Risk Assessment in Engineering

Principles, System Representation
& Risk Criteria

JCSS
Joint Committee on Structural Safety

Dedication

Development and dissemination of philosophy, science and technology constitutes the ultimate instrument for the safeguarding of society and civilization. This is realized by most of us, however, the successful implementation of this instrument in practice is not obvious; it depends on individuals.

No one individual can be given a specific assignment in this context, it works differently, the assignments are taken by individuals, the dedication and distinction of which the rest of us rely and depend upon.

The present document has been developed on the basis of discussions and contributions realized within the Joint Committee on Structural Safety over the past 6 years. The result should be seen as a joint effort of all members of the committee.

One member on this committee stands out from the rest of us, Franco Zuccarelli. Since the very early developments of the present document Franco showed true devotion to help ensure that the document would enhance decision making in society and industry, ultimately helping us all in improving the development of society.

Franco Zuccarelli died of illness on November 5, 2005, two days after sending me his latest comments concerning this document. This document is dedicated to Franco.

June, 2008.

Michael Havbro Faber

President of the JCSS

Preface

The present document has been produced by the Joint Committee on Structural Safety (JCSS) during the period 2001-2006 and reports on part of the work performed within the Working Party 2 on Risk Assessment in Civil Engineering.

The document should be seen as an aggregation of background information on the various aspects of relevance for risk assessment in engineering. In this respect the present document rests on a number of basic documents on risk assessment in engineering produced by the members of the JCSS in the same period of time.

Finally, an also an Annex to the present document including examples of the application of the various formulations for risk assessment in engineering has been produced and is under continuous further development.

The background documents and the Annex are available from: http://www.jcss.ethz.ch/.

1   Introduction

The present document constitutes the Joint Committee on Structural Safety (JCSS) *Risk Assessment in Engineering, Principles, System Representation and Risk Criteria*. Risk assessment is in the following understood as a process of decision making based on risks. The developed guideline is a consensus between the members of the JCSS in regard to what can be considered as a best practice for risk based decision making in the field of engineering.

The guideline is addressed to decision makers and professionals responsible for or involved in establishing decision support. The purpose of the document is to outline the basic premises for the utilization of risk assessment in establishing rational decisions for the benefit of and in consistency with the preferences of society and other stakeholders. In this way the present document provides the general philosophy to be followed and points to a best practice in the treatment of the many aspects of this complex problem.

It is underlined that the guideline contains a framework for risk based decision making which is both generic, i.e. in principle context independent, but also represents an integral approach. This implies that explicit consideration is given to the interaction between all relevant agents, i.e. technical systems, nature, humans and organizations in the assessment of the risks associated with the system considered. Only when an integral approach is taken to risk assessment it can be ensured that the significant risk contributions originating from the interactions between the different agents are accounted for. In fact any risk assessment not accounting for this interaction must in general be seen as subject to crude simplifications whereby the transparency of the results of the assessment is severely limited. It is advocated to take a holistic perspective to risk assessments also in regard to time. Risk assessments should consider all phases of the life of a technical system from the early concept phases to the end of the service life including decommissioning. In addition also intergenerational aspects of risks and decision making must be considered in the context of sustainable societal developments.

The guideline provides decision support for risk and safety management at both *strategic*, *normative* and *operational* levels. Decision makers at strategic and normative levels are normally responsible for the risks associated with not only one asset, i.e. structures, infra-structure networks and activities, but for a portfolio of assets. If risk assessments are not performed consistently for the individual components of the asset it is not possible to assess the portfolio risk. Furthermore, and more importantly it is then also not possible to device the rational strategies in terms of resource allocation and actions of risk control and reduction.

The approach advocated in the present document is new in the sense that it emphasizes the need for a generic, scientifically based methodology with a holistic perspective and furthermore describes the principles on how to do it. The approach is largely philosophical and generally methodological and does not depend on the latest development in e.g. numerical methods and specific techniques for specific technical investigations. Thereby it is ensured that future inevitable technological improvements will not result in the present document becoming obsolete.

Finally it should be noted that the focus of the present document is engineering risk assessment and decision support. However, the principles are general and can be applied in all areas.

2 Framework for risk assessment

2.1 Engineering Risk assessment and decision making

The development and management of the societal infrastructure is a central task for the continued success of society. The decision processes involved in this task concern all aspects of managing and performing the planning, investigations, designing, manufacturing, execution, operations, maintenance and decommissioning of objects of societal infrastructure, such as traffic infra-structure, housing, power generation, power distribution systems and water distribution systems. The main objective from a societal perspective by such activities is to improve the quality of life of the individuals of society both for the present and the future generations. From the perspective of individual projects the objective may simply be to obtain a maximal positive economic return of investments.

Decision making for the purpose of assessing and managing risks should be seen relative to the occurrence of hazards; i.e. risk management in the situations before, during and after the events of hazards. This is because the possible decision alternatives or boundary conditions for decision making change over the corresponding time frame. Before a hazard occurs the issue of concern is to optimize investments into so-called preventive measures such as e.g. protecting societal assets, adequately designing and strengthening societal infrastructure as well as developing preparedness and emergency strategies. During the event of a hazard the issue is to limit consequences by containing damages and by means of rescue, evacuation and aid actions. After a hazard event, the situation is to some degree comparable to the situation before the event, however, the issue here is to decide on the rehabilitation of the losses and functionalities and to reconsider strategies for prevention measures. In Figure 1 the different decision situations and the focus of earthquake risk management is illustrated as an example.
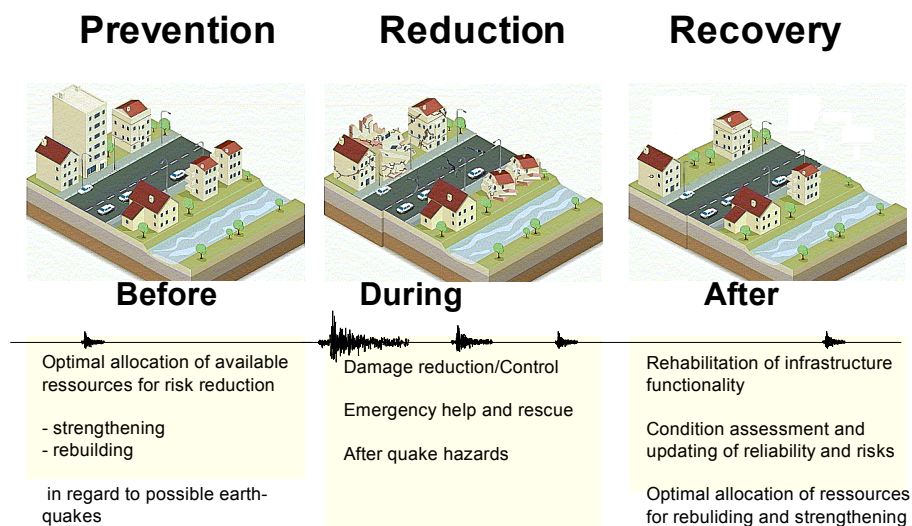

Figure 1 Decision situations for management of earthquake risks.

If all aspects of the decision problem would be known with certainty, the identification of optimal decisions would be straightforward by means of traditional cost-benefit analysis. However, due to the fact that our understanding of the problems involved in the decision problems often is far less than perfect and that we are only able to model the involved processes of physical phenomena as well as human interactions in rather uncertain terms, the decision problems in engineering is subject to significant uncertainty. Due to this, it is not possible to assess the outcomes of decisions in certain terms. There is no way to assess with

certainty the consequences resulting from the decisions we take. However, what can be assessed are the risks associated with the different decision alternatives. Based on risk assessments, decision alternatives may thereby be consistently ranked. If the concept of risk as the simple product between probability of occurrence of an event with consequences and the consequence of the event is widened to include also the aspects of the benefit achieved from the decisions, then risk may be related directly to the concept of utility from the economic decision theory and a whole methodical framework is made available for the consistent identification of optimal decisions. This framework is considered the theoretical basis for risk based decision making and the following chapters are concerned about the application of this for the purpose of risk management in engineering.

2.2   Decisions and decision maker

A decision may be understood as a committed allocation of resources. The decision maker is an authority or person who has authority over the resources being allocated and responsibility for the consequences of the decision to third parties. The intention of the decision maker is to meet some objective, the value of which is at least in balance with the resources allocated by the decision. The decision maker faces the problem of choosing between a set of decision alternatives which may lead to different consequences in terms of losses and benefits. The objective aimed for by the decision making represents the preference of the decision maker in weighing the different attributes which may be associated with the possible consequences of the decision alternatives.

It is thus clear that the formulation of the decision problem will depend very much on the decision maker. Who are the stakeholder, the beneficiaries and the responsible parties? Each possible decision maker will have different viewpoints in regard to preferences, attributes and objectives. It is important to identify the decision maker, since the selection and weighting of attributes must be made on behalf of the decision maker.

Engineering decision making and risk assessment for the management of hazards is usually performed on behalf of society. It is thus useful to consider a society as an entity of people for which common preferences may be identified, exogenous boundary conditions are the same and which share common resources. It is clear that this definition may be applied to unions of states or countries, individual states and countries as well as local communities depending on the context of the decision making, however, it is seen that the geographical limitations are not essential, even though they often in reality are implicitly given by the other attributes. Considering a state or a country as a society it may be realized that such a society may comprise a hierarchical structure of societies defined at lower levels, such as cantons, municipalities and communities; each society with their set of attributes partly defined through the societies at higher level.

