) A "new failure mode" is introduced by including the possibility of wave in deck in the load description. c) A combination of a and b accounting for both wave in deck and the possibility of a member failure.

The economical model follows the model described in Kübler and Faber (2002), where a further development of the methods for implementing consequences of fatalities in decision analysis (see e.g. Skjong and Ronold 1998, Rackwitz 2000) for offshore structures is described.

Nomenclature

The following list of cost items is an attempt to show the distribution of cost for a field development and the abbreviation used in this paper. This is mainly based on Almlund (1991).

Total cost of field development: C_D or CAPEX

- Construction cost for installation (including structure, topside equipment, piles, transport and installation, management and engineering, etc) C_{CC}.
- Well drilling and down-hole activities: C_W
- Hydrocarbon transportation system: C_{HCT}
- Sub-sea systems: C_{SUB}

Total construction cost for installation: C_C

- Topside (process, drilling area, living quarter, utilities and outfitting, wellhead area, structure): C_{TS}
- Substructure: C_{SS}
- Piles: C_{PL}
- Transport and installation: C_{MI}
- Management, Project team, engineering, insurance: C_{TE}

Cost of failure: C_F

- Loss of lives (fatalities): C_{FF} = NF ICAF
    - NF: Number of Fatalities
    - ICAF: Implied cost of avoiding a fatality
- Material losses: C_{FM}

Reconstruction cost: C_{RC}

- Assumed equal to construction cost for installation C_C. The transport system and wells are assumed intact.

[2] Gross error may be built in to the structure as a result of design error, a fabrication error or operational error.

Cost of operation: OPEX

- Cost of operating the facility including maintenance, well services, process, man-hours, catering, etc.

Income / Revenue: I_{NPV}

- Net present value of income taking into account operational costs. Income is modelled according to a standard production profile.

Generalising the different cost elements as a ratio with the cost of field development as a common reference:

Construction cost versus Field development cost:	ρ_{CC}	$= C_C / C_{FD}$
Income versus Field development cost:	ρ_I	$= I_{NPV} / C_{FD}$
Cost of failure (material costs):	ρ_{FM}	$= C_{FM} / C_{FD}$
Implicit cost of avoiding a fatality versus Field development cost:	ρ_{ICAF}	$= ICAF / C_{FD}$
Cost of substructure versus total installation:	ρ_{SS}	$= C_{SS\_Fix} / C_{CC}$

Economical optimal decision model

A framework for decision theory for establishing economical optimal RSR for an offshore jacket structure is established in Kübler and Faber (2002). For further details, Kübler and Faber (2002) should be consulted.

Decision theoretical formulation

Following Sørensen et al. (1994), optimal design in structural engineering may be seen and formulated as a decision problem within the framework of Bayesian decision analysis, see also Raiffa and Schlaifer (1961). In short, the decision problem may be formulated as an optimization problem, where the expected life cycle benefit of the structure is maximized. Due to the fact that income and costs occur at different times, the expected benefit is capitalized (by means of its net present value) to the point in time when the decision is made.

In the present study the construction costs C_C, the income obtained through the production I, the failure costs C_F and the reconstruction costs C_{RC} are included in the life cycle benefit. Each of these consequences depends on a set of design parameters, which for the present case are represented by the reserve strength ratio (RSR).

Simplified Decision Analysis

When searching for the optimal design of a structure, it should be taken into account that the structure may fail in the future and that it may be reconstructed if feasible. This again depends on the future potential income / revenue.

The decision/event tree shown in Figure 1 illustrates the pursued approach. The first node in Figure 1 represents the design and construction of the structure. At this time the decision is made in regard to the reliability of the structure. After the structure has been realized, in principle two events may follow. The structure may survive (event E_1) or it may fail. If the structure fails, there are again two possibilities. Either it is economically feasible to reconstruct the structure or it is not (event E_2). If economically feasible, the structure is reconstructed and thereafter again two events may follow. Either the structure fails (event E_4) or the structure survives (event E_3). Hence, in the present study, only the expected costs and incomes up until the time of the second failure are taken into account.

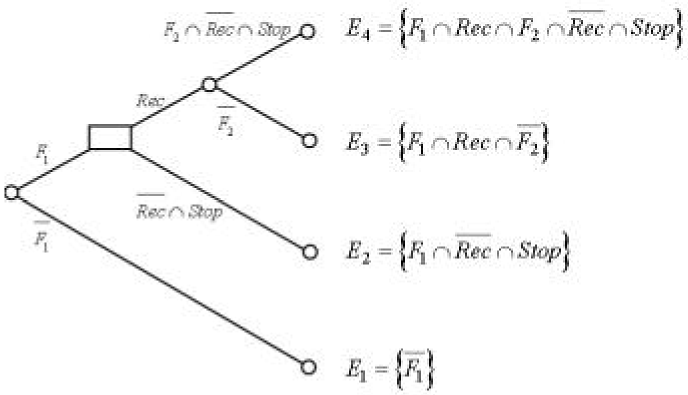

Figure 1: Simplified decision analysis

The expected life cycle benefit may be written as

$$E[B] = E[C_I] - E[C_C] - E[C_{RC}] - E[C_F], \qquad (1)$$

where the expected value operations are performed in regard to the uncertainties associated with the loading and the load capacity of the structure. The incomes and costs are discounted by a discounting function $d(t)$.

$$d(t) = e^{-g \cdot t} \qquad (2)$$

Here, $g = \ln(1+r)$, r denotes the annual interest rate and t is the time at which the consequence (income or cost) occurs.

In this paper the yearly income and the yearly cost of operating the facility is integrated into the income factor, as the available data for income for a field is often given with reduction for the operating cost.

