2

Risk Picture – Definitions and Characteristics

This chapter defines risk quantitatively and presents the dimensions and elements of risk. The chapter further gives an extensive illustration of how risk is expressed. Further discussion about interpretation of risk may be found in Aven and Vinnem (2007) and Aven (2003).

2.1 Definition of Risk

2.1.1 Basic Expressions of Risk

The term 'risk' is according to international standards (such as ISO 2002) 'combination of the probability or an event and its consequence'. Other standards, like ISO 13702 (ISO 1999b), have a similar definition: 'A term which combines the chance that a specified hazardous event will occur and the severity of the consequences of the event.'

Risk may be expressed in several ways, by distributions, expected values, single probabilities of specific consequences, *etc.* Most commonly used is probably the expected value.

An operational expression for practical calculation of risk is the following, which underlines how risk is calculated, by multiplying probability and numerical value of the consequence for each accident sequence i, and summed over all (I) potential accident sequences:

$$R = \sum_i (p_i \cdot C_i) \qquad (2.1)$$

where:

p = probability of accidents
C = consequence of accidents

This formula expresses risk as an expected consequence. The expression may also be replaced by an integral, if the consequences can be expressed by means of a continuous variable.

It should be noted that the expression of risk as expected consequence is a statistical expression, which often implies that the value in practice may never be observed. When dealing with rare accidents, an average value will have to be established over a long period, with low annual values. If during 40 years we have five major accidents with a total of ten fatalities, this corresponds to an annual average of 0.25 fatalities per year, which obviously can never be observed.

The definition in Equation 2.1 is sometimes called ‘statistical risk’ or technological risk. Some authors have referred to this expression as ‘real risk’ or ‘objective risk’. These two last terms give misleading impression of interpretation of risk. ‘Risk’ is always reflecting interpretations and simplifications made by, for instance the analyst, and as such to some extent subjective. It is therefore misleading to give the impression that some expressions are more objective than others.

‘Risk aversion’ is sometimes included in the calculation of risk, see for instance Equation 2.9. Risk will be a combination of the probability of an accident, the severity of the consequence, and the aversion associated with the consequence. This is not supported by the author. It is acknowledged that risk aversion is an important aspect associated with the assessment of risk, in particular relating to the evaluation of risk results. However, risk aversion should not be mixed with technological risk analysis. Risk aversion is a complex phenomenon. It is misleading to give the impression that this complex process may be adequately captured by a single parameter, risk aversion, a.

Further details about risk definitions, risk aversion and ethical adjustment of the risk assessments are presented in Aven and Vinnem (2007).

2.1.2 Dimensions of Risk

When accident consequences are considered, these may be related to personnel, to the environment, and to assets and production capacity. These are sometimes called ‘dimensions of risk’, which are those shown in the list below. Some subcategories are also presented in the following:

- Personnel risk
    - fatality risk (see Section 2.1.3 for definition)
    - impairment risk (see Section 2.1.4 for definition)
- Environmental risk (see Section 2.1.5 for definition)
- Asset risk (see Section 2.1.6 for definitions)
    - material damage risk
    - production delay risk.

It might be considered that fatality risk is a subset of injury risk, and that the latter is the general category. Fatality risk and injury risk are nevertheless quantified in so different ways that it may seem counterproductive to consider these two aspects as one category.

It should be noted that risk to personnel is mainly focused on fatality risk, or aspects that are vital for minimisation of fatality risk. This reflects the focus of the QRA on major accidents, as opposed to occupational accidents as noted in the introduction. This focus may, on the other hand, underscore the fact that occupational accidents are a major contribution to fatality risk. In Norwegian operations for instance, all fatalities on installations during the last 20 years have been due to occupational accidents.

There is no universal definition of the term 'major accident'. One often used interpretation is that 'major accidents' are accidents which have the potential to cause five fatalities or more.

Somebody may react to the classification of 'impairment risk' as a sub-category of 'personnel risk'. Impairment risk is discussed in greater depth in Section 2.1.4. At this point it is sufficient to note that although the impairment mechanisms are related physical arrangements (such as escape ways), it is indirectly an expression of risk to personnel.

2.1.3 Fatality Risk

Fatality risk assessment uses a number of expressions, such as; platform fatality risk, individual risk, group risk and f–N curve. It should be noted that some of these expressions are calculated in a particular way in the case of offshore installations. The offshore way of expressing risk is the main option chosen, but differences are indicated.

2.1.3.1 Platform Fatality Risk

The calculation of fatality risk starts with calculating the Potential Loss of Life, PLL. Sometimes, this is also called Fatalities Per Platform Year, FPPY. PLL or FPPY may be considered as the fatality risk for the entire installation, if it is calculated for the entire installation. There are two ways to express PLL:

- Accident statistics, PLL = No of fatalities experience in a period (usually per year).
- Fatality risk assessment (through QRA), whereby PLL is calculated according to Equation 2.2 below.

From the PLL, either Individual Risk (IR) or Group Risk (GR) may be computed. The PLL value can, based on a QRA, be expressed as follows:

$$PLL = \sum_{n} \sum_{j} (f_{nj} \cdot c_{nj}) \tag{2.2}$$

where:

f_{nj} = annual frequency of accident scenario (event tree terminal event) *n* with personnel consequence *j*

c_{nj} = expected number of fatalities for accident scenario (event tree terminal event) *n* with personnel consequence *j*

$N =$ total number of accident scenarios (event tree terminal event) in all event trees

$J =$ total of personnel consequence types, usually immediate, escape, evacuation and rescue fatalities.

The types of personnel consequences which are relevant for analysis of fatality risk may be illustrated as follows:

- Immediate fatalities — which occur in the immediate vicinity of the initial accident, or immediately in time.
- Escape fatalities — which occur during escape from the place of work prior to or immediately after the initial accident back to a shelter area (temporary refuge).
- Evacuation and rescue fatalities — which occur during evacuation from the installation or during rescue from sea and/or evacuation means.

A comment on the use of the expression 'escape fatalities' may be appropriate. Sometimes (for instance in regulations) 'escape' is used as the process of leaving the installation when orderly evacuation is not possible. 'Evacuation' may on the other hand sometimes be used as the expression for the entire process of leaving the workplace until a place of safety is reached. None of these alternative definitions are used in this book, which uses the interpretation stated above.

The annual frequency of an accidental scenario, f_{nj}, may be expressed as follows, if it is assumed that the factors are related (dependent) as shown below:

$$f_{nj} = f_{leak,n} \cdot p_{ign,n} \cdot p_{protfail,n} \cdot p_{escal,n} \cdot n_{nj} \qquad (2.3)$$

where

$f_{leak,n} =$ frequency of leak

$p_{ign,n} =$ conditional probability of ignition, given the leak

$p_{protfail,n} =$ conditional probability of failure of the safety protective systems, such as ESD, blowdown, deluge, passive fire protection, *etc.,* given that ignition has occurred

$p_{escal,n} =$ conditional probability of escalation, given ignited leak and failure protective systems responses

$n_{nj} =$ fatality contribution of the accident scenario (fraction of scenarios that result in fatalities).

Equation 2.3 reflects the failure of the five main barrier functions: containment, ignition prevention, protection, escalation and fatality prevention; see further discussion in Subsection 2.5.2.

2.1.3.2 Individual Risk

There are principally two options with respect to the expression individual risk, namely:

- FAR (Fatal Accident Rate), or
- AIR (Average Individual Risk).

AIR is also known by other acronyms, such as IR (Individual Risk) or IRPA (Individual Risk Per Annum). The following sections will use AIR.

The FAR value is the number of fatalities in a group per 100 million exposed hours, whereas the AIR value is the average number of fatalities per exposed individual. The following are the equations which define how the individual risk expressions are computed:

$$FAR = \frac{PLL \cdot 10^8}{Exposed\ hours} = \frac{PLL \cdot 10^8}{POB_{av} \cdot 8760} \tag{2.4}$$

$$AIR = \frac{PLL}{Exposed\ individuals} = \frac{PLL}{POB_{av} \cdot \frac{8760}{H}} \tag{2.5}$$

where:

POB_{av} = average annual number of manning level

H = annual number of offshore hours per individual (on-duty and off-duty hours).

It should be noted that 8760 is the number of hours in one year. The ratio of 8760/H is therefore the number of individuals required to fill one position offshore. Three persons per position is quite common in Norwegian offshore operations, whereby H is 2920 hours per year, 1460 on-duty hours and 1460 off-duty hours. If the schedule is two weeks 'on' [the installation]; four weeks 'off', three persons per position is required, and an average of 8.7 periods are spent offshore each year.

From the definitions above it is obvious that AIR and FAR values are closely correlated. The following is the relationship:

$$AIR = H \cdot FAR \cdot 10^{-8} \tag{2.6}$$

If H is 2920 hours and FAR is 5.0, then AIR equals 0.00015. Thus, it is without consequence whether FAR or AIR is calculated. One may be derived from the other, as long as the shift plan is known.

Onshore, H would not be summed over on-duty and off-duty hours, because off-duty hours are not spent in the plant.

FAR and AIR values may be calculated as average values for different groups, for instance the entire crew on an installation, or groups that are associated with specific areas on the installation.

When ‘exposed hours’ are considered in relation to the definition of the FAR values for offshore operations, this expression may be interpreted in at least two ways:

- On-duty hours (or working hours) are most typically used for occupational accidents, exposure to these are limited to the working hours.
- Total hours on the installation (on-duty plus off-duty hours) are most typically used for major accidents, exposure to these is constant, irrespective of whether a person is working or not, used in Equation 2.4
- When helicopter transportation risk is considered, the exposed hours are those spent in the helicopter.