The following represents six general decision making levels. However, a further specification of the possible decision makers may depend on the political structure of the considered country.

1. Supranational authority

2. National authority and/or regulatory agencies

3. International private company

4. Local authority

    5. Private owner

    6. Private operator

    7. Specific stakeholders

The decision might not succeed in meeting the objective; one might allocate resources and yet, for a number of reasons, not achieve the objectives. The decision maker might have several conflicting objectives. The degree by which an objective is achieved is measured in terms of attributes (or criteria).

2.3 Attributes of decision outcomes

There are essentially three types of attributes - natural, constructed and proxy. Natural attributes are those having a common interpretation to everyone (cost in dollars, number of fatalities and other measurable quantities). For many important objectives, such as improving image and increasing international prestige, it is difficult or impossible to come up with natural attributes. The attributes to be used must essentially define what is meant by the objective. Constructed attributes may be used for this, these are made up of verbal descriptions of several distinct levels of impact that directly indicate the degree to which the associated objective is achieved and a numerical indicator is assigned to these levels. Examples of constructed attributes turning into natural attributes with time and use are the gross national product GNP (aggregate of several factors to indicate economic activity of a country), the Dow Jones industrial average etc. Finally, there are cases where it is difficult to identify either type of attribute for a given objective. In these cases indirect measurements may be used. The attributes used to indicate the degree to which the objective is achieved are called proxy attributes. When an attribute is used as proxy attribute for a fundamental objective, levels of that attribute are valued only for their perceived relationship to the achievement of that fundamental objective. The decision maker will make decisions consistent with her/his values, which are those things that are important to her/him, especially those that are relevant to her/his decision. A common value is money, according to which the decision maker will attempt to increase his wealth. Others might be personal, such as happiness or security, or social, such as fairness.

2.4 Preferences among attributes - utility

Having determined the set of attributes, the objectives must be quantified with a value/utility model. This is done by means of converting the attribute values to a value scale by means of judgment of relative value or preference strength. The value scale is often referred to as a utility function. In some cases it may not appear obvious how to directly transfer different attribute values into one common value scale. To overcome this apparent problem, it is possible to consider multi-attribute decision problems. However, it is emphasized that the solution to a multi-attribute will imply a weighing of the different attributes against each other and more transparency in the decision process is thus achieved by making this weighing directly.

The multi-attribute value problem is a problem of value trade-offs. These trade-offs can be systematically structured in utility functions. These are scalar valued functions defined on the consequence space, which serve to compare various levels of the different attributes indirectly. Given the utility function the decision maker's problem is to choose that alternative from the space of feasible alternatives, which maximizes the expected utility.

The expected utility is used as a relative measure, making it possible to choose between various actions. The action with the largest expected utility will be chosen from among the possible actions. Thus, no absolute criterion for the acceptability of the considered action is given from decision theory.

2.5   Constraints on decision making

A decision analysis as such is a relative comparison of the defined alternatives from which the best alternative will be recommended. However, this does not ensure that the risk of the best alternative is acceptable with respect to e.g. the safety of the individual. In order to secure that e.g. the level of safety for persons is not violated, the corresponding risk can be calculated and checked against specified maximum levels. These levels should be regarded as basic constraints on the decision-making process.

2.6   Feasibility and optimality

Different decision alternatives will imply different potential losses and potential incomes. The representation of risk in terms of expected utility facilitates decision making in correspondence with the preferences of the decision maker in accordance with the decision theory. In Figure 2 an illustration is given of the variation of utility, measured in terms of expected benefit of an activity, as a function of different decision alternatives.
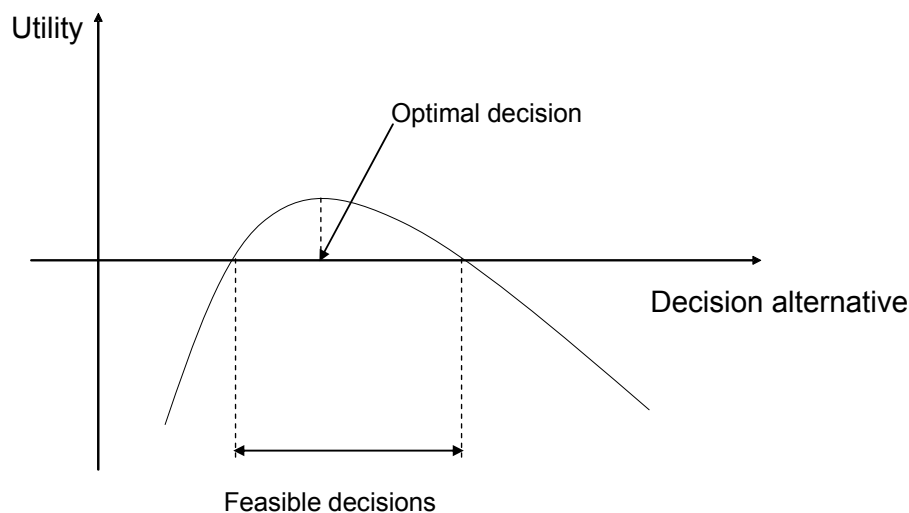

Figure 2. Illustration of variation of utility (expected benefit) as a function of different decision alternatives.

Decisions which do not yield a positive benefit should clearly not be chosen. Optimally, the decision yielding the largest utility is selected, but, as outlined in the foregoing, there could be constraints on the decision alternatives which are not explicitly included in the formulation of the utility function. In these cases not all feasible decision may be acceptable. This is considered in more detail in Section 4.5.

3   System modeling

Decision making can be seen as being equivalent to participate in a game where the decisions (moves) by the decision maker aim to optimize the utility in correspondence with the preferences the decision maker is representing. The main opponent in the game is nature, but also the individuals of society which by lack of knowledge, by accident or by malevolence

may impose damage to the society must be accounted for. Figure 3 illustrates risk based decision making in a societal context from an intergenerational perspective. Within each generation, decisions have to be made, which will not only affect the concerned generation but all subsequent generations. It should be emphasized that the definition of the system in principle must include a full inventory of all potentially occurring consequences as well as all possible scenarios of events which could lead to the consequences.

At an intra generational level, the constituents of the game consist of the knowledge about the system and the surrounding world, the available decision alternatives and criteria (preferences) for assessing the utility associated with the different decision alternatives.
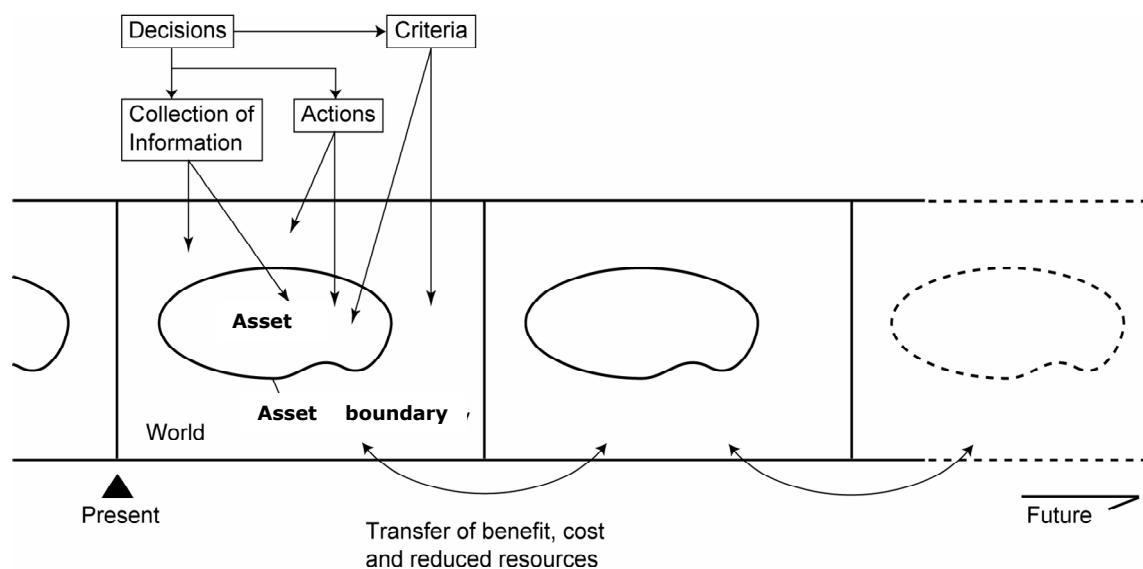

Figure 3. Main constituents in risk based intra-/intergenerational decision analysis.

Knowing the rules (constituents) of the game, i.e. the assets, the possible consequences and how all these factors interrelate with the world outside the assets and into the future is essential for winning the game. For this reason a very significant part of risk based decision making in practice is concerned about system identification/definition as well as the identification of acceptance criteria, possible consequences and their probabilities of occurrence. Playing the game is done by "buying" physical changes in the system or "buying" knowledge about the system such that the outcome of the game may be optimized.

It is instructive to consider a system to be comprised by an ensemble of interrelated constituents; buildings, structures, components, lifelines, technical equipment, procedural processes, humans and the environment. In a broad sense the constituents can also be termed assets. The individual constituents and the logical interrelation between the constituents provide the characteristics of the system. A system may be defined through any characteristic of the ensemble of the constituents which are not already a characteristic of the individual constituents; this definition follows the perspective that "more is different". Here, as we are dealing with systems associated with uncertainty and our main concern is risk, we will focus on the risk associated with the system performance.