Net expected value of income taking into account the operational cost is used in the following calculations ($i(t) = i_{net}(t) - OPEX(t)$):

$$I = \int_0^T i(t) \cdot d(t) \cdot R_{i,2}(t) dt = r_I \cdot C_D \cdot \int_0^T \tilde{i}(t) \cdot d(t) \cdot R_{i,2}(t) dt \qquad (3)$$

Hence, $E[B]$ is the expected net present value of the life cycle benefit of the structure and can be written as:

$$E[B] = \int_0^T i(t) \cdot d(t) \cdot R_{i,2}(t) dt - C_D - \int_0^T C_C \cdot d(t) \cdot g_1(t) \cdot dt - \sum_{n=1}^{2} \int_0^T C_F \cdot d(t) \cdot g_n(t) \cdot dt \qquad (4)$$

where T is the design lifetime, $i(t)$ the income function, $d(t)$ the discounting function, $R_{i,2}(t)$ the "income reliability function" considering two possible failures. The income reliability function expresses the probability that at time t the income is obtained. It should not be confused with the structural reliability function. C_D are the field development cost, C_C are the construction costs (also representing the reconstruction costs), C_F the failure costs and $g_n(t)$ is the probability density function of the time to the n-th failure. Finally, t_0 is the latest point in time for an economically feasible reconstruction.

Inserting the relative description of the cost and income terms, including the effect of increased cost with strengthening, equation 4 becomes:

$$E[B] = C_D \cdot (r_I \cdot \int_0^T \tilde{i}(t) \cdot d(t) \cdot R_{i,2}(t) dt - 1 - r_{CC} \cdot r_{SS} \cdot r_{St} \cdot (RSR - RSR_0) \ldots$$
$$- r_{CC} \cdot \int_0^T d(t) \cdot g_1(t) \cdot dt - \sum_{n=1}^{2} \int_0^T (r_F + NF \cdot r_{ICAF}) \cdot d(t) \cdot g_n(t) \cdot dt) \qquad (5)$$

where RSR_0 is the RSR for the reference installations.

The assumption that failures occur as realisations of a stationary Poisson process allows for an analytical evaluation of Equation 5. Based on this assumption, only one failure event may occur in a sufficient small time interval. Therefore, the probability of the union is simply the addition of the probabilities of the individual events. The "income reliability function," which considers two possible failures including the reconstruction decision, may be derived as (Kübler and Faber 2002):

$$R_{i,2}(t) = \begin{cases} e^{-lt}\left(1+lt\right) & ;t \le t_0 \\ e^{-lt}\left(1+l t_0\right) & ;t > t_0 \end{cases} . \quad (6)$$

If the structure is given up after the first failure, the "income reliability function" $R_{i,1}(t)$ is identical to the classical reliability function of the structure.

By means of the annual probability of failure, the annual failure rate becomes:

$$l = \ln\left(\frac{1}{1-P_{f,a}}\right) \quad (7)$$

where $P_{f,a}$ is the annual probability of failure as a relation of the RSR, as shown in the following section.

Modelling the probability of failure of a structure

To determine the relation between the RSR and the annual failure rate, a probabilistic model according to Ersdal et al (2003) has been applied. Typical failure modes for a jacket structure:

- Overload due to excessive wave (including wave in deck), wind and current loading.
- Overload due to excessive wave (including wave in deck), wind and current loading after damage of a member or joint. A failure of an individual member may be due to fatigue, corrosion, gross error (e.g. insufficient design, fabrication error, damage during transport or installation), accidental loading (e.g. dropped object, boat collision).

Typical jacket structure failure will also include other environmental loads (e.g. earthquake loading) and accidental loads (e.g. boat collisions, fires, explosions). However in this study only wave, wind and current loading is evaluated, with or without prior damage to member or joint.

The probability of failure for the structural system can then be written as:

$$P_{f\_system} = P(sys|\overline{F}) \cdot P(\overline{F}) + P(sys|F) \cdot P(F) \quad (8)$$

where:

- P(sys) represent probability of system failure
- F represent failure in arbitrary member or node

Equation 8 may be written as:

$$P_{f\_system} = P(sys|\overline{F}) \cdot P(\overline{F}) + \sum_i \sum_j P(sys|F_{i,j}) \cdot P(F_{i,j}) + \sum_i \sum_j \sum_k P(sys|F_{i,j}, F_{k,j}) \cdot P(F_{i,j}, F_{k,j}) + \ldots \quad (9)$$

where:

- $F_{i,j}$ denotes failure in member or node i due to failure cause j.
- $F_{k,j}$ denotes failure in member or node k due to failure cause j.

Here it is assumed that the probability of system failure given a failure in a member or node is the same for all members and nodes. In this case the probability of system failure can be simplified to:

$$P_{f\_system} = P(sys|\overline{F}) \cdot P(\overline{F}) + P(sys|F_1) \cdot P(F_1) + P(sys|F_1, F_2) \cdot P(F_1, F_2) + \ldots \quad (10)$$

where:

- F_1 represent the first occurring failure in an arbitrary member or node.
- F_2 represent the second occurring failure in an arbitrary member or node.

The probability of failure due to fatigue and corrosion can be modelled with an established model for degradation in probabilistic analysis. The probability of a gross error can to some extent be modelled according to historic occurrence of gross errors found in inspections. In this study the reason for the failure is not further evaluated, and for simplicity the probability of a failure in any member or joint is increased from 0.001 to 0.1 to evaluate the effect.

Also the effect of a member or joint failure on the system strength is modelled rather crudely, by reducing the system strength to a stochastic value randomly by a uniform distribution selected between 0.3 and 0.7. The reduction in system strength when a brace in a X-jacket is damaged, will often be in the order of 0.8. For K and other jacket types the reduction will be larger. If the damaged member is a leg, the capacity will be reduced significantly, in many cases down to 0.0. The range between 0.3 to 0.7 is selected to represent these possible failures.

Only the first two terms in equation 10 is included in the calculations (two or more simultaneous failures is not evaluated).