If FAR values from different activities are to be added, then they must have the same basis. This is discussed thoroughly later.

It should be noted that at present, the total number of working hours offshore on the entire Norwegian Continental Shelf is just above 30 million hours per year. This implies that during a three year period, roughly 100 million hours are accumulated. In practical terms, we can therefore express that the observed FAR value during the last three years, is the number of fatalities during this period. This reflects occupational accidents only. For instance, only one fatality (on a crane vessel) occurred in the period 2003–2005, the average FAR value is around 1.0 for this period. In the previous period, 2000–2002, the corresponding value was five fatalities.

2.1.3.3 Example: Calculation of FAR Values

For an offshore installation, the following are the main characteristics that are used in order to form the example shown in Table 2.1.

- The average number of persons on the platform is 220.
- Each person has an annual number of 3000 exposure hours offshore.
- Elements of risk are shown in Table 2.1.

Table 2.1. Example, risk contributions

Location/accident type	Average manning	Fatalities per accident				
		1	2–5	6–20	21–100	101–220
Quarters						
Occupational accidents	140	0.010	0			
Fatalities, evacuation	140	0.001	0			
Process/utility equipment						
Occupational accidents	80	0.012	0			
Immediate fatalities	80	0.010	0			
Fatalities, evacuation	80	0	0	0.01	0.003	0.0008
Total						
Occupational accidents	220	0.022	0			
Immediate fatalities	220	0.010	0			
Fatalities, evacuation	220	0.001	0	0.01	0.003	0.0008
Sum all groups	220	0.033	0	0.01	0.003	0.0008

Table 2.1 presents frequencies of fatality consequences for five groups of fatalities. The last line sums up the different contributions from occupational accidents, immediate fatalities and evacuation fatalities, implying that fatalities during escape and rescue have been disregarded.

The summed results are used as the basis in order to calculate the PLL, FAR and AIR values for the installation, as shown in Table 2.2. The risk values for the installation are the following:

- PLL = 0.386 fatalities per year
- FAR = 20.0 fatalities per 10^8 manhours
- AIR = $0.6 \cdot 10^{-3}$ fatalities per year.

Table 2.2. Example, calculation of PLL, FAR, AIR

Risk values	**Average manning**	**Fatalities per accident**				
		1	**2–5**	**6–20**	**21–100**	**101–220**
Sum frequencies	220	0.033	0	0.01	0.003	0.0008
Geometrical mean consequence		1	3.2	10	44.7	148
PLL contribution		0.033	0	0.1	0.134	0.118
Total PLL	0.386					
FAR value	20.0					
AIR value	0.00058					

2.1.3.4 Group Risk

The most common measure of risk is risk to individuals. Experience has shown however, that society is concerned about the effects of accidents on society as a whole. Some measure of risk to society *i.e.,* the total effect of accidents on society (or the affected group), is therefore required. This is what Group Risk (GR) is used to express.

Acceptance criteria are usually expressed for individual risk levels. Sometimes it is necessary also to be able to express acceptability for the group risk. A relationship between individual risk and group risk is therefore sometimes necessary.

Group risk is often expressed in terms of an ‘f–N’ diagram, see example later in this chapter. The derivation below shows how the f–N diagram may be connected to individual risk measures in situations where there are a limited number of people exposed to the risk. The derivation is a generalization of an expression first described by Schofield (1993). The paper by Schofield includes consideration of risk aversion, which is reproduced in the following, although the use of risk aversion in not recommended in most risk calculations.

Let *POB* be the number of personnel on the installation at any one time (not assumed in this illustration to vary).

Let F_N denote the annual frequency with N or more fatalities.

Let f_N denote the annual frequency of exactly N fatalities.

Then it follows immediately:

$$f_N = F_N - F_{N+1}, N = 1,....., POB - 1 \tag{2.7}$$

$$f_N = F_N, N = POB \tag{2.8}$$

Consider F_N to have the form:

$$F_N = \frac{F_1}{N^b}, 1 \le b \le 1.3 \tag{2.9}$$

This equation is actually valid for all values of $b \geq 1.0$, but $b = 1.3$ is considered in relation to its interpretation to be an upper limit (Schofield, 1993). The factor b is usually called the 'aversion factor', which – as noted above takes account of the fact that it is usually harder for a society to accept an accident with 10 fatalities than 10 accidents with 1 fatality each, even though the frequency of the former is only one tenth of the latter *i.e.,* the expected value is the same. With $b = 1.3$, $F_{10} = F_1/20$, whereas $F_{10} = F_1/10$ with $b = 1.0$.

It is recommended that risk aversion is considered as a separate factor, then b should be set to 1.0. The general expression is that b may exceed 1.0, but we have advised against using an aversion factor in the calculation of risk. The derivation of equations below is therefore based on the value $b = 1.0$. From Equations 2.7, 2.8 and 2.9 it follows that:

$$f_N = F_1 \frac{1}{N(N+1)}, N = 1,......POB - 1 \tag{2.10}$$

$$f_N = \frac{F_1}{N}, N = POB \tag{2.11}$$

Let AIR now be the average individual risk for an average employee on the installation, expressed as the probability of death per annum. Let there be in total K groups of POB persons, where each individual spends H number of hours offshore per annum, such that:

$$H \cdot K = 8760 \tag{2.12}$$

Then, by combination, we have the following:

$$\frac{1}{K \cdot POB} \sum_{1}^{POB} N \cdot f_N = AIR \tag{2.13}$$

Combination of Equations 2.10, 2.11 and 2.13 gives the following:

$$F_1 = K \cdot POB \cdot AIR \cdot \left[1 + \sum_{1}^{POB-1} \frac{1}{N+1} \right]^{-1} \qquad (2.14)$$

By using **(2.14)** the F_N-plot can be determined for any given set of values *AIR, POB, K, b*. The frequency of fatalities in the range $N_1 \leq N \leq N_2$ is given by:

$$f(N_1, N_2) = \sum_{N_1}^{N_2} f_N = F_1 \sum_{N_1}^{N_2} \frac{1}{N+1}, \; N_2 < POB \qquad (2.15)$$

$$f(N_1, N_2) = F_1 \cdot \left[\frac{1}{POB} + \sum_{N_1}^{N_2} \frac{1}{N(N+1)} \right], \; N_2 = POB \qquad (2.16)$$

2.1.3.5 Example: f–N diagram Transformation

PLL, FAR and AIR values were calculated for the example installation referred to on Page 20. Using the equation for F_1 above, the F_N values may be calculated, and plotted in the diagram. Please note that f–N diagrams commonly use logarithmic scales for both axes. The f–N diagram expresses the frequency of accidents with N fatalities or more, and as such is always a cumulative frequency.

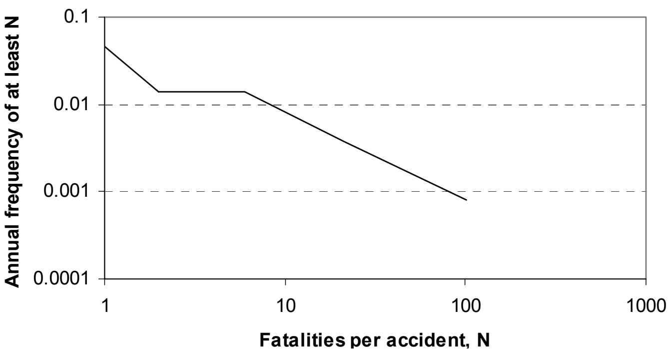


Figure 2.1. Example f–N diagram

2.1.4 Frequency of Impairment

Frequency of impairment is an indirect way to express risk aspects that are vital for the safety of personnel. The aspects for which the impairment frequencies are calculated are usually called ‘main safety functions’, or just ‘safety functions’. ‘Main safety functions’ are aspects that assist in ensuring the safety of personnel in the event of a major accidental event. When frequencies of impairment are calculated, these may be based on physical modelling of responses to accidental loading, and one will thereby avoid the problems of explicitly calculating the consequences of an accident in terms of fatalities.

The frequencies of impairment are usually calculated somewhat differently, reflecting differences in UK and Norwegian legislation, but cover essentially the same overall functions. The wording of the main safety functions is somewhat different in the two countries' legislation. Typically, the following are calculated:

- UK: Impairment of temporary refuge, including the following functions: (according to Safety Case Regulations)
    - Life support safety function
    - Command safety function
    - TR Egress safety function
    - Evacuation safety function
- Norway: Impairment of several safety functions (according to Facilities regulations):
    - Impairment of Shelter Area
    - Impairment of Escape ways
    - Impairment of emergency control function
    - Impairment of support structure
    - Impairment of escalation function

Thus, only one impairment frequency is required to be quantitatively determined under UK legislation, whereas typically five are calculated in Norway. The scope of what is covered is nevertheless virtually the same. The impairment frequency, $f_{imp\ i}$, is calculated as follows:

$$f_{imp,i} = \sum_n f_n \cdot p_{imp,n,i} \tag{2.17}$$

where:

$p_{imp,n,i}$ = probability of impairment for scenario n with for safety function i
N = total number of accident scenarios.

2.1.5 Environment Risk

The environment risk from offshore installations is dominated by the largest spills from blowouts, pipeline leaks or storage leaks. Process leaks, although more frequent, are not normally capable of causing extensive damage to the environment. The quantified risk to the environment is usually expressed as one of the following:

- Expected value of spilled amount.
- Frequency of events with similar consequences for the environment.