In describing a system, a spatial and temporal representation of all constituents is required; this includes a description of the interrelations between all relevant exposures (hazards), the assets and the possible consequences. Exposures to physical objects like structures and

lifelines may e.g. comprise loads caused by operation and events of nature. Exposures might also be related to events originating from procedural mishaps and generally comprise any unforeseen or unintended behavior of humans; this in turn may occur due to natural and organizationally given boundary conditions as well as malevolence. Direct consequences are related to damages on the individual constituents of the system, whereas indirect consequences are understood as any consequences beyond the direct consequences, i.e. associated with loss of system functionalities.

The appropriate level of detail or scale depends on the physical or procedural characteristics or any other logical entity of the considered problem, as well as the spatial and temporal characteristics of consequences. The important issue when a system model is developed is that it facilitates a risk assessment and risk ranking of decision alternatives which is consistent with available knowledge about the system and which facilitates that risks may be updated according to knowledge which may be available at future times. Furthermore, the system representation should incorporate options for responsive decision making in the future in dependence of knowledge available then.

It is furthermore important that the chosen level of detail is sufficient to facilitate a logical description of events and scenarios of events related to the constituents of the system which individually and/or in combination may lead to consequences. In addition to this, the representation of the system should accommodate, to the extent possible, for collecting information about the constituents. This facilitates that the performance of the system may be updated through knowledge about the state of the individual constituents of the system.

3.1   Knowledge and uncertainty

Knowledge about the considered decision context is a main success factor for optimal decision making. In real world decision making lack of knowledge (or uncertainty) characterizes the normal situation and it is thus necessary to be able to represent and deal with this uncertainty in a consistent manner.

In the context of societal decision making with time horizons reaching well beyond individual projects or the duration of individual decision makers, the uncertainty related to system assumptions are of tremendous importance. Rather different assumptions can be postulated in regard to future climatic changes, economic developments, long term effects of pollution etc. It is obvious that if the wrong assumptions are made, then also the wrong decisions will be reached.

To the degree that uncertainties and their dependencies might influence the assessed risks it is thus important that they are accounted for in the calculation of risks. The present section provides guidelines, i.e. guiding principles as well as recommended application of these, on how to represent uncertainties in the assessment of risks.

The consistent treatment of knowledge and the associated uncertainty play a key role not least when managing risks for portfolios of assets; the consistent representation of knowledge and uncertainty assures that results of risk estimates obtained for different assets and for individual hazards can be integrated and aggregated. This implies that risk assessment for e.g. objects or networks subject to several different types of hazards such as e.g. traffic accidents as well as rock-fall can be performed by integrating the different model components from the corresponding application areas with due consideration to the uncertainties which influence these models. In the same way risks assessed for two different objects may also be aggregated.

If different system representations could be valid, due to lack of knowledge, it is essential to take this into account in the process of risk based decision making. This is e.g. the case when considering possible future climatic changes, when modeling extreme earthquake excitation and when assessing consequences for hazard events which go beyond historically recorded experience.

There exist a large number of propositions for the characterization of different types of uncertainties. It has become standard to differentiate between uncertainties due to inherent natural variability, model uncertainties and statistical uncertainties. Whereas the first mentioned type of uncertainty is often denoted aleatory (or Type 1) uncertainty, the two latter are referred to as epistemic (or Type 2) uncertainties. However this differentiation is introduced for the purpose of setting focus on how uncertainty may be reduced rather than calling for a differentiated treatment in the decision analysis. In reality the differentiation into aleatory uncertainties and epistemic uncertainties is subject to a defined model of the considered system.

For the decision analysis, the differentiation is irrelevant; a formal decision analysis necessitates that all uncertainties are considered and treated in the same manner. The relative contribution of the two components of uncertainty depends on the spatial and temporal scale applied in the model.

The risk assessment should include a description of all relevant assumptions made in connection with the system identification, as well as the modeling of consequences and frequencies. The level and type of knowledge available to support the assumptions, as well as the modeling of consequences and frequencies, should be explicitly stated.

In some cases information is available in terms of observations of e.g. accidents or events of natural hazards. In case such information is available it should always be attempted to utilize this for the modeling of frequencies of the events. The same applies for consequences for which experience from previous events might be utilized. Such models should account for the statistical uncertainty representing the effect of limited data as well as possible model uncertainties originating from the use of the models for other cases than the case from which they were obtained.

In many cases parameters which are known to have influence on the risks are simply not known in a given situation. This may e.g. be the case if the aggregated risk for all tunnels is assessed without accounting for detailed information about the geometry of the tunnels. In such cases it is important to account for the lack of knowledge, by representing the unknown tunnel geometry parameters as uncertain parameters in the formulation of the risk analysis models.

Commonly the assessment of frequencies and consequences depend on models based on experience and engineering understanding. In such cases the uncertainty associated with the models should be described preferably in quantitative terms.

In general the documentation of the knowledge should address all relevant uncertainties due to inherent natural variability as well as model uncertainties and statistical uncertainties. Independent on whether such uncertainties are neglected, assessed qualitatively or quantitatively, as a general rule; their treatment and modeling should always be stated clearly. Neglecting uncertainties in the risk assessment should always be justified by sensitivity studies.

The quantitative representation of uncertainties in risk assessment, should take basis in the probability theory. The Bayesian statistics provides a basis for the consistent representation of uncertainties independent of their source and readily facilitates the joint consideration of purely subjectively assessed uncertainties, analytically assessed uncertainties and evidence as obtained through observations.

All uncertainties should be represented in accordance with available data and/or unbiased estimated, based on experience and expertise.

It is underlined that possible extreme consequences may be subject to considerable uncertainty, due to the fact that only very little information and experience is available on these. Indirect consequences due to the perception of adverse events by the public are poorly understood and the associated large uncertainty should be accounted for accordingly in the risk assessment.

Generally, uncertainties are best represented through random variables with specified probability density functions and corresponding parameters. If two or more uncertainties can be assumed to be statistically or otherwise dependent, this dependency should be accounted for in the probabilistic modeling. Statistical dependency may be appropriately represented through correlation. Functional dependency or common cause dependency is appropriately represented through hierarchical probabilistic models. Only if the prevailing dependencies are correctly accounted for when assessing the risks for different objects and systems will it be possible to aggregate the risks correctly.

As an example, consider the risks due to rock-fall events along a road. There may be several objects i.e. tunnels, bridges and galleries along the road, each separated by road way segments. The aggregated risk for the considered road would conveniently be assessed through the sum of the risks for all objects. However, in this case the risks for each of the objects depend on common factors including the average traffic volume per hour (over the day), the time of the event of rock-fall (day/night), the type of traffic and the consequences due to disruption, each of which might be associated with uncertainty. When assessing the total risk aggregated over all objects on the considered roadway, it is thus necessary to aggregate the risks conditional on the common uncertain parameters first and thereafter to integrate the aggregated risks over the uncertain common parameters. In principle this operation is quite simple, but in essence very important, as it will yield a significant effect on the aggregated risks. If risks are aggregated without consideration of common uncertain factors, the resulting total risk may be grossly at error.

3.2   System representation

The risk assessment of a given system is facilitated by considering the generic representation illustrated in Figure 4. A main issues in the representation of systems is to facilitate and enhance the identification of scenarios of event which, starting from exposures such as loads and attacks by chemical substances, induce damages and failures and further onto consequences.
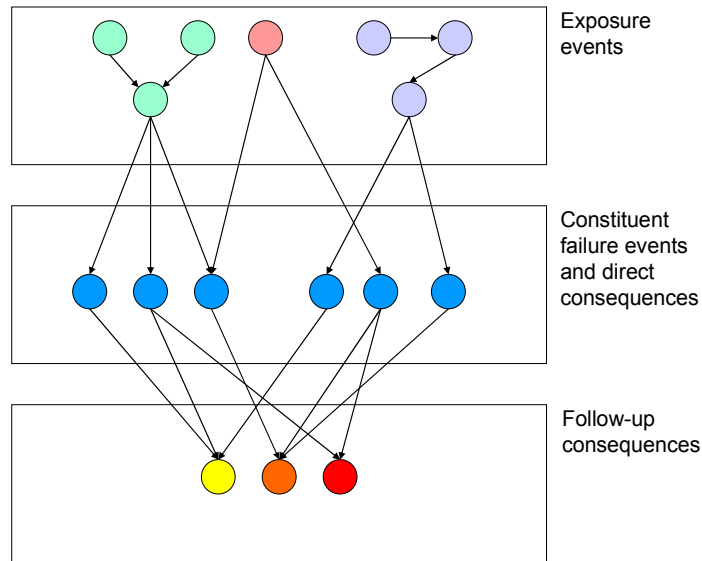
Figure 4.   Generic system representation in risk assessments.

The exposure to the system is represented as different exposure events acting on the constituents of the system. The constituents of the system can be considered as the systems first defense in regard to the exposures. The damages of the system caused by failures of the constituents are considered to be associated with direct consequences. Direct consequences may comprise different attributes of the system such as monetary losses, loss of lives, damages to qualities of the environment or just changed characteristics of the constituents.

Direct consequences, are thus defined as all marginal (not considering loss of system functionality) consequences associated with damages or failures of the constituents of the system. Based on the combination of events of constituent failures, and the corresponding consequences indirect consequences may occur.