Wave Height

The maximum wave height in one year, H, is assumed to follow a Gumbel distribution, i.e. the distribution function reads:

$$F_H(h) = \exp\left\{ -\exp\left[-\frac{h - a_H}{b_h} \right] \right\} \quad (11)$$

where α_H and β_H are parameters of the distribution.

Wave load

The wave loading is approximated by the following equation:

$$W = a_1 \cdot C_1 \cdot H^{C_3} \quad (12)$$

where α_1 is a factor introduced to account for the model uncertainty in the load model, H is the wave height, C_1 and C_3 are load coefficients that must be curve-fitted to calculated load data for the specific jacket.

In the cases when wave in deck loads are included, the following load model is used:

$$W = a_1 \cdot C_1 \cdot H^{C_3} + a_2 \cdot C_4 \cdot (r \cdot H - AG) \quad (13)$$

where α_2 is a factor introduced to account for the model uncertainty in the load model, ρ is the wave crest to wave height factor, C_4 is a load coefficients that must be curve-fitted to calculated load data for the specific jacket, and AG is the air gap, here defined as the distance between the highest still water level (taking into account astronomical tide and storm surge) and bottom of steel on topside.

Resistance

The resistance is modelled as an ultimate capacity of the structure, described on a system basis. The expected value of the ultimate capacity is assumed to be equal to the 100 year loading ($C_1 \cdot H_{100}^{2.2}$), the loading with the annual probability of exceedance of 10^{-2}. This is multiplied by the Reserve Strength Ratio (RSR), the ratio between ultimate collapse load of the structure and the design load (the load with the annual probability of exceedance of 10^{-2}), and β?s a factor counting for model uncertainty in the resistance model.

$$R = b \cdot RSR \cdot C_1 \cdot H_{100}^{C_3} \quad (14)$$

Limit state equation

A failure function for ultimate collapse of the structure can be modelled by the following equation:

$$g = R - W \quad (15)$$

Probability of failure is given by $P_f = P(g \le 0)$.

Stochastic model

The parameters of the stochastic model are given in Table 1.

Table 1: Parameters used in the simulations – base case (choices commented below)

Parameter	Description	Values	Comments
RSR	Reserve strength ratio	Fixed at 2.0	The RSR is assumed to be 2.0 for the structure evaluated in this paper, but the failure probability is also evaluated for RSR values of 1.5 and 2.5 to evaluate the sensitivity to the RSR.
β	Resistance model uncertainty	Normal distributed mean value = 1.0 Standard deviation = 0.1	β is in the base case normal distributed with a mean value of 1.0 and a COV of 0.1 as recommended by Efthymiou et al (1996). The "Guideline for Offshore Structural Reliability Analysis" issued by DNV (1996) recommends a COV for the base shear capacity of a jacket structure to be 0.05 - 0.10. Based on this recommendation, a COV=0.05 is also evaluated.
H_{100}	100 year wave	Fixed at 28.6 m	Wave height with a annual probability of exceedance of 10^{-2}
α, α_1	Load model uncertainty	Normal distributed: mean value = 1.0 Standard deviation = 0.15	α is in the base case normal distributed with a mean value of 1.0 and a COV of 0.15 as recommended by Haver (1995). The base case with COV=0.15 on load model uncertainty, and the Weibull distribution on wave height, gives a total COV on the wave loading on 0.26. The "Guideline for Offshore Structural Reliability Analysis" issued by DNV (1996) recommends a COV on the wave loading of 0.4, which indicates a much higher COV of α than recommended by Haver (1995). Efthymiou et al (1996) recommends a COV not greater than 8%. In order to evaluate a certain range of the different recommendations in the COV of wave loading, the COV of α is varied in the range of 0.05 to 0.25 (giving a variation in COV on wave loading of 0.21 to 0.33). The sensitivity to the variation in COV in the load model is further evaluated.
α_2	Load model uncertainty – wave in deck loading	Normal distributed: mean value = 1.0 Standard deviation = 0.15	Assumed equal to α_1. A reasonable assumption is that the uncertainty for this type of loading will be more than wave on jacket loading, but due to a lack of data the same distribution is used.
H	Annual maximum wave height	According to Eq. 2. with: α_H = 21m β_H = 1.63m	The parameters for wave height distribution are obtained by fitting a Gumbel distribution to the data for the Kvitebjørn field in Northern North Sea (Statoil 2000).
C1	Load coefficient	Fixed at 1.0	The value used for C_1 is not important for the present study, as C_1 appears in both terms in the equation (resistance and load). A more realistic value for C_1 is in the order of 0.01 to 0.05 depending on the size of the jacket and the water depth.
C3	Load coefficient	Fixed at 2.2	For many Northern North-Sea jackets C_3 is found to be approximately 2.2, which is used in this paper.
C4	Wave in deck load coefficient	Fixed at 720	The ratio between C4 and C1 is used in the calculations. This ratio is estimated by the momentum of the incoming wave for a 100m wide deck structure (solid) and related to the C1 factor.
ρ	Wave crest factor	Fixed at 0.62	

Description of the cases

The base case is as described in Table 1 where wave in deck loading is not included and the probability of member failure is equal to zero. This case should be consistent with the case described in Kübler and Faber (2002). However, the limit state function is defined differently, so a small difference in the results can be found. The remaining cases evaluated in this study are presented in Table 2.

Table 2: Cases studied

Case	Epistemic uncertainty	Probability of member failure	Air Gap
1	Included as described in Table 1	0.0	Infinite
2	α = 1.13, β = 1.0	0.0	Infinite
3	Included as described in Table 1	0.001	Infinite
4	-“-	0.01	Infinite
5	-“-	0.0	22m
6	-“-	0.0	20m
7	-“-	0.0	18m
8	-“-	0.001	22m
9	-“-	0.001	20m

Epistemic uncertainties are removed in case 2. It is assumed that the wave load distribution is well known. In order to fit the load distribution to the same distribution without the uncertainty parameter, a bias of 1.13 is included resulting in a close fit between the assumed measured wave load distribution and the wave load distribution obtained by the stochastic description. Hence, the α is fixed to 1.13 and β is fixed to 1.0.