Consequence is often measured in restoration time. 'Restoration time' is the time needed for the environment to recover after a spill, to the conditions existing before the spill. This is further discussed in Subsection 6.10. Previously, the expression 'expected spilled amount' has been commonly used. Expected spilled amount per year, Q_{sp}, is expressed as:

$$Q_{sp} = \sum_n f_n \cdot q_n \tag{2.18}$$

where:

$q_n =$ amount spilled for scenario n.

The accumulated frequency, $f_{spill\ cons\ i}$, of events with similar consequences (restoration time) is assessed as follows:

$$f_{spill\ cons\ i} = \sum_n f_n \cdot p_{n,i} \tag{2.19}$$

where:

$p_{n,i} =$ probability of environmental consequence i for scenario n.

2.1.6 Asset Risk

The asset risk is comprised of possible damage to equipment and structures, as well as the resulting disruption of production. Risk is expressed similarly for material damage and production delay. Asset risk is usually expressed as either of the following:

- Expected damage to structures and equipment.
- Expected duration of production delay.
- Frequency of events with similar consequences, either in extent of damage or duration of production delay.

Expected value of damage per year (or expected duration of production delay), D, is expressed as:

$$D = \sum_n f_n \cdot d_n \tag{2.20}$$

where:

$d_n =$ extent of damage (duration of delay) for scenario n.

The accumulated frequency, $f_{damage\ cons\ i}$, of events with similar consequences is assessed as follows:

$$f_{damage\ cons\ i} = \sum_n f_n \cdot p_{D,n,i} \tag{2.21}$$

where:

$p_{D,n,i}$ = probability of damage consequence i for scenario n.

The expected value of damage and production delay are, as for the expected amount spilled, entirely artificial values, as the events are rare, and usually large, once they occur.

2.2 Risk Elements

2.2.1 Personnel Risk

When personnel risk is considered in the case of an offshore installation, only risk for employees (historically usually called second party, but now often called first party) is considered, whereas risk for the public (third party) is not applicable. For risk to personnel, the following may be considered as elements of risk:

- Occupational accidents
- Major accidents
- Transportation accidents
- Diving accidents.

These elements are common for production installations and mobile drilling units. It is stressed that these risk contributions statistically have to be considered separately. The discussion below is mainly concerned with the risk to personnel on production installations, relating to how such risk is commonly regarded.

Transportation from shore is also often considered. There are advantages and disadvantages associated with this approach. One disadvantage is that important variations associated with the installation may be masked by the risk contribution from transportation. It may also be argued that the risk contribution from helicopter transport cannot be significantly influenced by the offshore operations.

In other circumstances, it is very relevant to include the risk contribution from transportation. This occurs if two field development alternatives are being compared, involving significantly different extents of transportation. Another argument is that the risk contribution from helicopter transportation is a significant source of risk for offshore employees, and as such should be included in order to illustrate the total risk exposure. It should be noted that current Norwegian legislation actually requires that the risk from helicopter transportation should be included in the overall risk estimation for offshore personnel.

2.2.2 Risk to Environment

The following hazards relating to production installations and associated operations may lead to damage to external environment:

- Leaks and seepages from production equipment on the platform as well as subsea
- Excessive contamination from production water and other releases
- Large spills from blowouts
- Pipeline and riser leaks and ruptures
- Spills from storage tanks
- Accidents to shuttle tankers causing spill.

It is usual that the third, fourth and fifth of these items are considered in relation to offshore installations. If two different transport alternatives are considered, then number six in this list also has to be included. The two first elements are usually considered as 'operational discharges', and are not included in environmental risk assessment.

2.2.3 Risk to Assets

Risk to assets is usually considered as non-personnel and non-environment consequences of accidents that may potentially have personnel and/or environment consequences. It may be noted that modelling of risk to assets in many circumstances is relatively weak. The following types of hazards may cause accidental events which have the potential to damage the assets:

- Ignited and unignited leaks of hydrocarbon gas or liquid
- Ignited leaks of other liquids, such as diesel, glycol, jet fuel, *etc.*
- Fires in electrical systems
- Fires in utility areas, accommodation, *etc.*
- Crane accidents
- External impacts, such as vessel collision, helicopter crash, *etc.*
- Extreme environmental loads.

Usually all of these types of accidental events are included in asset risk. However, there may be a need to coordinate with a regularity (or production availability) analysis, if such analysis is carried out.

A regularity analysis considers all upsets which may cause loss of production capacity, both from unplanned and planned maintenance. Some accidental events of the least magnitude, especially the utility systems, may be included in both types of analysis. This is not a problem, as long as any overlap is known, implying that double counting may be removed if a total value is computed.

A summary of how the different risk elements are usually considered in QRA studies for production installations is presented in Table 2.3, which distinguishes between manned and unmanned installations. Risk associated with material handling and diving are usually outside the scope of such studies.

2.3 Risk Presentation

The general requirement for the presentation of QRA results is that it should be as detailed as possible. There are usually quite a lot of detailed results available from a QRA, but they are seldom provided for the insight of the reader.

The main objective in the presentation of QRA results is to illustrate relative comparisons of contributions and mechanisms that may show the elements of the risk picture. Thus as many details and illustrations as possible should be presented. Some general principles for presentation of results are stated below.

Table 2.3. Risk elements for production installations

Risk element	**Manned installation**	**Unmanned or not normally manned installation**	**Comments**
Accidents on the installation	Occupational accidents	Occupational accidents	
	Major accidents	Major accidents	Including all types, related to HC leaks, external impact and environmental loading
Accidents during transportation	Accidents during helicopter transport from shore	Accidents during helicopter transport from shore	Required to be inclu-ded for offshore em-ployees as per Nor-wegian regulations
		Accidents during shuttling between unmanned and manned installation	Usually included for the not normally manned installation
	Accidents during material handling of supplies and transport from shore	Accidents during material handling of supplies and tran-sport from shore	Usually not included
Diving accidents	Not included	Not included	Usually carried out from dedicated vessel, not considered for the fixed installations

The most important, in addition to overall presentations of results, is that contributions to risk are illustrated in a number of ways. The following sections present most of the relevant ways that risk may be presented, including the contribution of the following parameters:

- Different types of scenarios
- Types of failures in an MTO (Man, Technology and Organisation) perspective
- Type of activity which contributes to risk
- Barrier failures that led to the actual scenario
- Location where the initiating accident occurred
- Relevant cause (where applicable) of accident initiation.

2.3.1 Fatality Risk

2.3.1.1 Overview

Fatality risk should, as a minimum, be presented using the following parameters, irrespective of whether risk acceptance criteria are formulated for each of them or not:

PLL	PLL is the annual risk exposure of the entire installation, and is thus an important measure of overall risk.
FAR/AIR	FAR or AIR are alternative expressions of individual risk, and are thus complementary to the PLL value. FAR and AIR are usually average values for groups, such as the entire population and smaller groups. Norwegian regulations require that risk is calculated for the most exposed persons.
Group risk	Usually presented as an f–N diagram (see illustration in the following).

It should be noted PLL may sometimes be expressed for a particular group on an installation during the execution of a particular task, thus it may occasionally depart from what is referenced above, the entire population of an installation and a whole year. It is then important to state clearly what is the reference for the PLL *i.e.,* what group and the duration of the operation in question.

2.3.1.2 Potential Loss of Life (PLL)

PLL values can be presented with the different contributions, arising from the different hazards that are applicable, as shown in the following table.

Table 2.4 also shows the relative contributions and the average size of the accident in terms of fatalities per accident.

Table 2.4. PLL contributions from accident types

Hazard category	**Annual PLL values**	**%**	**Fatalities/accident**
Blowout	$4.1 \cdot 10^{-3}$	27.3	5.3
Process accidents	$9.6 \cdot 10^{-4}$	6.4	0.7
Riser, pipeline accidents	$5.3 \cdot 10^{-3}$	35.3	4.1
External accidents	$2.3 \cdot 10^{-4}$	1.5	1.4
Occupational accidents	$2.6 \cdot 10^{-3}$	17.3	1.1
Helicopter accidents	$1.4 \cdot 10^{-3}$	9.3	2.8
Total all categories	$1.5 \cdot 10^{-2}$	100	2.3

Figure 2.2 shows the contributions to total PLL from different accident accidental effects:

- Immediate fatalities
    - occupational accidents
    - major accidents
- Helicopter accidents
- Fatalities during escape and evacuation.

The 'immediate fatalities' are those fatalities that occur as a direct result of the initiating event, either in a major accident or an occupational accident. All fatalities are virtually always 'immediate' in the case of an occupational accident.

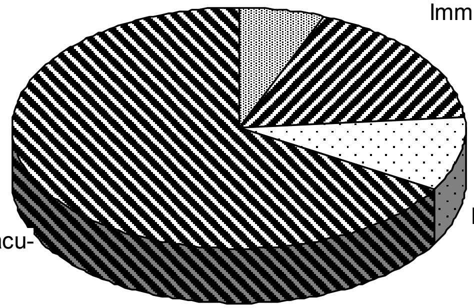


Figure 2.2. Contributions to PLL from types of fatalities

2.3.1.3 Average Fatality Risk

Relative contributions to FAR/AIR are often the same as the contributions to PLL. FAR or AIR should be presented in respect of the following categories:

- for personnel located in each main area of the installation
- for each main group of personnel
- contributions to total risk from different accident types
- contributions to total risk from different phases of the accident.