Indirect consequences could be caused by e.g. the sum of monetary losses associated with the constituent failures as well as the loss of functionality of the system caused by the effect of one or more constituent failures. Indirect consequences, may thus be defined as any consequences associated with the loss of the functionalities of the system and by any specific characteristic of the joint state to the constituents and the direct consequences themselves. The indirect consequences in systems risk assessment play a major role, and the modeling of these should be given great emphasis. It should be noted that any constituent in a system can be modeled as a system itself. A system could be a road network with constituents being e.g. bridges, see Figure 5, or an offshore oil and gas field with constituents being Floating Production, Storage and Offloading facilities (FPSO's), see Figure 6. The bridges and FPSO's in turn could also be systems with constituents structural members. Depending on the level of detail in the risk assessment, i.e. the system definition, the exposure, constituents and consequences would be different.
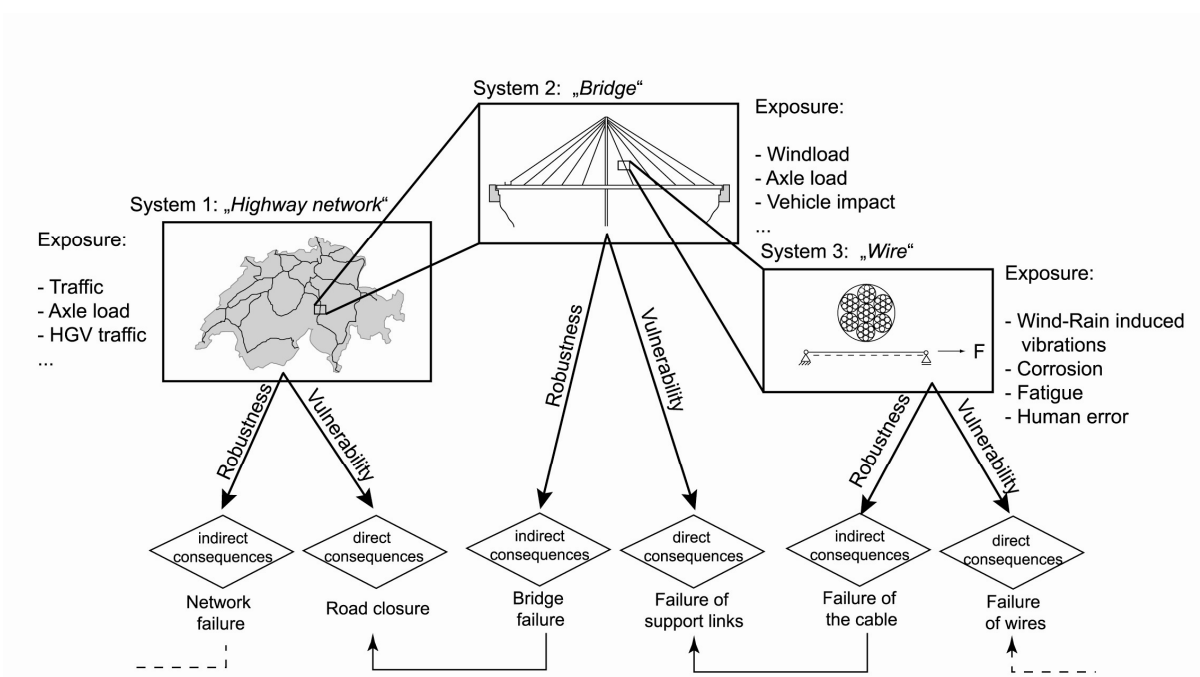
Figure 5. Generic system characterizations for a roadway network and infrastructure object at different scales in terms of exposure, vulnerability and robustness.
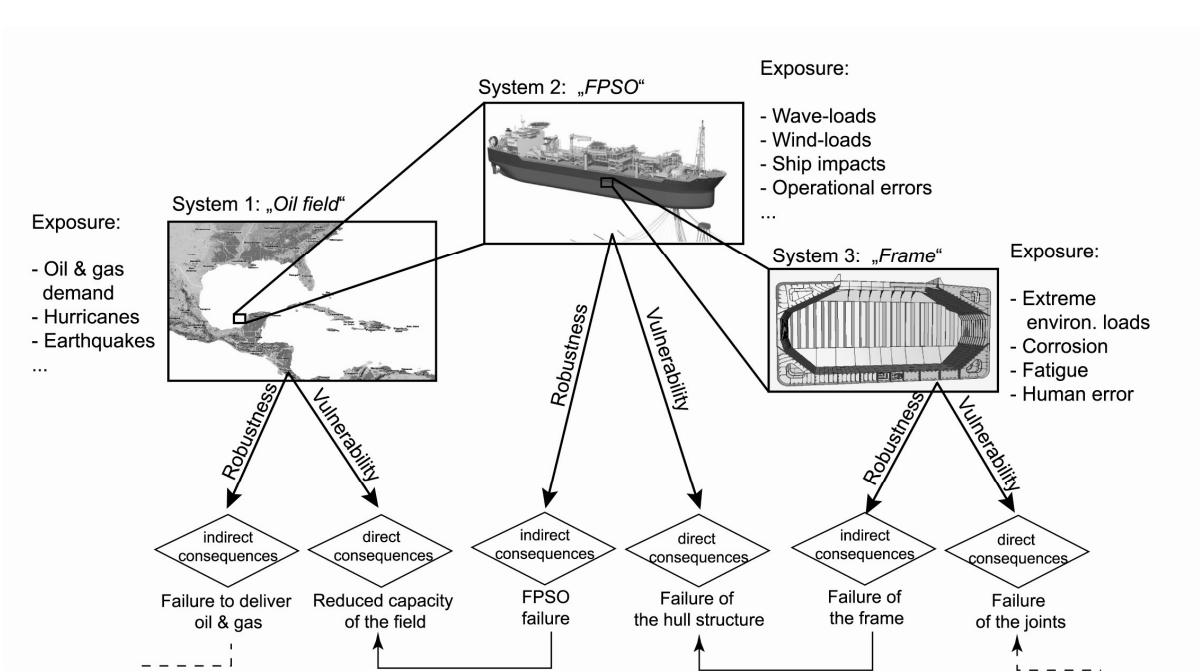

Figure 6. Generic system characterizations for an offshore oil and gas production field and individual facilities at different scales in terms of exposure, vulnerability and robustness.

The vulnerability is related to the risk associated with the direct consequences and the lack of robustness is related to the degree the total risk are increased beyond the direct consequences.

Indeed the system representation outlined in the above is only meaningful subject to a definition of what is considered to be exposures, constituents, direct and indirect consequences. However, in practical applications, the definition of these is generally given by

the decision problem itself. If we want to determine the optimal allocation of the reliability of bridges in a road network in regard to e.g. earthquake events, the exposures would be the potential earthquake loads, the constituents would be the individual bridges, the direct consequences would be any consequence associated with the failure of any individual bridge in isolation and the indirect consequences would be loss of network functionalities plus consequences due to possible budget overruns caused by loss of individual bridges. Considering the design of a structure, the exposures would be any operational or environmental loads acting on the structures, including possible aggressive chemical environmental effects. The constituents would include the structural components, joints as well as passive and active protective and monitoring systems, which serve to provide the structure with a sufficient safety. Direct consequences would be material damages, loss of lives and damages to qualities of the environment caused by the damage or failure of any individual constituent. Indirect consequences would comprise the monetary consequences of the loss of the functionality provided by the structure, as well as additional material losses imposed on surrounding assets, including buildings, lifeline systems, environment and humans.

3.3   Exposures and hazards

The hazards or exposures acting on the constituents of a system are defined as all possible endogenous and exogenous effects with the potential to cause consequences. A probabilistic characterization of the exposure to a system requires a joint probabilistic model for all relevant effects relative to time and space.

The characteristics of exposures are very different, depending on the individual exposure types. Exposures such as technical failures, accidents, explosions, rock-fall, and landslides are generally very suddenly occurring events. Floods and fire storms are generally more slowly evolving, while climatic changes and e.g. droughts are much slower. Exposures like human errors and malevolence, in turn, have their own patterns over time and space. In a risk management context, the characterization of exposures must take these differences into account in order to facilitate a realistic assessment of the possible consequences as well as to allow for the identification of possible relevant measures of risk prevention and loss reduction.

For suddenly occurring events, usually the probability of the event itself is needed; e.g. the probability that a flood will occur or the probability of an earthquake. Part of the safety against such events is carried by the probability that they will not occur at all. However, more characteristics or indicators are needed to facilitate the modeling of the possible consequences of the event. Considering earthquakes, typically applied indicators are the Peak Ground Acceleration and the earthquake magnitude. Considering explosion events, e.g. the exceedance probability of the pressure at a given location would be of interest. These characteristics or indicators are useful, because knowledge about them provide basis for assessing the potential damages caused by the exposures, such as e.g. liquefaction of soil and damages to buildings caused by the dynamic excitation from the earthquake.

It is important to note that in many risk assessments the joint representation of several exposures is required. This is e.g. the case when considering loads acting on structures where joint occurrences of live loads, dead loads and environmental loads together with chloride induced deterioration can constitute an important scenario for the assessment of the risks for a road way bridge.