Figure 2 indicates that when excluding the epistemic uncertainty, the probability of failure is slightly reduced, as one would expect. The difference is increasing with increasing RSR values. In the normal area for RSR values (up to 2.5) the difference is negligible. Further, it can be seen an increasing failure probability as the probability of a possible member failure is increased. In estimation of the probability of system failure, this indicates that including possible member failure will be of importance, even for small probabilities of a possible member failure. Also, Figure 2 clearly indicates that the probability of failure increases as the air gap is reduced. A rather extreme underestimation of the probability of failure could be the result of not taking into account wave in deck forces for large values of RSR, based on the present model.

Economical data

Cost of field development, installation and substructure

Data from 4 recent jacket projects in Norway is collected from Esso (1999), Hydro (1999), Statoil (1997) and (1999). The collected data consists of the cost of field development, the construction cost for the installations and the substructures. The data is presented in Table 3. All economic data is extracted from the “Plan for Development and Operation”. These data may not be the final numbers, but should be the best guess of the final numbers early in the design phase.

Air gap is discussed in this paper, and increasing air gap may be constrained by risers and lifting barges. An air gap increase beyond a certain limit, not defined in this paper, may result in a sudden jump in costs. These types of costs are not evaluated in this paper, and the numbers given in Table 3 can not be regarded as representative for this situation.

Table 3: Economical numbers extracted for recent jacket projects (MNOK)

	Topside	Jacket	Drilling	Subsea	HC Transport	Field Development Cost: C_{FD} or CAPEX
Kvitebjørn	4168	995	997	0	1424	7584
Grane	7745	1575	3045	0	2685	15050
Ringhorne	3039	586	3280	437.5	812.5	8155
Huldra	1086	488	1097	9	1367	4047
Mean value						8709

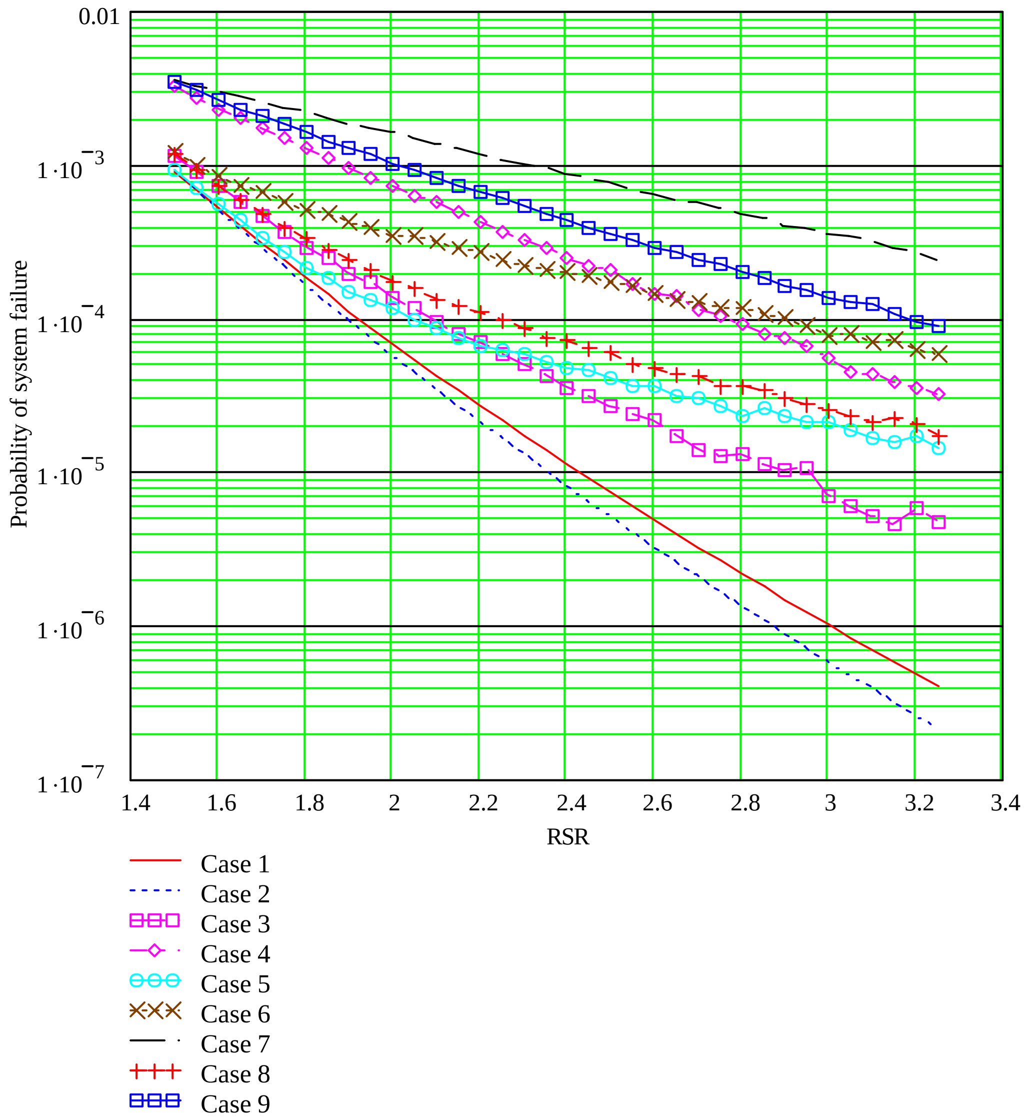

Figure 2: Comparison between probability of failure for the different cases

In order to obtain the normalised coefficients the construction costs is related to field development cost and substructure cost to construction cost. The resulting coefficients are shown in **Error! Not a valid bookmark self-reference.**.