Figure 2.3 shows typical FAR values for different areas of a platform. The minimum that should be presented in this regard is:

- FAR value for personnel spending on-duty and off-duty time in accommodation area.
- FAR value for personnel who spend on-duty hours in 'hazardous' areas on the installation (*i.e.* outside accommodation area) and off-duty time in the accommodation area.

It is often appropriate to use FAR or AIR to compare different concepts or different layout solutions. There are, on the other hand, some situations where it is not appropriate to compare FAR (or AIR) values. Examples of such situations are comparison of:

- Field development alternatives involving different numbers of personnel.
- Field development alternatives that are drastically different, for instance if a new field can be developed with a separate installation or tied into an existing, possibly with extensive modification being required.

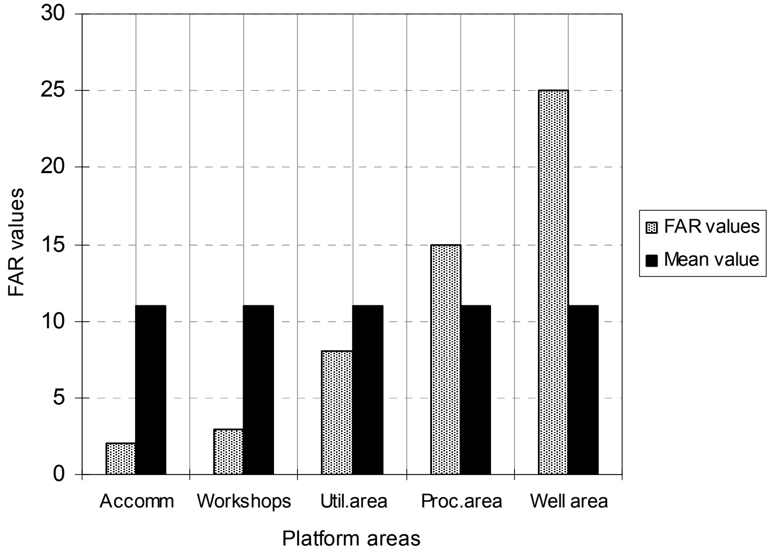


Figure 2.3. FAR values in different platform areas, and mean platform value

PLL has to be used for comparison in these situations, in order to get an understanding of the overall risk, as shown in the following example.

2.3.1.4 Activity Based Variations of Fatality Risk

Different activities have very different FAR levels. Figure 2.4 shows how the average FAR level may vary for a worker who takes part in well intervention as well as process operation. The FAR level during a short helicopter trip is also shown. Further, he is only exposed to the structural failure associated risk level, as well as the possible need for all onboard to evacuate, during sleep in the quarters. Office employees working inside the accommodation block for the entire day would also be exposed to this low risk level. The following points should further be noted:

- The actual values shown are typical, and may vary considerably, depending on the platform.
- The FAR level shown for helicopter transport (140 fatalities per 10^8 person flight hours) is the current helicopter risk level in the North Sea (see Section 3.1.5).
- The well intervention FAR rate shown relates to moderately hazardous operations. Other well intervention activities may give FAR values almost as high as during helicopter flights. These activities however often have relatively short duration.

2.3.1.5 Adding of FAR Values

It should be noted that FAR values may only be added if they apply to the same time period. The FAR values shown in Figure 2.4 can not be added, but the total FAR for a 24 hour period may be calculated in the following way:

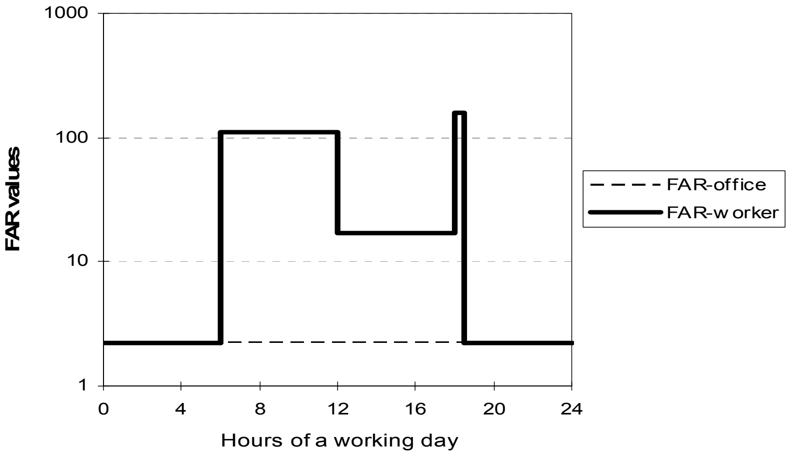


Figure 2.4. FAR variations depending on activity performed

$$FAR_{tot} = \sum FAR_i \cdot t_i \qquad (2.22)$$

where
FAR_{tot} = total FAR value over a working day
FAR_i = FAR value for period i
t_i = duration of period i.

The calculation of the daily average FAR for the platform worker experiencing the risk regime shown in Figure 2.4 is shown in the Table 2.5.

The PLL) for one such worker over a total working day is $0.89 \cdot 10^{-5}$ fatalities (per day), which is shown to correspond with a daily average FAR value of 36.9.

Table 2.5. Calculation of daily average FAR for offshore worker

Activity	FAR	Duration (hrs)	PLL ($\cdot 10^{-8}$)
Sleeping	2.28	6	14
Well intervention	114.2	6	685
Process operation	17.12	6	103
Helicopter transport	140	0.5	70
Sleeping	2.28	5.5	13
Total value	36.9	24	885

2.3.1.6 Example: Comparison of Field Development Schemes

There is a fixed installation which has been producing for some few years on a field, producing mainly oil and some associated gas. A second part of the field has been found, also with oil and associated gas, and two options exist for development of this part of the field:

- Subsea wells tied back to the existing fixed installation.
- A Floating Production Storage Offloading (FPSO) unit.

The comparison in these circumstances is focused on the additional PLL that might occur due to production from the second part of the field, including the modification phase and the remaining production period. If subsea completions are to be used and the existing installation is to house production from the second part of the field, then the following aspects need to be considered:

- Increased fatality risk during the modification phase.
- Increased fatality risk during the production phase, due to new equipment.
- Increased number of personnel onboard during modification and during production.

The total value of increased PLL in this case is compared to the total PLL for the FPSO. The possible fatality risk to workers in the construction yards is disregarded in both cases. This would, if included, add more risk for the FPSO alternative, because considerably higher yard manhours would be required, in order to construct a new hull. Figure 2.5 shows the calculated PLL for the two alternative development scenarios.

The FPSO alternative is seen to add 33% more PLL to the field development and residual production phase, mainly due to the higher number of personnel exposed to risk offshore.

This example assumes that the extra personnel needed during the modification phase can live on the installation itself *i.e.,* that one hundred extra beds are available. Some installations have this capacity, but not all. The alternatives would be the following:

- Connecting a flotel to the fixed installation by bridge, in order to increase the accommodation capacity, or
- shuttling extra personnel to the platform each day either from onshore or an adjacent platform.

These alternatives have significant implications for risk, as the next example shows.

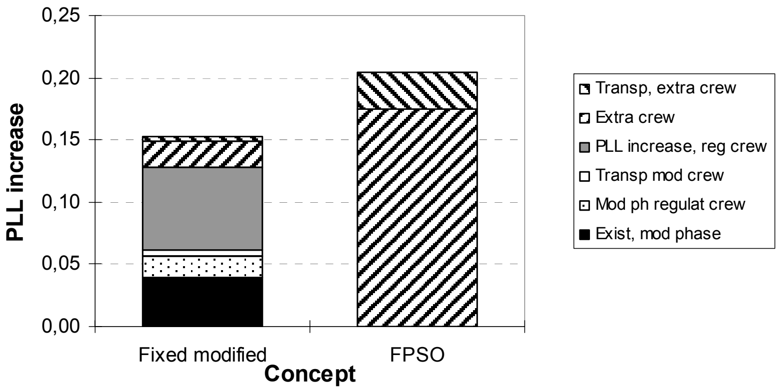


Figure 2.5. Comparison of PLL increase for two different field development concepts

2.3.1.7 Example: Flotel vs Helicopter Shuttling

When offshore modifications or tie-ins are being carried out, it is sometimes not possible to accommodate all personnel required for the work on the installation itself. It is then a choice between shuttling the personnel to shore or to another installation or providing a bridge-connected flotel beside the platform.

Figure 2.6 is provided to illustrate the difference in fatality risk (PLL). It is an add-on to Figure 2.5, when it is assumed that the extra personnel during the modification cannot be accommodated on the fixed installation, and have either to be shuttled to shore or accommodated on a bridge-connected flotel. The resulting total life cycle PLL values for the two alternatives are shown in Figure 2.6.