3.4 Consequences

The consequences which potentially may be caused by different hazards are manifold and generally depend strongly on the specific characteristics of the hazard as well as the location where it occurs and the assets which are exposed. As a general rule, consequences should be assessed in regard to loss of lives and injuries, damages to the qualities of the environment and economic losses. Considering e.g. the assessment of the risks on a roadway network, the consequences illustrated in Figure 7 might be relevant.
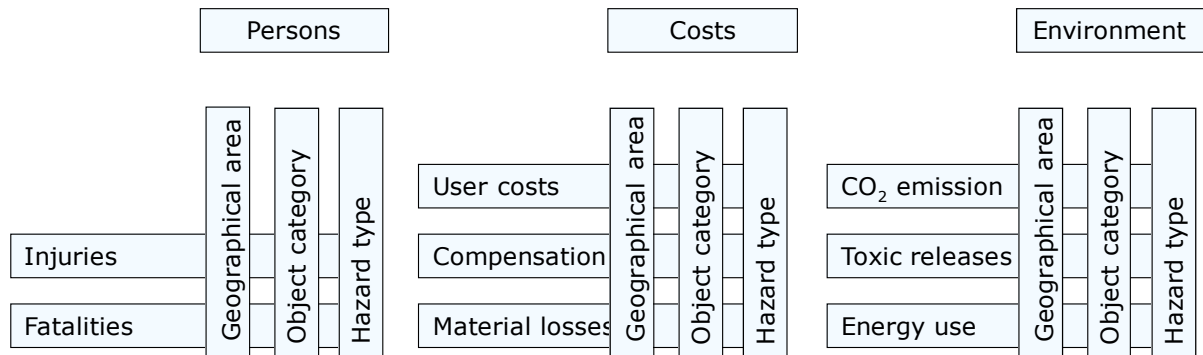

Figure 7. Example of different consequences to consider in a risk assessment for a roadway network.

The risk assessment is greatly facilitated by considering the generic representation of the development of consequences shown in Figure 4. However, in the assessment of consequences, it is useful to consider a further differentiation as illustrated in Figure 8. From Figure 8 is seen that two types of indirect consequences are differentiated, namely the indirect consequences due to physical system changes and the indirect consequences caused by the societal or public perception of these. The reason for this differentiation is to indicate how risk management may efficiently be supported by risk communication. The better and more targeted risk communication is undertaken before, during and after events of natural hazards, the smaller the consequences caused by perception will be. Often traditional risk assessments focus on the assessment of direct consequences and do not attempt to model the indirect consequences by rigorous modeling. Instead, indirect consequences are included by somehow amplifying the direct consequences by means of a risk aversion function, the characteristics of which generally are assessed subjectively.

Indeed it is a little puzzling that the often more important contribution to consequences is commonly modeled by means of the simplest possible approximation. The approach suggested here, where consequences are differentiated into different components is meant to circumvent excessively simplistic modeling, bringing the indirect consequences into focus and indicating the different ways they might be controlled.

A range of different terms to characterize the effect of hazards are applied across different disciplines. Among these, vulnerability, resilience, robustness and adaptive capacity are used most frequently. Vulnerability is commonly related to risk over time in terms of expected potential future losses considering all possible events which may lead to such. Robustness is often applied to characterize the response of a system to given changes in the system state variables. Different interpretations of robustness are available in the different disciplines. In structural engineering, a robust structural system is understood as a structure which will not loose functionality at a rate or extent disproportional to the cause of the change in the state variables. The term resilience in accordance with its Latin origin may be associated with a systems elastic ability to return to its original state after some perturbation. Usually, in risk

assessment resilience, is applied in a qualitative manner as a descriptor of a considered system's or society's ability to rehabilitate its main functions, e.g. such as e.g. livelihood, however, it must be appreciated that the considered system may indeed be very dissipative; changes in its state variables may be associated with significant losses. The same or similar meanings are typically associated with the term adaptive capacity which serves as a measure of the ability of a given system to adapt to new situations and thereby maintain and or even improve functionality. In the context of risk assessment the meaning of robustness is generally very close to the meaning of resilience and adaptive capacity.
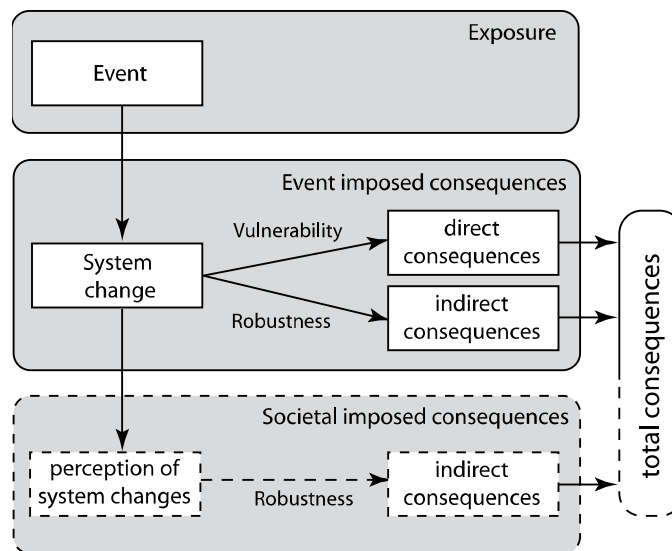

Figure 8. Representation of the mechanism generating consequences.

In view of the different and somewhat imprecise use of different terms for the characterization of systems in regard to how exposures may result in consequences of various degrees of severity, the terms vulnerability and robustness are defined more stringently in the following. In Chapter 4 mathematical expressions are to be provided for the quantitative assessment of both vulnerability and robustness.

3.4.1 Vulnerability

The vulnerability of a system is defined as the ratio between the risks due to direct consequences and the total value of the considered asset or portfolio of assets considering all relevant exposures and a specified time frame. Conditional vulnerabilities may be defined through the vulnerability conditional on given exposures.

3.4.2 Robustness

The robustness of a system is defined as the ratio between the direct risks and the total risks, (total risks is equal to the sum of direct and indirect risks), for a specified time frame and considering all relevant exposure events and all relevant damage states for the constituents of the system. A conditional robustness may be defined through the robustness conditional on a given exposure and or a given damage state.

4   Risk Assessment

4.1   Analysis and quantification of systems risk

Within different application areas of risk assessment various rather specific methodologies have been developed and this has had the effect that risk assessments across the boundaries of application areas are difficult to compare and even more difficult to integrate. Numerous procedural schemes for risk based decision making are available, but these focus on the project flow of risk assessments rather than the framework for risk assessment itself. Moreover, one of the most significant drawbacks of existing frameworks for risk assessment is that they have not been developed from a Bayesian perspective, i.e. do not sufficiently facilitate and enhance the potential for utilizing evidence and/or indications of evidence in the assessment of risks. Therefore the generic risk assessment framework illustrated in Figure 9 is proposed. This framework   facilitates a Bayesian approach to risk assessment and full utilization of risk indicators.

The risk R_E associated with one particular event E is assessed through the product between the probability p_E that the event takes place and the consequences c_E associated with the event, i.e.:

$$R_E = p_E \cdot c_E \tag{1}$$

Risks must be related to a time frame T, such as e.g. one year. Therefore it often is relevant to consider the risks associated with the number of a specific type of event $n(T)$ within the considered time frame T. In that case Equation (1) is appropriately written as:

$$R(T) = \sum_{i=0}^{\infty} P(n(T) = i) \cdot c \cdot i \tag{2}$$

where $P(n(T) = i)$ is the probability of i events of the considered type within the time frame T and c is the consequence associated with the occurrence of one event. However, Equation (2) may also conveniently be written as:

$$R(T) = E\big[n(T)\big]c \tag{3}$$

where $E\big[n(T)\big]$ is the expected number of events of the considered type within the time frame T. The expected number of events may be established by integration over the rate of occurrences ν as:

$$E\big[n(T)\big] = \int_T E\big[\nu(t)\big]dt \tag{4}$$

For different applications either of the two different formulations of risk may be convenient i.e., Equation (1) or (3).

As risks are normally associated with scenarios of events it is important to be able to quantify either the probability or the rate of occurrence of the scenarios, and this in general necessitates a probabilistic modeling involving conditional probabilities or rates respectively. In the following only the presentation for the quantification of risks is shown on the basis of probabilities, however, it could equally well have been presented in terms of rates.

In Figure 9 the asset which is considered subject to a risk assessment is assumed to be exposed to hazardous events (exposures EX) with probabilistic characterization $p(EX_k)$, $k = 1, n_{EXP}$, where n_{EXP} denotes the number of exposures. It is assumed that the considered asset includes n_{CON} individual constituents, each with a discrete set of component damage states C_{ij}, $i = 1, 2..n_{CON}$, $j = 1, 2..n_{C_i}$, where n_{C_i} is the total number of different damage states of constituent i. The probability of direct consequences $c_D(\mathbf{C}_l)$ associated with the lth of n_{CSTA} possible different state of damage of all constituents $\mathbf{C}_l$, conditional on the exposure event EX_k is described by $p(\mathbf{C}_l|EX_k)$ and the associated conditional risk is $p(\mathbf{C}_l|EX_k)c_D(\mathbf{C}_l)$. The vulnerability of the asset is defined through the risk due to all direct consequences (for all n_{CON} constituents) which may be assessed through the direct risk R_D, i.e. the expected value of the conditional risk due to direct consequences over all n_{EXP} possible exposure events and all constituent damage states n_{CSTA}:

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l|EX_k)c_D(\mathbf{C}_l)p(EX_k) \tag{5}$$

The vulnerability is then quantified through the index I_V as:

$$I_V = \frac{R_D}{V_A} \tag{6}$$

where V_A is the attribute utilized to measure the value of the direct risk, e.g. the monetary value of the constituents of the considered system, the number of lost human lives or the quantified qualities of the environment.
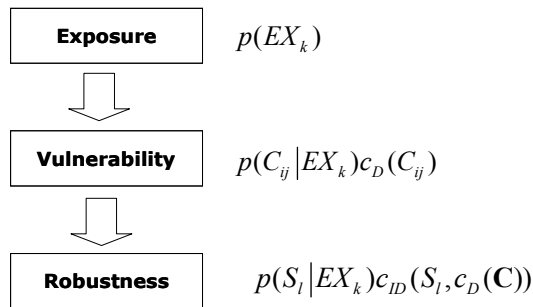

Figure 9. Suggested generic and indicator based risk assessment framework.