Table 4: Relative economical numbers for recent jacket projects

	$\rho_{CC} = C_{CC} / C_{FD}$	$\rho_{SS} = C_{SS} / C_{CC}$	C_{SS}/C_{FD}
Kvitebjørn	0.680775	0.192717	0.131197
Grane	0.619269	0.168991	0.104651
Ringhorne	0.444513	0.161655	0.071858
Huldra	0.38893	0.310038	0.120583

Income

From the same data, the net present value (NPV) of income (sales minus operational cost) seems to be estimated to around 1.5 to 2 times the total investments in the field development (CAPEX). These estimates are based on a rather pessimistic oil price, and it is likely that these are meant as conservative decision support estimate. The real income is in most cases expected to be higher. In this study a mean value for ρ_I (C_I/C_{FD}) is assumed to be 3.0, and a variation between 1 and 5 is studied.

The income function of an offshore facility can be subdivided into three phases, namely the *build-up*, the *plateau* and the *decline* phases. In the *build-up* phase, the producers are installed and set on stream. During the *plateau phase*, the production is limited by the processing or transport capacity, and the maximal annual income is obtained, from which the processing and transport costs have to be subtracted.

The *decline phase* succeeds the plateau phase and during this phase, the oil and/or gas production decreases exponentially, which is described by the decline factor d_{dec}. For water injected processing, this factor lies in the range from 0.03 to 0.22 and depends on several reservoir and production specific parameters (Almlund 1991). For this example, the decline factor was assumed to be $d_{dec} = 0.22$ and the time t_{op}, i.e. the beginning of the declining phase was set to $t_{op} = 6$ years. The *decline phase* ends with the decommissioning of the structure. This point in time is assumed to be $T = 25$ years.

<u>*Consequences due to fatalities*</u>

In order to account for possible fatalities, Nathwani et al. (1997) established the Life Quality Index (LQI). From this index, Skjong and Ronold (1998) derived the amount of money, which optimally should be invested to avert a fatality *ICAF*. According to Rackwitz (2001), the societal loss due to losses of lives, can and should be taken into account in the design decision problem by including its cost equivalent C_{FF}, i.e. the expected number of fatalities NF multiplied with the ICAF.

The ICAF value is estimated to 20 MNOK (Skjong and Ronold 2001). For the present study the implied cost of avoiding a fatality as a ratio of the field development costs are used. For the four jacket structures used in this example, this ratio is presented in Table 5.

Table 5: Relative economical numbers for recent jacket projects

	ρ_{ICAF} = ICAF / C_D
Kvitebjørn	0.002637
Grane	0.001329
Ringhorne	0.002452
Huldra	0.004942

<u>*Cost of material losses of a failure*</u>

The material cost of failure consists of (Fyhn Nilsen 2002):

- Environmental losses
- Removal of wreck
- Production loss as a result of downtime after the incident
- Loss of reputation
- Liability expenses
- Long term effects

The cost of environmental losses will be dependent on the amount of environmental spill and the medium (oil or gas) that is produced at the actual installation. For the installation mentioned in this paper, both gas production and oil production is relevant, and cost of the environmental losses will be significantly different. Actual numbers are available from shipping accident (Exxon Valdez, Braer), and can to some extent be relevant. According to Fyhn-Nilsen (2002) the environmental related costs of the Exxon Valdez accident has been estimated to 30000MNOK, and for Braer and Sea Empress in the order of 2000MNOK. The Exxon Valdez case may be viewed as an extreme case and not fully representative for an accident on the Norwegian continental shelf. As a result an estimate of 1000MNOK is used in this evaluation.

The removal of the wreck can be estimated based on the costs for removing installations, and a cost between 1000MNOK and 2000MNOK may be a relevant estimate.

Income from production for a Norwegian field can be as high as 50MNOK per day. The downtime will be dependent on the availability of facilities that can be used as replacements. In some cases building of new facilities may be necessary. In cases where a replacement facility can be used, downtime can be estimated to 50 – 100 days. In cases where a new build is necessary, a downtime of more than a year seems appropriate. At an average it is assumed that production can be restarted after 200 days, and the cost of production loss can be estimated to 10000MNOK.

The cost of lost reputation is difficult to assess. This will be different for a small, unknown operator and a worldwide energy consortium. The marked value of Exxon was reduced by approximately 24000MNOK as a result of the Exxon Valdez incident (Fyhn Nilsen 2001). A total collapse of a jacket structure may not result in the same amount of environmental spill, and it could be argued that a reduced number is relevant. However, the possible loss of lives would to some extent could have the same effect on marked value. As the uncertainty around this is rather large, it is here assumed that a loss of 10% of the marked value of a medium to small-scale company may be relevant, resulting in an estimate of 10000MNOK.

As a simplification, liability expenses (damage to third party property and personnel) and long-term effects (consequences that emerge after normalisation that would not be there without the accident) are not evaluated any further. Refer to Fyhn Nilsen (2001) for further description of possible models to include these expenses.

Total material cost as a result of an accident then adds up to be in the order of 22500MNOK, resulting in a factor ($\rho_{FM}=C_{FM}/C_{FD}$) of 2.6 times the field development costs.

In Pinna et al. (2001), the ratio of failure costs to construction costs for a Monopod are indicated to lie in the range of 3 to 7. Pinna et al (2201) further indicates that with the condition of a short reconstruction period, a ratio of 10 is indicated to be appropriate. In case of extraordinary severe failure consequences, including both complete failure and clean up costs, the ratio is indicated to be as high as 20. Relative to the field development cost, the ratio between failure costs and field development cost is indicated to be as high as $\rho_{FM}=10$ as a maximum value.

In this study an expected value of 2.6 times the field development cost is assumed, and a range from 0.2 to 5 times the field development cost is studied.