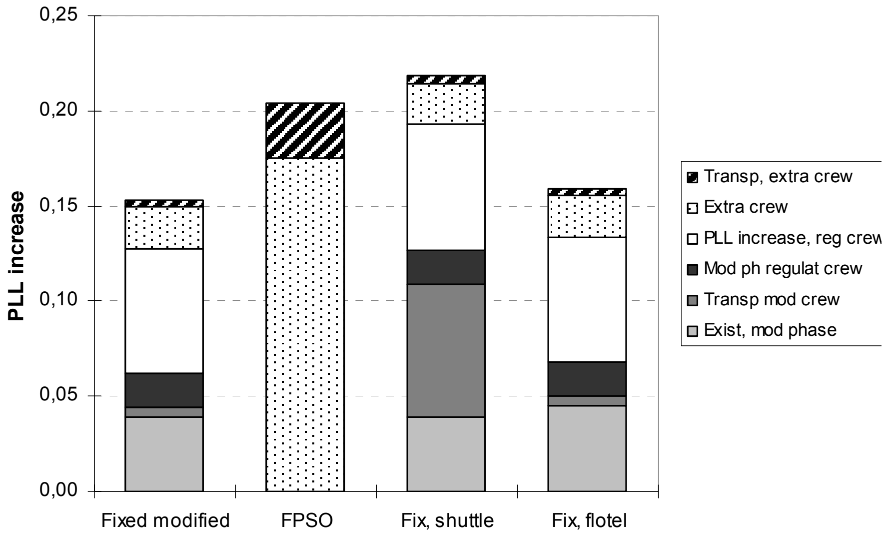


Figure 2.6. Comparison of development schemes with shuttling and flotel

The life cycle risk is increased by virtually 50% if all personnel have to be shuttled to shore each day. Such an extent of shuttling is too extensive to be the normal solution, but is used in order to illustrate the most extreme case. As shown, this is the highest PLL value in Figure 2.6, whereas the alternative with flotel for provision of extra beds is almost as low as the alternative using the fixed installation alone for all purposes.

2.3.2 Group Risk

The group (or societal) risk may be presented by an f–N curve for fatalities. The f–N function was introduced in Section 2.1.3.3, where the possibility to include risk aversion also was discussed. Risk aversion is initially omitted from the discussion in the following, but the importance of aversion is also illustrated. Figure 2.7 shows the usual shape of the f–N diagram, which is just a particular way to draw a cumulative function.

It should be noted that the f–N diagram usually requires both axes to be drawn with a logarithmic scale, because the range of values is usually several orders of magnitude on both axes. Typically, fatalities can range from 1 to the maximum present on board at any one time. On large installations this may reach several hundred persons. Figure 2.8 shows how the same diagram would look, if linear scaling were used on both axes. An actual example from a platform QRA is presented in Figure 2.9.

Figure 2.7. f–N diagram, double logarithmic scaling

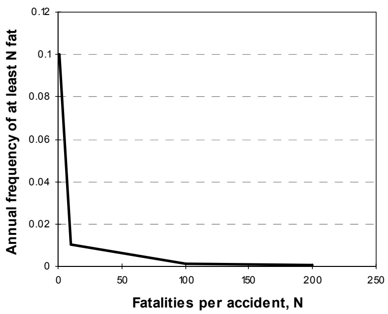


Figure 2.8. f–N diagram, linear scaling

The two next diagrams (Figure 2.10; Figure 2.11) show important aspects of f–N diagrams. The first diagram illustrates the importance of risk aversion, if this is included. The curves in Figure 2.10 have been produced for the following case:

- POB: 25
- Upper tolerability limit, AIR: $1 \cdot 10^{-3}$ per year
- Number of hours exposed offshore: 3200 hours per annum (50% on-duty, 50% off-duty)

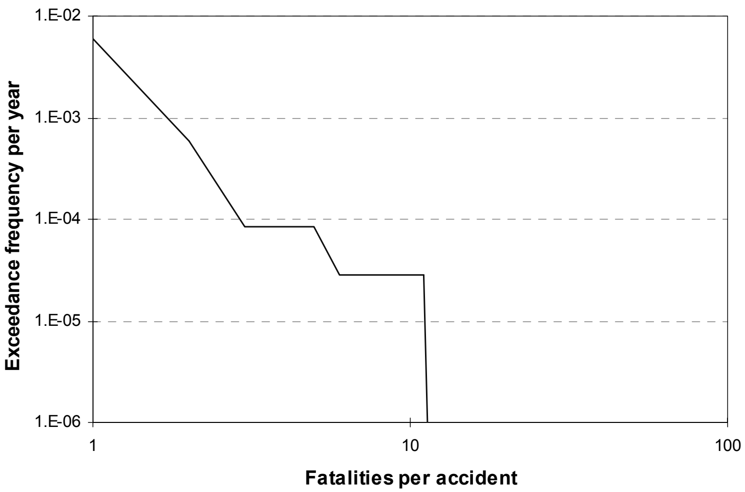


Figure 2.9. f–N curve for offshore installations, all fatalities

The two curves are developed in order to present the variation dependent on the extent of risk aversion, ranging from no aversion (b = 1.0), to maximum aversion (b = 1.3) (see Section 2.1.3.4). The difference between the two cases may seem insignificant but for accidents with at least 20 fatalities, the difference is a factor of 1.8 (0.0009 *vs* 0.0005 per year).

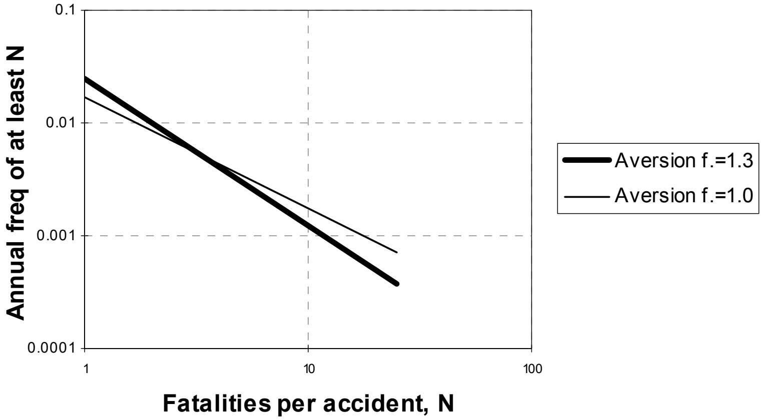


Figure 2.10. Variation of group risk curve as a function of aversion factor

Figure 2.11 has been developed in order to show how differences in upper tolerability limit for AIR (thereby also FAR) values affect the f–N diagram in situations where finite numbers of people are subjected to risk. No risk aversion has been included in the presentation.

It is obvious from the diagram that the values of the diagram are linearly dependent on the value of the AIR (or FAR implicitly). This is also obvious from Equation 2.14.

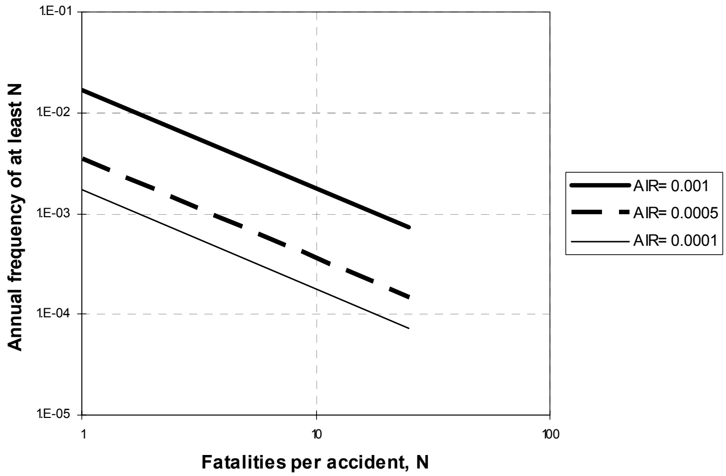


Figure 2.11. Group risk curve for different values of AIR limit

2.3.3 Impairment Risk

Impairment risk is usually related to impairment of so-called 'Main Safety Functions'. There are often three to five main safety functions defined, each of which has a separate impairment frequency. These frequencies should therefore be presented individually. Typical contributions to annual frequency of impairment of escape ways for a wellhead platform are shown in Table 2.6.

Table 2.6. Annual impairment frequency, escape ways

Hazard category	Annual impairment frequency	%
Blowout	$7.3 \cdot 10^{-5}$	48.5
Process accidents	$8.2 \cdot 10^{-6}$	5.4
Riser, pipeline accidents	$1.97 \cdot 10^{-5}$	13.0
External accidents	$5.0 \cdot 10^{-5}$	33.1
Total all categories	$1.51 \cdot 10^{-4}$	100

Impairment of escape ways is here presented per hazard category, as required by Norwegian regulations. Also the total value is shown; this is not required by Norwegian regulations. Impairment of escape ways is sometimes expressed on a 'per area' basis.

2.3.4 Risk to Environment

Table 2.7 shows one way to express results for risk to the environment. The table must be accompanied by a definition of the consequence categories. These are often based on the effect on the coastline bearing in mind the following aspects:

- Amount of oil reaching the shore
- Length of coastline affected by spill
- Extent of areas of special environmental value (including areas with particular value) that are affected

Table 2.7. Annual frequency of environmental damage, for categories of spill effects

Environmental consequence category	Corresponding amount spilled (tons)	Annual frequency
Minor effect	10	$3.4 \cdot 10^{-3}$
Moderate effect	500	$8.6 \cdot 10^{-4}$
Major effect	10,000	$9.7 \cdot 10^{-6}$

Sometimes, the expected value of the spilled amount per year (at source or that reaching shore) is given as a measure of risk. This would be a value such as 0.56 tons per year, if the amounts corresponding to the consequence categories in Table 2.7 are used. It is clearly seen that such a value is virtually meaningless for prediction purposes. There will never be anything like 0.56 tons spilled in any one year, if we consider major accidents. Either the amount is nil, or a substantial amount. The expected value is virtually useless when the probabilities are very low, and the consequences are high values. This applies to prediction of future spills. For some other purposes, like comparison of concepts or systems, the expected values may be quite useful.