Using this definition of vulnerability in the context of management of risks provides a clear representation of the expected value of immediate monetary losses, e.g. the amount of economic resources which should be allocated for renewal of societal infrastructure. It might also provide an assessment of loss of lives and damages to the qualities of the environment on the short term; however, provides little information about how the consequences are contained over both time and geography. To assess these additional consequences the indirect consequences must be considered carefully.

The functionality of the considered asset depends on the state of the constituents. It is assumed that there are n_{SSTA} possible different states of the constituents S_m associated with

indirect consequences $c_{ID}(S_m, c_D(\mathbf{C}_l))$. The probability of indirect consequences conditional on a given state of the constituents $\mathbf{C}_l$, the direct consequences $c_D(\mathbf{C}_l)$ and the exposure EX_k, is described by $p(S_m|\mathbf{C}_l, EX_k)$. The corresponding conditional risk is $p(S_m|\mathbf{C}_l, EX_k)c_{ID}(S_m, c_D(\mathbf{C}_l))$. The risk due to indirect consequences is assessed through the expected value of the indirect consequences in regard to all possible exposures and constituent states, as:

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l)) \times p(S_m|\mathbf{C}_l, EX_k) p(\mathbf{C}_l|EX_k) p(EX_k) \tag{7}$$

The robustness of a system may be quantified by means of a robustness index I_R expressed through the ratio between direct risks and total risks, i.e.:

$$I_R = \frac{R_D}{R_{ID} + R_D} \tag{8}$$

which allows for an assessment of decisions in regard to their effect on robustness.

In the foregoing, no mention was made in regard to the time reference period to which the probabilities and consequently also the risks have to be related. A clear specification of these is of course necessary as this will influence the decision making, the assessment of risk acceptance as well as the general modeling of uncertainties as well as the assessment of probabilities.

The definition of the system is of tremendous significance in the definition of exposure, vulnerability and robustness. However, in common practical engineering risk assessments the differentiation is rather straightforward. Considering e.g. structures, the exposures would typically include loads and aggressive chemical environments, the constituents would comprise the structural members and joints, direct consequences would relate to the marginal consequences of damage or failure of each individual structural member and joint, and finally the indirect consequences be related to e.g. collapse of the structure as well as impaired functionality.

In more general terms it is useful to think about a considered system in terms of constituents supporting some functions. Loss of functionality would in most cases constitute the main contribution to indirect consequences.

Finally, it should be mentioned that risks may be represented in various manners, including distribution functions of consequences, showing with what probability different ranges of consequences will occur. Other representations include density functions for risk estimates showing the uncertainty due to epistemic uncertainties. The best representation depends on the purpose of the risk assessment.

In case the risks are to be aggregated (see Section 4.8) with risks assessed in previous assessments, it is of course important that the risks are represented in a consistent manner, and very importantly that possible dependencies between the independently assessed risks are accounted for in the aggregation.

4.2   Indicators of risk

The risk assessment framework allows for utilization of any type of quantifiable indicators in regard to the exposure, vulnerability and robustness of the considered system. Due to the hierarchical structure of the risk assessment, in terms of conditional events the framework is greatly supported by modern risk assessment tools such as e.g. Bayesian Probabilistic Nets and Influence Diagrams.

Risk indicators may be understood as any observable or measurable characteristic of the systems or its constituents containing information about the risk. If the system representation has been performed appropriately, risk indicators will in general be available for what concerns both the exposure to the system, the vulnerability of the system and the robustness of the system, see Figure 10.

In a Bayesian framework for risk based decision making, such indicators play an important role. Considering the risk assessment of a load bearing structure, risk indicators are e.g. any observable quantity which can be related to the loading of the structure (exposure), the strength of the components of the structure (vulnerability) and the redundancy, ductility, effectiveness of condition control and maintenance (robustness).
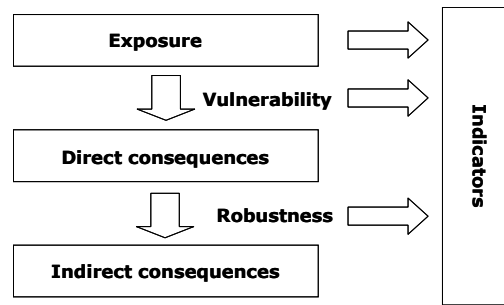

Figure 10. Risk indicators at different levels of the system representation.

In Figure 11 the concept of indicators is illustrated considering the risk assessment of a suspension bridge.

The indicators listed in Figure 11 may readily be utilized for the purpose of Bayesian updating of the probabilities required in the risk assessment.

Considering e.g. updating of the probability that one particular constituent i, is in a particular state j, i.e. $P(C_{ij})$ given the indicator e the updated probability $P(C_{ij}|e)$ becomes:

$$P(C_{ij}|e) = \frac{P(e|C_{ij})P(C_{ij})}{P(e|C_{ij})P(C_{ij}) + P(e|\overline{C_{ij}})(1 - P(C_{ij}))} \qquad (9)$$

where $P(e|C_{ij})$ is the likelihood of the indicator.

Scenario representation	Physical characteristics	Indicators	Potential consequences
Exposure	Flood Ship impact Explosion/Fire Earthquake Vehicle impact Wind loads Traffic loads Deicing salt Water Carbon dioxide Design errors Malevolence	Use/functionality Location Environment Design life Societal importance	
Vulnerability	Yielding Rupture Cracking Fatigue Wear Spalling Erosion Corrosion	Design codes Design target reliability Age Materials Quality of workmanship Condition Protective measures	**Direct consequences** Repair costs Material losses Injuries and fatalities Damages to environment
Robustness	Partial collapse Full collapse	Design codes Ductility Joint characteristics Redundancy Segmentation Condition control/monitoring Emergency preparedness	**Indirect consequences** Rebuilding costs Clean up costs Rescue costs Loss of functionality Injuries and fatalities Socio-economic losses Damages to environment Loss of reputation

Figure 11. Risk indicators at different levels of the system representation.

4.3 *Comparison of decision alternatives*

The basis for ranking different decision alternatives $\mathbf{a} = (a_1, a_2, .., a_{n_d})^T$ is the corresponding risk or more generally the corresponding expected utilities $E\left[U(a_j)\right], j = 1, 2, .. n_d$:

$$E\left[U(a_j)\right] = \sum_{i=1}^{n_{O_j}} p(O_i \left| a_j \right) u(a_j, O_i) \tag{10}$$

where $E\left[\cdot\right]$ is the expectation operator, n_{o_j} is the number of possible outcomes O_i associated with alternative a_j, $p(O_i \left| a_j \right)$ is the probability that each of these outcomes will take place (given a_j) and $u(a_j, O_i)$ is the utility associated with the set (a_j, O_i). This presentation assumes a discrete set of outcomes but can straightforwardly be generalized to continuous sample spaces. Considering the consequence modeling proposed in Section 4.1 Equation (10) can be rewritten as:

$$E\left[U(a_j)\right] =$$

$$\sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l \left| EX_k, a_j \right) c_D(\mathbf{C}_l, a_j) p(EX_k, a_j) + \tag{11}$$

$$\sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l, a_j), a_j) \times p(S_m \left| \mathbf{C}_l, EX_k, a_j \right) p(\mathbf{C}_l \left| EX_k, a_j \right) p(EX_k, a_j)$$

The simplest form of the decision analysis is the so-called prior-analysis. In the prior-analysis the expected utility is evaluated on the basis of statistical information and probabilistic

modelling available prior to any decision and/or activity. The prior decision analysis is illustrated by a simple decision tree in Figure 12. In prior and posterior decision analysis the optimal decision $a^* \in \mathbf{a}$ is identified from:

$$\max_{\mathbf{a}} \ U^*(a) = \max_{\mathbf{a}} E'_{\mathbf{X}}\left[U(a, \mathbf{X})\right] \tag{12}$$

where $U(\cdot)$ is the utility and $\mathbf{X}$ is a vector of random variables representing all uncertainties influencing the decision problem, see also the decision/event tree in Figure 12.
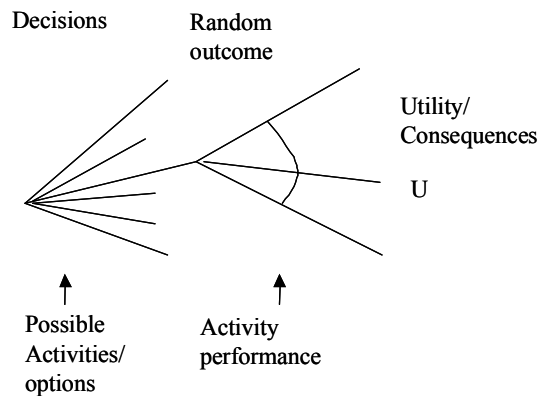

Figure 12. Decision/event tree for prior and posterior decision analysis.