<u>*Cost of strengthening*</u>

The cost of construction of the substructure is assumed to be dependent of the strength of the structure. If the structure is built with an average strength (assumed to be represented with $RSR_0=2.0$) the cost is assumed to be C_{SS_FIX}. If the RSR of the structure is chosen different from the average, the cost is assumed to be linearly varying according to the following formula:

$$C_{SS} = C_{SS\_Fix} \cdot (1 + r_{St} \cdot (RSR - RSR_0)) \tag{16}$$

The factor $?_{St}$ is representing the ratio of increase in cost to increase the RSR.

$$C_{SS\_Fix} = r_{SS} \cdot C_{CC} = r_{SS} \cdot r_{CC} \cdot C_D \tag{17}$$

For a well-balanced structure (a structure where all members are optimized, i.e. increasing the global strength will result in increasing the strength of each individual member and joint), the whole structure has to be strengthened in order to improve the RSR. However, for most jacket structures, other load situations (transport with barge to field, lifting or launching, fatigue, earthquake, etc) will also be critical and dimensioning for parts of the structure.

Table 6: Weight distribution in a jacket

	Portion of weight
Frame braces	0.16
Legs	0.20
Plane braces	0.10
Leg nodes	0.19

Plane nodes	0.06
Mudmat, pile sleves etc.	0.29

To increase the RSR the frame braces will have to be strengthened and the legs to some extent. This part of the structure represent between 25 – 50% of the total weight, as indicated in Table 6. To increase the RSR with 50% (from 2 to 3), assuming a linear increase in weight in order to increase the strength, a weight increase of 12.5 to 25 % is needed based on this assumption. Due to buckling being critical for some members, the relationship will not be fully linear, and some additional weight increase should be expected. As a result a 25% increase is assumed ($?_{St}$ = 0.25), and a variation from 10% to 50% is studied.

Summary of economical coefficients used in the study and their range

The economical optimal analysis is based on the expected values for the coefficients as presented in Table 7. As the chosen values for the study will not apply for all structures, the variables are also studied over a range as indicated in the last column.

Table 7: Chosen value for coefficients and the range of the coefficients

Coefficient	Chosen value	Range studied
ρ_{CC}	0.5	(0.4 – 0.7)
ρ_{SS}	0.2	(0.15 – 0.3)
ρ_{ICAF}	0.003	(0.001 – 0.005)
ρ_{I}	3	(1 – 5)
$?_{St}$	0.25	(0.1 – 0.5)
ρ_{FM}	2.6	(0.5 – 5)
NF (number of fatalities)	50	(1 – 100)
T (Lifetime of field)	25	
r (interest rate)	0.07	
RSR_0	2.0	

Numerical investigations / Case study

Based on the presented framework for decision theory and the economical data presented for 4 recent Norwegian jacket field developments, the cases presented earlier in this paper is valuated and the optimal RSR is calculated for each case.

Sensitivity to the economical parameters used

With reference to Table 7, the coefficients with a range is studied with the influence on the optimal RSR. For all these factors the range divided by the expected value is plotted in Figure 3.

The consequence of loss of lives (NF=50), and the ratio between income and field development cost is very small. The influence of cost of loss of lives will be increased if the ratio of ICAF and field development cost is larger. It should however be mentioned that the income factor ρ_I has a significant impact on the optimal time of possible reconstruction t_0.

The material cost of failure and the factors indicating the portion of cost that is needed to strengthen the structure is clearly significant.

A so called F-N diagram can based on the calculations be established as shown in Figure 4. The effect of the number of persons on the installation is negligible with the relevant values of the ratio of ICAF to field development costs (ρ_{ICAF}). However, if the ICAF values are closer to the field development cost, the cost of avoiding a statistical fatality makes significant impact on the optimal RSR, as shown in Figure 4. This will not be relevant for offshore structures, but may be more relevant for an onshore structure.

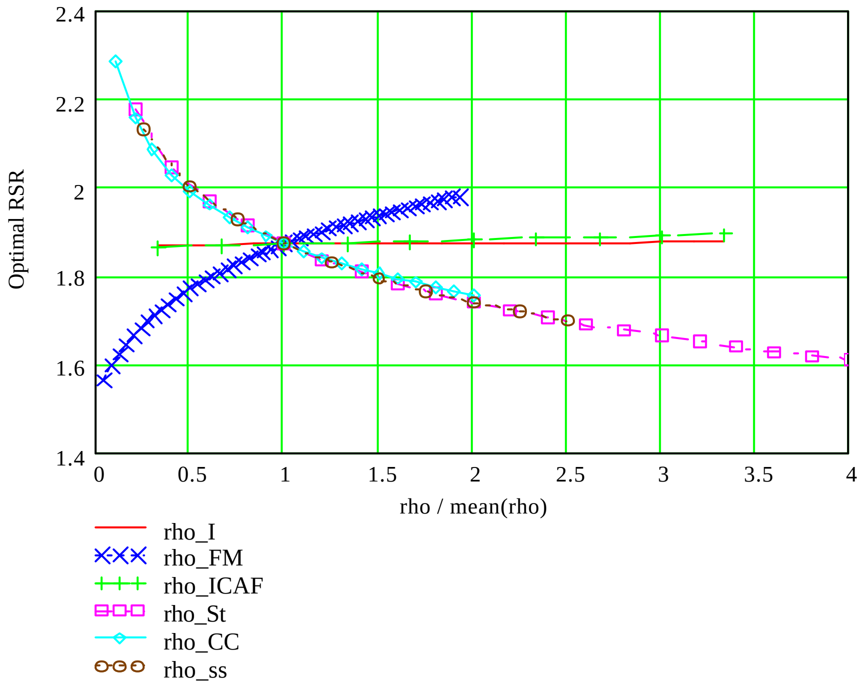

Figure 3: Sensitivity to the economical parameters for the optimal RSR

This indicates that avoiding fatalities does not influence the optimal safety for an offshore jacket structure using this method of estimating the optimal safety. This is due to the small portion of cost that the implicit cost of avoiding a fatality compared to the field development cost (here represented by ρ_{ICAF}).