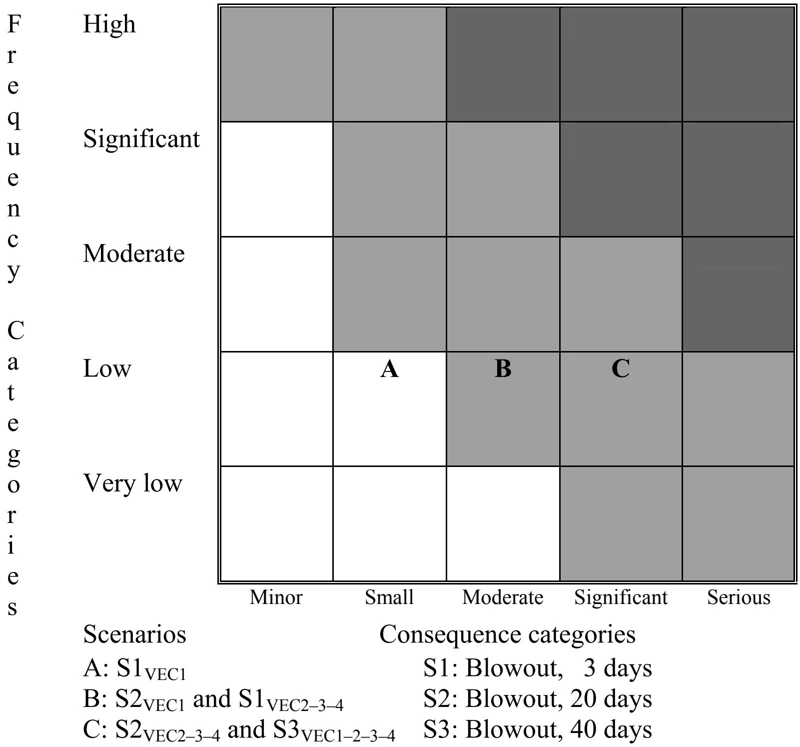


Figure 2.12. Risk matrix with results plotted

Another way to present risk to the environment is by the use of a matrix presentation, as shown in Figure 2.12, which uses the following consequence categories:

- Minor damage: < 2 years
- Small damage: 2–5 years
- Moderate damage: 5–10 years
- Significant damage: 10–20 years
- Serious damage: > 20 years

There are also other alternative result presentations that may be chosen. The blowout scenarios S1; S2; S3; imply different durations, as shown in the diagram. There are four Valued Ecological Components (VECs) considered, these are denoted VEC1; VEC2; VEC3; VEC4. There are different frequencies for each consequence category for each VEC; this is indicated in the matrix by the results falling in boxes, A, B and C.

2.3.5 Asset Risk

There are normally two dimensions of asset risk that are presented separately; Material damage risk and Production delay (deferred production) risk. In actual situations the production delay often dominates material damage if both are converted to monetary values. Table 2.8 presents an example of material damage risk contributions for a wellhead platform. The risk of production delay may be presented in a number of ways:

- Expected value *i.e.,* expected delay per year due to accidents.
- Frequencies of consequences of different magnitude, similar to the presentation for material damage above, see Equation 2.21.
- Exceedance diagram showing the accumulated frequency of delays of a certain duration or longer.

Table 2.8. Annual frequency, material damage

Hazard category	**Annual damage frequency**		**% total loss**
	Partial loss	**Total loss**	
Blowout	$1.07 \cdot 10^{-3}$	$2.61 \cdot 10^{-4}$	79.8
Process accidents	$2.06 \cdot 10^{-3}$	$5.76 \cdot 10^{-6}$	1.8
Riser, pipeline accidents	$1.62 \cdot 10^{-4}$	$1.04 \cdot 10^{-5}$	3.2
External accidents	$9.62 \cdot 10^{-3}$	$5.0 \cdot 10^{-5}$	15.3
Total all categories	$1.29 \cdot 10^{-2}$	$3.27 \cdot 10^{-4}$	100

There are often four or five categories presented, the following are used in the WOAD® database (WOAD, 1994), and could be considered a 'standard' to some extent:

- Total — Total loss of the unit including constructive total loss from an insurance point of view. The platform may be repaired and put into operation again.
- Severe damage — Severe damage to one or more modules of the unit; large/medium damage to load-bearing structures; major damage to essential equipment.
- Significant damage — Significant/serious damage to module and local area of the unit; damage to several essential equipments; significant damage to single essential equipment; minor damage to load-bearing structures.
- Minor damage — Damage to several non-essential equipments; minor damage to single essential equipment; damage to non-load-bearing structures.
- Insignificant damage — Insignificant or no damage; damage to part(s) of essential equipment; damage to towline, thrusters, generators and drives.

Figure 2.13 shows an exceedance diagram for production delay. Three curves are shown, the total, and the two most important contributions, blowout and process accidents. There are also other contributions which are not shown. It should be noted that the expected value for the exceedance curve, can be expressed as:

- 1.5 days of production delay per year.
- Equivalent of 0.40% reduction of production availability.

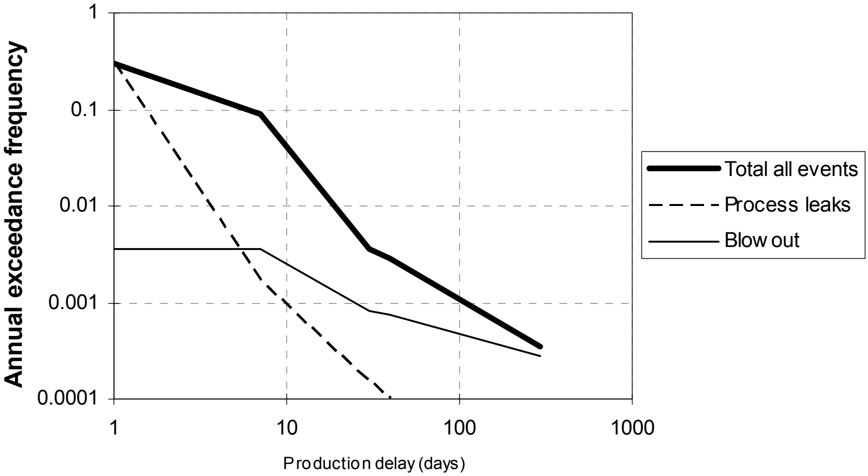


Figure 2.13. Production delay curve in an exceedance fashion

About 60% of the contribution to production delay comes from short duration events, but there is also substantial contribution from events of longer duration and rare occurrences. A more informative presentation of values is therefore as follows:

- On average 0.85 days per year of short duration delays (up to one week).
- 1% probability per year of long duration damage; on average, 66 days delay.

2.3.6 Load Distribution Functions

The exceedance diagram is similar to the f–N diagram for fatalities, shown in Figure 2.9. Figure 2.14 presents the annual exceedance frequency for collisions with a North Sea wellhead platform. This is similar to the presentation of production delay, as shown in Figure 2.13. There are four curves shown for the three contributions from merchant vessels, shuttle tankers and supply vessels, and the total frequency.

It may be argued that the load distribution functions are not risk expressions, but that they present intermediate results that are used in the further risk calculations. This may be the case, but sometimes these loads correspond to what is seen as a design requirement or feature, such that some persons may be interested in these results as a risk output. For instance for collision loads, this may be the case. These curves may be used as input to structural design against collision loads.

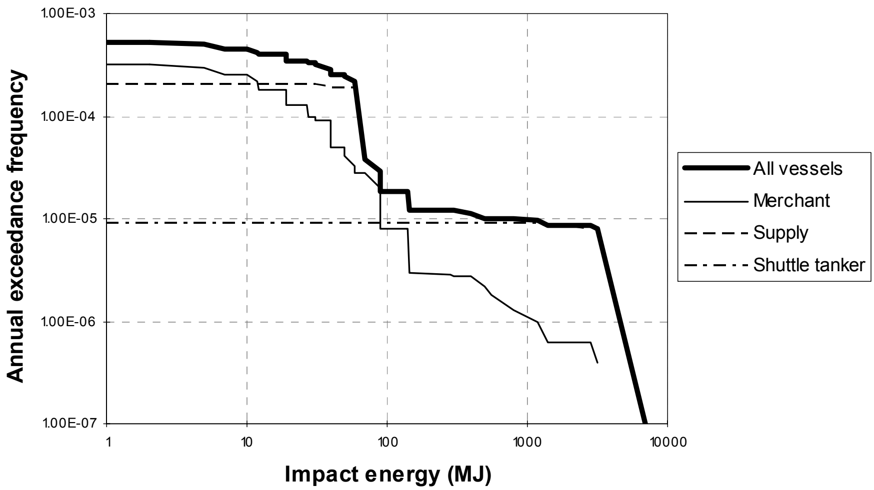


Figure 2.14. Typical exceedance frequency for collision risk

2.4 Uncertainties

2.4.1 Basis for Uncertainty Consideration

Risk quantification is often characterised by a mixture of the classical statistical approach and the Bayesian (subjective) approach. Most professionals are trained in the former approach, where the probability of end events is considered to be independent of the analyst, and as a quantity characterising the object being studied. The classical concept of probability implies that the results of the risk analyses are calculations (estimations) of these 'true' probabilities.

The alternative is the Bayesian approach, where the concept of probability is used to express the analyst's measure of uncertainty or degree of belief. There is still significant resistance among risk analysts to the idea that their results are not 'objective' risk results, but rather subjective values. Most risk analysts would, however, accept that there are some elements of their work which are subjective values. For example, subjectively assessed conditional probabilities are commonly used for some of the nodes of the event trees, typically where simplifications of complex physical phenomena are introduced.