Prior decision analysis thus forms the basis for the simple comparison of utilities associated with different activities and may therefore be applied for purposes of ranking and optimization.

Posterior decision analysis has the same form as prior decision analyses, however, changes in the branching probabilities and/or the utilities in the decision/event tree reflect that new evidence has been obtained or that the considered problem has been changed as an effect of changes of the system or the world surrounding the system.

Pre-posterior decision analysis may be illustrated by the decision tree shown in Figure 13.
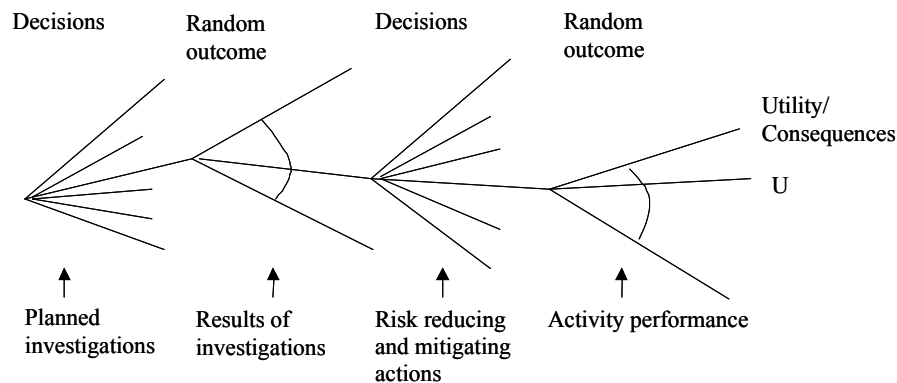

Figure 13. Decision tree for pre-posterior decision analysis.

Using pre-posterior decision analysis optimal decisions in regard to knowledge improvement may be identified. Furthermore, options are built in to the decision making to accommodate for subsequent adaptation of actions which are optimal subject to the improved knowledge.

Such options may e.g. be formulated as decision rules $d(\mathbf{z})$ which specify the line of action as a function of the achieved knowledge $\mathbf{z}$.

In pre-posterior decision analysis the optimal decision $a^* \in \mathbf{a}$ is identified from:

$$\max_{\mathbf{a}} U^*(a) = \max_{\mathbf{a}} E'_{\mathbf{Z}} \left[E''_{\mathbf{X}|\mathbf{Z}} \left[U(d(\mathbf{Z}), \mathbf{X}) \right] \right] \tag{13}$$

$'$ and $''$ refer to the probabilistic description of the events of interest based on prior and posterior information respectively.

Decision analysis can be either formal or informal. Whereas in principle a formal decision analysis includes all possible branches in the decision event tree and accounts for all available knowledge, an informal decision analysis can be understood as an analysis where simplifications are performed either in the probabilistic modelling or in the representation of the event/decision tree. In general it is very difficult if not impossible a priori to assess the validity of decisions based on informal decision analysis and formal decision analysis should thus be the general aim.

The decision theoretical basis outlined in the foregoing may be readily applied for the identification of optimal decisions in regard to risk management. Following the framework outlined in Section 4.1, decisions may be related to how to reduce or avoid exposures, how to reduce vulnerability and how to improve robustness. In addition to this it is also possible and should be considered to formulate the decision problems as explicit functions of information (risk indicators) concerning the exposure, the vulnerability and the robustness which may become available at future times. Thereby the risk management process can be adapted to the available knowledge at any given point in time and optimized accordingly.

4.4 Risk perception

Depending on the situation at hand, decision makers may feel uneasy with the direct application of expected utility as a basis for decision ranking due to principally two reasons: either the decision maker is uncertain about the assessment of the utility/consequence or about the assessment of the probabilities originating from the analysis of the performance of the system and its constituents.

This corresponds to not knowing the rules of the game (see Section 3) and can be seen as the main reason for the emergence of and recent implementation of the precautionary principle in societal decision making e.g. relating to new technologies. In principle the effect of misjudging the utility associated with a particular outcome corresponds to misjudging the probability that the outcome will occur, namely that possible outcomes associated with marginal utility are assessed wrongly. This may lead to both over- and under-estimation of the expected utility, which in turn would lead to different decisions. In order to make decisions which are conservative, decision makers therefore feel inclined to behave risk averse – i.e. give more weight in the decision making to rare event of high consequences (typically an event for which knowledge and experience is limited) compared to more frequent events with lower consequences (for which the knowledge and experience may be extensive); this may in turn lead to decisions biased towards not to engage in activities which actually could indeed be profitable.

From a personal perspective risk averse and even the opposite, risk prone behavior, is fully legitimate to the extent that it of course must represent the preferences of the decision maker.

However, from a societal perspective where important issues include the safeguarding of human lives and qualities of the environment, a non-neutral risk behavior is highly problematic and may lead to a non-uniform allocation of available resources depending on hazard types and different sectors of engineering. From the societal perspective and under the assumption that all relevant outcomes and all uncertainties have been included into the formulation of the utility function, this behavior is fundamentally irrational and also inappropriate. What is extremely important, however, is that the perception of the public and the corresponding societal consequences in case of adverse events is explicitly accounted for as a possible indirect consequence in the formulation of the utility function as illustrated in Figure 8.

Ideally, the public would be informed about risk based decision making to a degree where all individuals would behave as rational decision makers, i.e. not overreact in case of adverse events - in which case the risk averse behavior would be eliminated. This ideal situation may not realistically be achievable but should be considered as one possible means of risk treatment in risk based decision making.

It is a political responsibility that societal decisions take basis in a thorough assessment of the risks and benefits including all uncertainties affecting the decision problem. In some cases, however, due to different modeling assumptions, different experts in decision making may identify differing optimal decisions for the same decision problem. The problem then remains to use such information as a support for societal decision making.

4.5 Risk reduction measures

The various possibilities for collecting additional information in regard to the uncertainties associated with the understanding of the system performance as well as for changes the characteristics of the system can be considered to comprise the total set of options for risk treatment. The risk treatment options may, in the context of risk based decision making, be considered the available decision alternatives. Risk treatment is decided upon for the purpose of optimizing the expected utility achieved by the decision making.

Following the previously suggested framework for risk assessment, risk treatment can be implemented at different levels in the system representation, namely in regard to the exposure, the vulnerability and the robustness, see Figure 14. Considering the risk assessment of a load carrying structure, risk treatment by means of knowledge improvement may be performed by collecting information about the statistical characteristics of the loading (exposure), the strength characteristics of the individual components of the structures (vulnerability) and by systems reliability of the structural system (robustness). The improved knowledge facilitates that decisions are optimized using the pre-posterior analysis outlined in Section 4.3.

Risk treatment through changes of the system characteristics may be achieved by restricting the use of the structure (exposure), by strengthening the components of the structure (vulnerability) and by increasing the redundancy of the structural system (robustness).
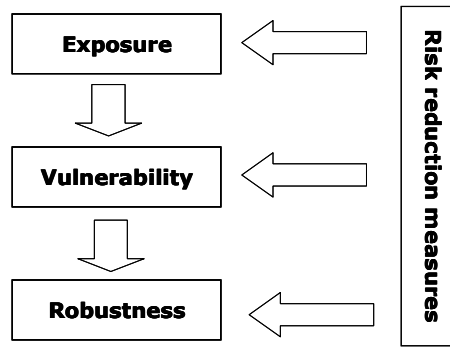
Figure 14. Illustration of how risk treatment might be performed at different levels of the system assessed.

Options for risk treatment should in general be assessed and evaluated in terms of their risk reducing effect, i.e. their efficiency R_{RE}. This may be simply assessed through the reduction of total risks achieved through the measure ΔR divided by the cost of the measure C_R, i.e.:

$$R_{RE} = \frac{\Delta R}{C_R}$$

(14)

By assessing the efficiency of different measures of risk reduction, a prioritization of measures may be established for what concerns reduction of exposures, reduction of vulnerability as well as improvement of robustness for the situations before, during and after the vent of hazards.

4.6   Acceptance of risk

It is generally accepted that the decisions in regard to the planning, design, execution, operation and decommissioning of societal infrastructure should take basis in an optimization of life-cycle benefits using principles of risk assessment as outlined in the foregoing.

However, in addition to risks due to economic losses the decision maker has to take into account also the risks to persons, as well as potential damages to qualities of the environment.

Whenever, on the basis of risk assessments, decision alternatives have been identified and ranked by comparing the expected value of benefits or losses, the risks must be considered in regard to their acceptability. It is suggested to differentiate between tangible and intangible risks, i.e. risks which may easily be expressed in monetary terms and risks which are not.

Intangible values especially concern loss of lives and injuries. Intangible values may, however, also include qualities of the environment. Such qualities could e.g. concern bio diversity. Which intangible values should be considered in a given case must be identified during the system identification.

As a general principle; the regulations in force for the different application areas must be fulfilled and it must be shown that risks are acceptable in accordance with these. Many existing regulations specify requirements to what is denoted individual risks and collective risks. Requirements to maximum individual risks aim to protect individuals, mostly in situations of occupational hazards. Collective risk acceptance criteria are generally applied in

the context of societal planning, including codification. Here no particular differentiation is made in this regard, as the perspective is taken that risks for any individual at any given location engaged in occupational activities or exposed to hazards originating from societal infra-structures, buildings or activities should be limited according to the Societal Willingness To Pay (SWTP) to avoid fatalities.