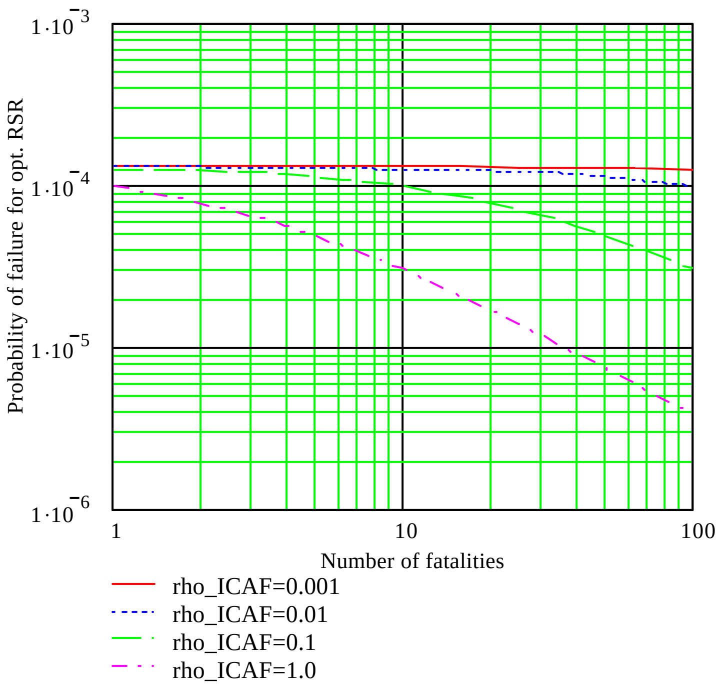

Figure 4: Calculated probability of failure for the optimal RSR with large ICAF values

Sensitivity to epistemic uncertainty

When removing the epistemic uncertainty, the probability of failure is slightly reduced (ref Figure 2). However, this does not change the optimal RSR significantly, as the expected benefits are mainly parallel adjusted as shown in Figure 5. Both based on Figure 2 and Figure 5 it seems reasonable to conclude that a relatively large change in the epistemic uncertainty does not result in significant change in the resulting probability of system failure or the final decision.

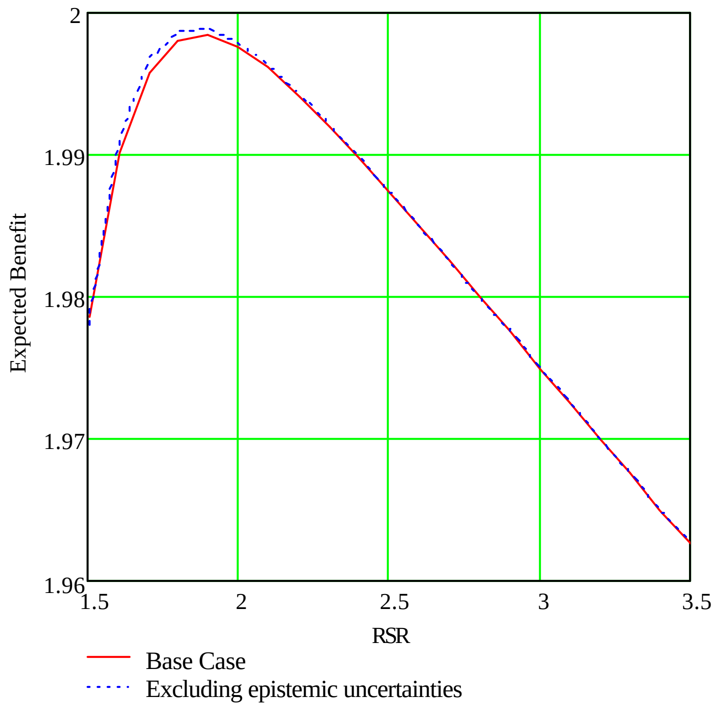

Figure 5: Expected benefit for Case 1 and Case 2

Sensitivity to possible member failures

When a possible member failure is introduced, the effect of shifting for the maxima of the expected benefit is more significant. This results in an increasing optimal RSR with increasing probability of member failure, as shown in Figure 6.

The model for the effect of member failure in this study is to crude to draw general conclusions. However, the results clearly show an increasing trend when the probability of a possible member or node failure increases. Figure 6 indicates that this should be addressed when estimating an optimal RSR, at least in cases where the probability of any member or node failure exceeds $1 \cdot 10^{-3}$, which is a likely number for many jacket structures on the Norwegian continental shelf.

Sensitivity to wave in deck loading

Also the possibility of wave in deck loading when reducing the deck height influences the optimal point of the expected benefit, as shown in Figure 7. However, the shift in the expected benefit is moderate for air gap of 22 m and 20 m.

The figure clearly shows that the air gap and possible wave in deck loading should be included in the estimation of optimal RSR, at least when the air gap reduces to a certain level compared to the wave with probability of exceedance of 10^{-2}. In this case, and indicator for when to take wave in deck loading into account is about when the 10-4 wave crest elevation reaches the deck of the structure.

Alternatively the optimal air gap could be estimated in a parallel optimisation.