The approach adopted in this book is the Bayesian approach, whereby the risk values are considered to be expressions of the uncertainty related to whether accidents will occur or not. The implication of this consideration is that uncertainties shall not be quantified in QRA studies, because the risk assessment in itself is an expression of uncertainty.

This does not, however, imply that the subject of uncertainty is without interest. It will be important for the analysts to be aware of what is influencing the extent of subjectivism in the analysis, in order to focus on results that minimise the inherent uncertainty. We will therefore consider aspects and factors that are important for the extent of subjectivism in an analysis. The difference is, however, that no attempt is made to quantify these elements of uncertainty. A more thorough discussion of these aspects is presented in '*Foundations of Risk Analysis*', Aven (2003).

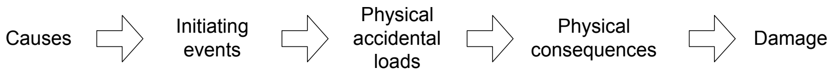
2.4.2 Influence of Uncertainty

There will always be uncertainty as to whether certain events will occur or not, what the immediate effects will be, and what the consequences for personnel, environment, or assets may be. This uncertainty reflects the insufficient information and knowledge available for the analysis, in relation to technical solutions, operations, and maintenance philosophies, logistic premises *etc.* The uncertainty will be reduced as the field development project progresses. But there will always be some uncertainty about what may be the outcome of accidental events, even when the installation has been installed and put in operation.

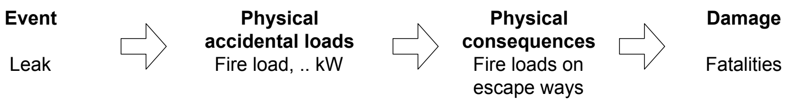
The uncertainties are expressed by the probabilities that are assigned. There is as such no other expression of uncertainty. But it is nevertheless important to consider and reflect on what are the sources of uncertainty.

It is generally accepted that there are three main sources of uncertainty in QRA studies. The first source is related to variation in the populations being used in the calculations *i.e.,* whether there is a broad basis of relevant data available or not. The second aspect of uncertainty causation is related to the extent of simplification made in the modelling of risk aspects. The third element is related to completeness of the knowledge about relevant phenomena and mechanisms.

It is important to consider how risk is calculated in order to understand the influence of uncertainties. The calculation of event sequences (see further discussion of event sequences in Chapter 4) from an initiating event to a final situation may be illustrated as follows:



Historically, the causes of events have often been omitted in QRA studies. For example, the causes of a leak of hydrocarbons may not be addressed particularly. This is discussed in detail in Section 5.1. One example of risk calculations relating to an event sequence may be as follows:



The extent of assumptions that have to be made will usually increase as one gets further into the accident sequence, and more and more uncertainty is introduced. There are more sources of uncertainty associated with calculation of fatality risk compared to physical accidental loads or consequences. This should also be considered when choosing the risk parameters to be used in decision-making (see discussion in Section 5.13).

The way to treat uncertainties in the analysis should be defined prior to performing this evaluation. It is recommended here that the Bayesian approach should be chosen. This implies that sensitivity studies should be carried out in order to illustrate uncertainties in the analysis, in relation to critical assumptions and data used in the analysis.

The NORSOK Z–013 standard expresses that the 'best estimate' risk levels from the risk analysis, rather than the optimistic or pessimistic results, should be used as basis for decision-making. This is based on a classical statistical approach, and some interpretation is needed. The implication of this requirement is that expected values should be used, rather than alternative values.

Where the analyst considers that a particular evaluation, or calculation, is particularly uncertain, it is common practice to aim to 'err' on the conservative side. This is considered good practice, but care should be taken to ensure that the conservatism is not exaggerated. For instance, if a maximum blast load is calculated as 1.2 bar, then we may be certain about what effects of fragments on personnel may be (disregarding other effects in this example) and consider conservatively that 50% of the persons present may be injured by fragments. The conservatism in calculating the fraction of persons injured is OK, but we should not apply conservatism on all the factors leading up to the frequency of blast loads from such explosions.

2.4.3 Calculation Based on Observations

There is one situation where it may be appropriable to consider variability in a statistical sense. This may be illustrated with the following example. Let us consider three offshore installations that have been in operation for many years. The number of hydrocarbon (HC) leaks (all leaks, also the smallest) that have occurred over the years, is shown in Table 2.9.

Table 2.9. Experience data for installation, manhours and HC leaks

Installation	HC leaks during 15 year period	Manhours during 15 year period
A	100	80 mill
B	65	50 mill
C	25	100 mill

Let us first of all calculate the average frequencies for the three installations individually, as in Table 2.10. The average number of HC leaks per year is 50% higher on installation 'A' compared to installation 'B', whereas the number of leaks per million manhours are quite similar for these two installations. The average frequencies for installation 'C' are considerably lower. The question may be whether these differences are statistically significant?

Table 2.10. Average number of leaks for example

Installation	Average number of leaks per year	Average number of leaks per million manhours
A	6.67	1.25
B	4.33	1.30
C	1.67	0.25

Based on an assumed Poisson distribution, we may now calculate 90% prediction intervals for the three installations. This implies the intervals that we can compare next year's occurrences with, in order to conclude whether there are significant improvements or increases.

The interpretation of statistical significance in this context is different from that used in the classical interpretation of risk assessment. A 90% prediction interval means that if all sources and mechanisms of risk are unchanged in the future from what is was in the past, the future observations (here number of leaks) will fall within the interval given with an assigned probability of 90%. If future observations fall outside the interval, we have strong evidence for concluding that that conditions have changed to an extent that risk is influenced. This is referred to as 90% confidence level.

It should be noted that this approach is different from the confidence intervals used in the classical approach to risk assessment, although the approaches appear to be the same. The basis for the confidence interval is an assumption that 'true' values exist, generated by averages of properties of an infinite thought-constructed population of similar situations, which is not part of our assumptions here.

Table 2.11. Average number of leaks for example

Installation	Average number of leaks per year	Prediction interval (number of leaks per year)
A	6.67	2 – 11
B	4.33	0 – 8
C	1.67	0 – 5

If there is one HC leak on Installation A next year, this will represent a statistically significant reduction. On the other hand, even if there are no leaks at all on Installation B, there is insufficient data to conclude there is no significant reduction.

If we, as a last illustration, calculate the average of Installations A and B, then we have a larger database, and the basis for conclusions about significant changes is broader, as shown in Table 2.12.

If next year there is one HC leak on each of the Installations 'A' and 'B', then there is a significant reduction. Moreover, if there are three leaks on installation 'C' and 6 million manhours worked, then this corresponds to 0.5 leaks per million manhours, which is a statistically significant reduction, compared to the average of 'A' and 'B'.

Table 2.12. Average number of leaks for Installations 'A' and 'B'

Installation	Average number of leaks per installation per year	Prediction interval (number of leaks per year)
Average of A and B	5.5	2.5 – 8.5
Average per 1 million manhours	1.27	0.58 – 1.96

We are now able to compare prediction intervals for these three installations. It will be seen that all three prediction intervals overlap to some extent, implying that possibly the differences in average number of leaks per million manhours are due to statistical variations. Let us therefore consider 80% confidence level in Table 2.13. Now the prediction intervals of installations A and B do still overlap. For Installation C, there is still a slight overlap with Installation A, and differences may be due to statistical variations. With 70% confidence level there would not have been any overlap. This would imply that there is about 70% probability that the average FAR level on Installation A is higher than on Installation C. Finally, the Figure 2.15 shows the prediction intervals with 90% and 80% confidence levels.

Table 2.13. Prediction intervals for installations A, B and C, 80% confidence

Installation	Prediction intervals (80%)	
	Lower limit	**Upper limit**
A	0.38	1.69
B	0.00	2.10
C	0.00	0.45

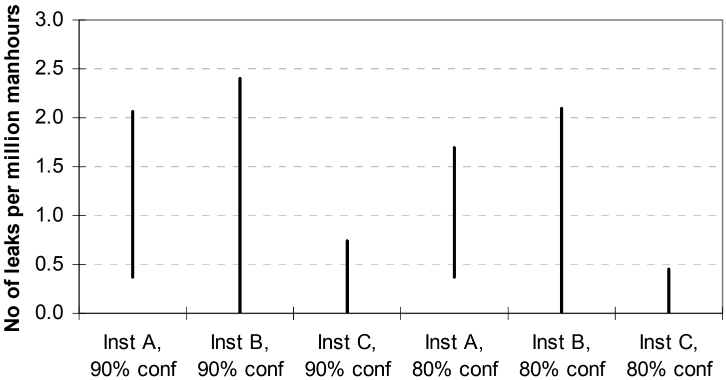


Figure 2.15. Comparison of prediction intervals for different confidence levels

2.5 Basic Risk Modelling Concepts

This chapter has introduced some essential concepts related to calculation and presentation of risk. Some further concepts are needed, for use in the modelling of hazards and risks. 'Defence in depth', 'barriers', 'root causes' 'risk influencing factors' and 'risk reducing measures' are discussed in the following. Further concepts and terms are given in the Glossary section, see page 549.

2.5.1 Defence in Depth

Defence in depth is a term that is closely associated with accident prevention in complex industries. This principle has been introduced in different ways by several authors in the past. Haddon's ten accident prevention strategies (Haddon, 1980) and the principles of the investigation logical tree, Management, Oversight and Risk Tree (MORT), reflect the same basic principles:

- Contain energy at source, AS WELL AS
- Stop flow of energy between source and target, AS WELL AS
- Protect targets against energy.