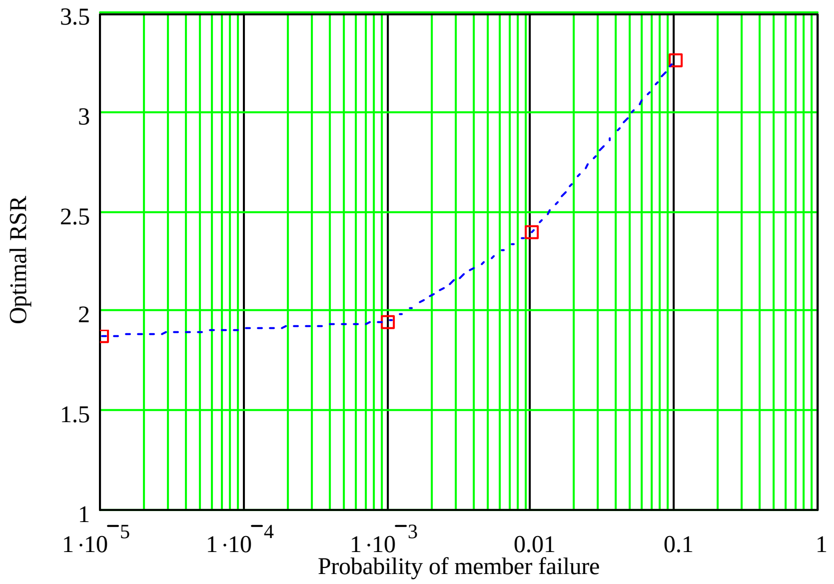

Figure 6: Optimal RSR with increasing probability of member failure

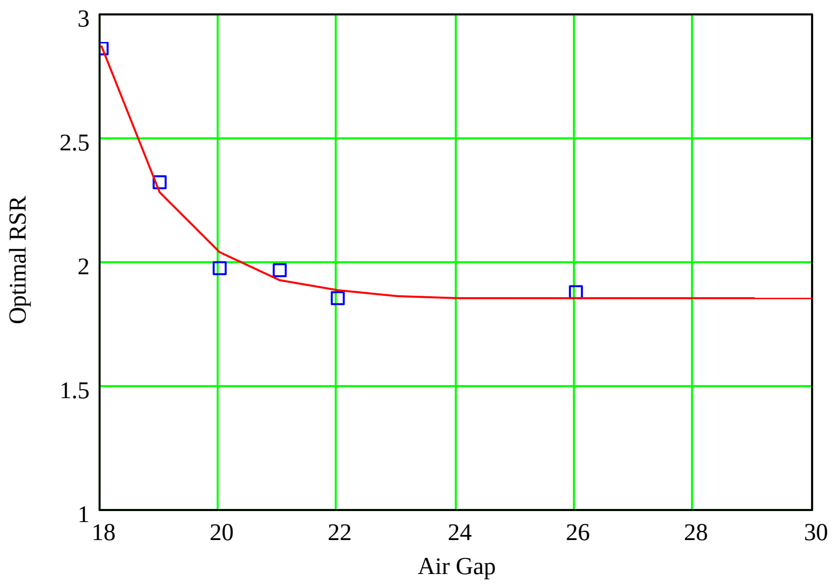

Figure 7: Optimal RSR with increasing air gap (calculated points and curve fit)

Discussion

Common design practise are in general deterministic with fixed requirements to the strength of the structure, or in some cases probabilistic with fixed acceptance criteria. The implicit requirement in such deterministic regulations indicates that RSR values should be 2.0 and higher depending on the ratio of permanent and live loads to the environmental loads (Ersdal 2004). Permanent loads and live loads are not included in this study, so the comparable RSR value will be 2.0. Based in the calculated optimal RSR, values as low as 1.6 are indicated. With acceptance criteria in the area 10^{-4} to 10^{-5}, the results of reliability analysis in this paper would indicate a requirement to the RSR also around 2.0.

The economically optimal RSR values will in some cases be similar to the requirements of the regulations and standards, but in many cases the economical optimal RSR will be lower than 2.0. The result of an economical optimisation is then a reduction of the safety of the investment, but also for human safety.

A reasonable requirement for human rights (Shrader-Frechette, 1991) states: If all members of the society have an equal, prima facie right to life, and therefore to bodily security, as the most basic of human rights, then allowing one group of persons to be put at greater risk, without compensation and for no good reason, amounts to violating their rights to life and bodily security.

Even if the workers at offshore installations are compensated for the increased risk, there is still the question of the safety reduction is for a good reason. The additional safety needed to obtain the accepted safety level will in many cases be cheap, and there will be no good reason for not including this extra investment. In practise it will be difficult to compensate the workers differently for the risk they may encounter at different installations during their work.

The method applied in this paper with cost consequences of fatalities implies that a fixed amount of monetary value to avoid a statistical fatality is in conflict with the belief that an equal safety level (with improvement over time) should be the goal for risk related activities. There is also an ethical conflict when the total value of human life is measured in monetary terms, even if it in the case of ICAF is rewritten as the cost of saving a life. An ethical discussion is needed prior to accepting that the methods addressed in this paper can be used alone to define a safety level. The need for such a discussion is reinforced by the observation that the resulting optimal RSR values are more or less independent on the number of fatalities, with the present cost of field development.

From the national regulating body's perspective, the cost of failure may also depend on the cost of the rescue operation and the possibility of future loss in income due to a reduced willingness to continue this type of activities after an accident.

Conclusions

The Cost Benefit Analysis (CBA) method used for estimating the optimal RSR in this paper will in some cases contradict with the national safety regulations in some countries, e.g. Norway, when applied to the safety of human life.

Consequence of optimisation:

- The safety level is decreased compared to deterministic regulations and standards.
- Low emphasis on safety of human life with the present field development costs.
- Unequal safety on various installations driven by the material cost of failure leads to dissimilar risk to personnel.

The optimal RSR is highly sensitive to the possibility of member failures and a reduced air gap. However, more detailed analysis and models should be investigated in order to make general conclusions on the effect of possible member failure and the effect on optimal RSR. The air gap problem can be solved by utilising a combined optimisation of both RSR and air gap.

The optimal RSR is slightly sensitive to the inclusion of epistemic uncertainties, but this is small compared to the uncertainty with regards to the cost of failure.

Material cost of failure and portion of cost that goes to construction cost for the substructure and strengthening are the most important factors for the evaluation of optimised RSR.

With the cost of field development as indicated for the fields evaluated here and the ICAF values as described as relevant, the loss of lives has very little impact on the optimal RSR.

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