Professor James Reason (Reason, 1997) has focused on organisational causes which may result in a similar breakdown of defences, for instance by the TRIPOD model. Kjellén (2000) provides an in-depth discussion of accident models and principles.

If we adopt the 'energy flow' concept according to Haddon and MORT, barriers are the instruments that may be used to contain energy, stop energy flows and protect targets against energy. This interpretation implies that 'barriers' should be regarded as physical 'fences'. There are, on the other hand, many authors and experts who regularly refer to 'organisational barriers'. We will in this book maintain the principle that barriers are those actions or functions that may control (change) the flow of energy of some kind. This ties in with the term 'barrier function', which is introduced in Subsection 2.5.2.

An illustration of the defence in depth is perhaps most easily achieved through starting with a situation where this ability is completely lacking. The use of family cars on single lane roads (one lane in each direction) is a system without any defences in depth. If the operator (driver) loses control over the car, then other cars may easily be hit, possibly with severe (fatal) consequences. We have over the years made better cars, in the sense that there are zones that are specially designed in order to absorb energy during a collision. This implies that we have the driver to ensure that control over the energy is not lost, and we have some barriers on other cars, in order to protect personnel inside in case of a head-on collision. But we do not have any barriers in order to stop energy flow, if control is lost over a car.

So what can be done in order to provide in-depth defences? The solution to put a physical barrier in the middle of the road was started in Sweden and has gained wider application, at least in Scandinavia. The barrier between the lanes will stop the uncontrolled energy of a car that loses control and enters the opposite lane with head-on traffic. So we have a very effective barrier against head-on collisions. In theory we could also install some detection equipment in order to try to detect an unwanted development, before control is lost. This is not in widespread use. If we, for instance, could have a detector that discovers when the driver is about to fall asleep, we would improve the situation considerably. All these measures taken together would at the end of the day imply that defence in depth is available against head-on accidents.

The approach to barriers is most commonly used in relation to fire and explosion hazard, and may easily be illustrated in relation to this hazard. An overview of barrier systems and elements is presented in the following.

2.5.2 Barriers

The terminology proposed by a working group from 'Working together for safety', OLF (2004b), is used, involving the following levels:

- Barrier function
- Barrier system
- Barrier element
- Barrier influencing factor.

The differences between these levels may be explained as follows:

• Barrier function:	A function planned to prevent, control, or mitigate undesired events or accidents.
• Barrier system:	Technical, human and/or organisational measures designed and implemented to perform one or more barrier functions.
• Barrier element:	A component of a barrier system that by itself is not sufficient to perform a barrier function.
• Risk influencing factors:	Conditions that influence the performance of barrier systems.

The term 'barrier' is as such not given a precise definition, but is used in a general and imprecise sense, covering all aspects. The main emphasis in relation to barriers is often on barriers against leaks in the process area, comprising the following barrier functions:

- Barrier function designed to maintain integrity of the process system (covered largely by reporting of leaks as an event based indicator)
- Barrier function designed to prevent ignition
- Barrier function designed to reduce cloud and spill size
- Barrier function designed to prevent escalation
- Barrier function designed to prevent fatalities.

The barrier function may for instance be 'prevention of ignition', which may be divided in sub-functions; gas detection; electrical isolation as well as equipment explosion protection. One of the barrier elements in the gas detection sub-function is a gas detector; the process area operator may be another example. If we consider the process operator as the barrier element, there may be several barrier influencing factors, such as working environment; competence; awareness and safety culture. The different barriers consist of a number of coordinated barrier systems and elements.

The PSA regulations require the following aspects of barrier performance to be addressed:

- Reliability/availability
- Effectiveness/capacity
- Robustness (antonym vulnerability).

The reliability/availability is the only aspect of performance which varies significantly during operations, effectiveness/capacity and robustness are mainly influenced during engineering and design. Slow degradation may over a long time, on the other hand, change these values.

The following are aspects that influence reliability and availability of technical barrier systems:

- Preventive and corrective maintenance
- Inspection and test programmes
- Management and administrative aspects.

Figure 2.16 shows a simple block diagram which outlines the main barrier functions with respect to prevention of fatalities through fire and/or explosion caused by loss of hydrocarbon containment.

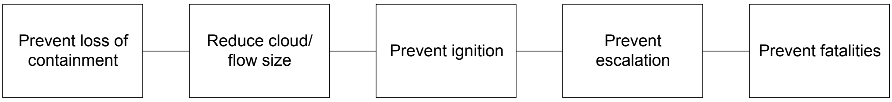


Figure 2.16. Barrier functions for hydrocarbon leaks

The barrier functions listed for hydrocarbon leaks in the process area, are also applicable to blowouts and leaks from risers and pipelines. For the blowout hazard, the integrity barriers are well control barriers. Well control barriers are outside the scope of the discussion in this chapter.

For marine and structural accidents, there are fewer barriers. The corresponding barrier functions may be:

- Barrier function designed to maintain structural integrity and marine control
- Barrier function designed to prevent escalation of initiating failure
- Barrier function designed to prevent total loss
- Barrier function designed to prevent fatalities.

Figure 2.17 shows a similar diagram for the loss of station-keeping by DP-operated shuttle tankers in tandem off-loading (see further discussion in Section 11.4) with respect to prevention of fatalities due to collision between the shuttle tanker and an FPSO.

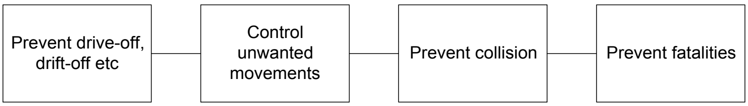


Figure 2.17. Barrier functions for shuttle tanker station-keeping failure due to DP-system failure

The relationship between barrier function, barrier elements, failures of barrier elements and risk influencing factors is illustrated in Figure 2.18. The function is to detect a valve in the wrong position, for which purpose there may be several barrier systems or elements. These may have failures, as indicted by two basic failure events in the fault tree. Risk influencing factors are shown as influences for the failures of the barrier elements. The diagram is from the BORA approach, see Subsection 6.2.6.1.

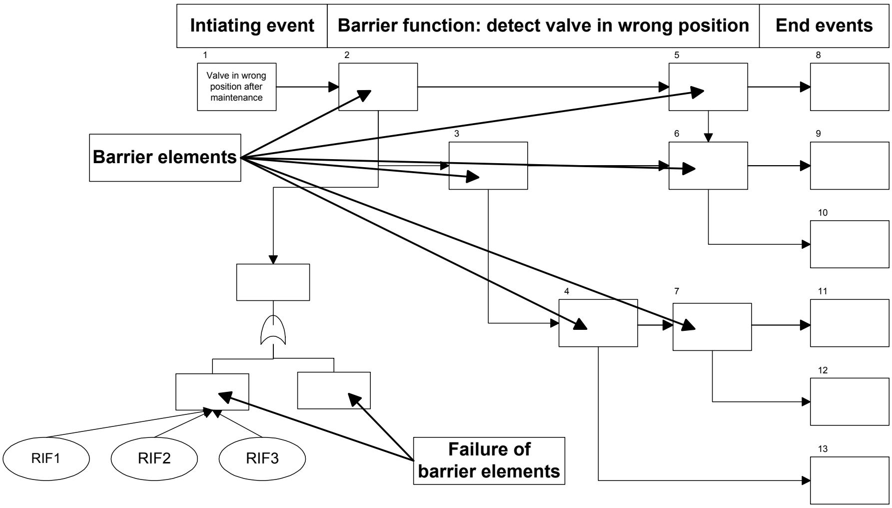


Figure 2.18. Relationship between barrier function, elements and risk influencing factors

2.5.3 Root Causes

A root cause is, according to the TapRoot® system, the most basic cause that can reasonably be identified that management has control over, in order to fix, and when fixed, will prevent or significantly reduce the likelihood of the problem's reoccurrence (Paradies and Unger, 2000).

Root causes are the most essential element of accident and incident investigations, because they are essential in order to prevent or reduce the likelihood of reoccurrence. It may be claimed that identification of root causes is often a weak element in the internal investigations made by the industry.

'Immediate causes' are often the main focus in internal investigations. Consider for instance the following illustrations from an investigation of a gas leak on an installation in the North Sea:

- Immediate cause: Operation of the wrong manual isolation valve by process personnel.
- Underlying causes: 'Best practice' for actual operation not described in manuals
  Valves not labelled
  Attitude on shift is not to use instructions for routine tasks.

Are these underlying causes (as claimed by the investigation team) root causes? No, they cannot be considered root causes, because they are not the most basic causes that management can control. Possible root causes may have been ‘too high time pressure’, ‘implicit acceptance by management that it is acceptable not to follow procedures’, or simply ‘bad safety culture’.

2.5.4 Risk Influencing Factors

Risk influencing factors (sometimes called barrier performance influencing factors) are factors that influence the performance of barrier systems and elements. Consider as an example the manual gas detection function performed by personnel performing manual inspection in the hydrocarbon processing areas. Factors that will influence the ability of such personnel to detect possible gas leaks are as follows:

- Procedures for manual inspections
- Organisation of work, work patterns
- Training of plant operators
- Experience of plant operators
- Motivation of plant operators
- *etc.*

What we here consider as influencing factors will often be considered as ‘barriers’ according to some of the definitions that are used.

It may be discussed whether ‘causal factors’ and ‘influencing factors’ are synonymous expressions, and to some extent they are. It may be argued that ‘influencing factors’ is a wider term than ‘causal factors’, but little emphasis is placed on this. Causal factors as well as influencing factors offer good opportunities to identify risk reducing measures, which may have a significant effect on the risk level.

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