For what concerns the assessment of the SWTP for reducing life and injury risks, an established practice and scientific basis does exist, see next section. In regard to other intangible values, such as loss of scenic beauty, noise and pollution, there is at present no firm scientific basis for addressing the societal acceptability of potential losses. However, it is important the all quantified risks are presented in a form which provides overview of all risks and facilitates risk communication. This will facilitate a differentiated and transparent selection of decision alternatives based on personal or political preferences.

In Figure 15 decisions are considered in terms of the continuous parameter p. The benefit function is expressed only in economic terms. From this perspective, it is clear that only a certain range of the decision parameter p will yield a positive benefit; this range corresponds to feasible decisions. An example could relate to the choice of the thickness of the plate of a rock-fall protection gallery. There is a certain choice of p, e.g. the thickness of the plate for which an incremental change of p is associated increments of losses and gains which are in balance; this is the optimal decision p, shown in Figure 15 as p^*.
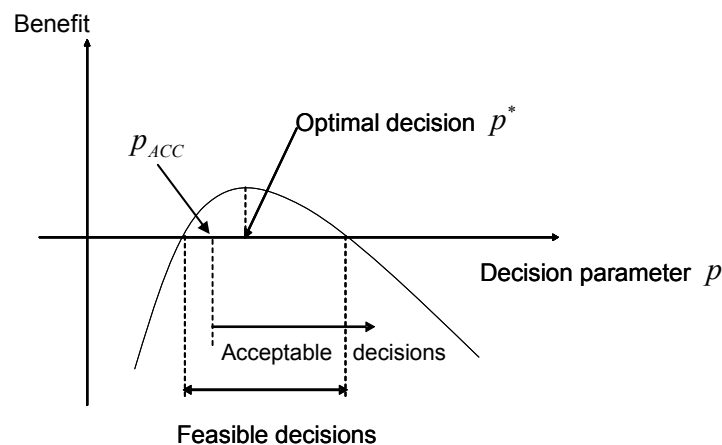

Figure 15. Illustration of the identification of acceptable decisions.

Having identified the optimal decision p^*, it is necessary to check whether this decision is admissible from the perspective of society. Following Figure 15 we need to assess the value of the decision parameters which exactly corresponds to the societal preferences in regard to investments into life saving activities; this value of p is denoted p_{ACC}. It is important to notice that acceptability thus not only depends on the level of risk itself but also the efficiency of risk reduction. Focus is thereby directed not only on the highest sources of risks but moreover on the risk reduction activities with the highest efficiency.

In general, the theoretical basis for the identification of risk acceptance are outlined in the background documentation to this document. In the following, however, the basic principles for setting acceptance criteria in regard to risks to persons are outlined.

Rational risk acceptance criteria in the context of societal decision making may be derived on the basis of socio-economic considerations. In this context, the issue of concern relates only

to involuntary risks. It is assumed that risk reduction always is associated with reallocation of societal economic resources. In the context of societal infrastructure with a life time typically in the order of decades or centuries, it is expedient that such economic resources are allocated with the highest possible efficiency and with due consideration of intergenerational acceptability.

At the level of societal decision making an efficient life saving activity may be understood as a measure which in the most cost effective manner reduces the mortality or equivalently increases the statistical life expectancy.

The incremental increase in life expectancy through risk reduction, the corresponding loss of economic resources, measured through the Gross National Product (GNP) together with the time used for work, all assessed for a statistical life in a given society, form the most important building stones for the assessment of the efficiency of risk reduction measures. Based on these demographical indicators, the Life Quality Index (LQI) facilitates the development of risk acceptance criteria.

The underlying idea of the LQI is to model the preferences of a society quantitatively as a scalar valued social indicator, comprised by a relationship between the GDP pro capite g, the expected life at birth ℓ and the proportion of life spend for earning at living w.

Based on the theory of socio-economics, the Life Quality Index can be expressed in the following principal form:

$$L = g^r \left[(1-w)\ell \right]^{1-r} \tag{15}$$

where the parameter r is a measure of the trade-off between the resources available for consumption and the value of the time of healthy life. Note that in some publications the LQI is referred to as a utility. However, it should not be understood as a utility in the Van Neumann/Morgenstern meaning of the word. Economists use this word in a wider sense.

In Equation (15) only the part of the GDP which is available for risk reduction investments is considered. This value g is estimated as 70% of the total GDP. Furthermore, the approach suggested by Cobb Douglas is followed whereby g is assumed to be proportional to a work related factor to the power β and a capital related factor to the power $(1-\beta)$. This means that g can be written as:

$$g = pw^\beta \tag{16}$$

In assessing the value of β one should keep in mind that part of nowadays capital is based on work in the past and part of present day work is intended to raise capital for the future.

The value of r in Equation (15) cannot be inferred directly but may be estimated from the fraction of life actually allocated for economic activity. After substituting (16) into (15) the value of w for which L reached its maximum may be derived from the condition:

$$\frac{\partial L}{\partial w} = \beta r \frac{L}{w} - (1-r) \frac{L}{(1-w)} = 0 \tag{17}$$

which leads to:

$$q = \frac{r}{1-r} = \frac{1}{\beta}\frac{w}{(1-w)}, \text{ or } r = \frac{w}{\beta - w\beta + w}$$

(18)

If β would be equal to 1.0 the value of r would be equal to w. The parameter q is encountered in an alternative LQI expression: $L = g^q \ell(1-w)/q$.

In modern western economies the value of w is known to be about 0.10. If it is assumed that these economies have reached their stationery optimum and using $\beta = 0.7$ it may be found that the preference parameter r should have a value of about 0.13.

Every risk reduction measure will affect the value of the LQI. The consideration that any investment into life risk reduction should lead to an increase of the LQI leads to the following risk acceptance criteria:

$$\Delta L = \frac{\partial L}{\partial g}\Delta g + \frac{\partial L}{\partial \ell}\Delta \ell \geq 0$$

(19)

or

$$\frac{\Delta g}{g} + \frac{(1-r)}{r}\frac{\Delta \ell}{\ell} \geq 0$$

(20)

A given measure with the purpose of reducing risks of life implies an allocation of Δg and a corresponding increase of life expectancy $\Delta \ell$. Based on Equation (20) the relationships between Δg and $\Delta \ell$ which lead to increases in the LQI may be determined which in turn can be utilized for assessing the corresponding probability of different types of failures of relevance for a considered system; this probability may then be utilized as a target value for structural design or assessment purposes. Considering structural reliability applications, the relative change in life expectancy $\Delta \ell / \ell$ may be exchanged by a change in mortality $d\mu$ as:

$$\frac{\Delta \ell}{\ell} = C_x \Delta \mu = C_x P_{D|F} \Delta v$$

(21)

where v is the failure rate, C_x a demographical economic constant corresponding to a given scheme x for mortality reduction and $P_{D|F}$ is the conditional probability of dying given a failure. Finally there is:

$$C_y = g\frac{r}{1-r}C_x N_{PE}\, P_{D|F}\, dv$$

(22)

where dC_y are the annual investments into life safety and N_{PE} is the number of persons exposed to the failure. In the Annex to this document the application of the LQI principle is outlined for typical cases in engineering decision making.

Finally it should be mentioned that refinements and alternative approaches to the above LQI model are possible. Reference to relevant literature are also provided in the Annex.

4.7   Sustainable discounting

Discounting of investments may have a rather significant effect on decision making. Especially in the context of planning of societal infrastructure for which relative long life times are desired and for which also the costs of maintenance and decommissioning must be taken into account, the assumptions in regard to discounting are of importance.
Considering time horizons of 20 to 100 years (i.e. over several generations), discounting should be based on long term average values, free of taxes and inflation. In the private sector, the long term real rate of interest is approximately equal to the return which may be expected from an investment. In the public sector the discounting rate, also in the context of life saving investments, should correspond to the real rate of economic growth pro capite. This corresponds to the rate at which the wealth of an average member of society increases over time.

4.8   Aggregation and portfolio loss assessment

For the purpose of understanding, managing, documenting and communicating risks at a strategic level, aggregation of risks and portfolio loss assessments are often required. Indeed the aggregation of risks may be seen as the ultimate goal of establishing a uniform basis for assessing risks; only if risks are assessed in a comparable way it will be possible to aggregate them. Furthermore, beyond the mere summation of risks over the various activities and objects e.g. constituting a roadway network, the efficient management of risks necessitates the various attributes of the risks are also known. This concerns especially the uncertainty with which the risk estimates for the individual components and activities are associated, but also and not least, possible dependencies, or common factors.

It is preferable for the management of portfolio risks that uncertainties are made available in regard to the assessed risks at the level of objects/segments. Knowing the uncertainty associated with the portfolio risk allows for assessing the size of required budgets to cover potential losses in a rational manner. Furthermore, it supports decisions on how to collect more information or how to refine the portfolio risk analysis with the purpose of reducing the uncertainties associated with losses. Reducing the portfolio risk uncertainty will lead to less surprises in terms of exceeded budgets, and will provide a better basis for efficient allocation of societal resources in general.

Two types of aggregations are generally relevant for the management of risks, namely aggregated modeled risks and aggregated observed losses. The modeled risks correspond to the risks assessed through analysis in accordance with the guidelines contained in the present document. The aggregated observed losses correspond to the recorded losses observed in the past. The recorded data on losses may not cover all types of modeled risk, however, both types of aggregated risks are of relevance in risk management. Whereas the modeled risks may provide a differentiated and detailed overview of the portfolio risks as well as sensitivities of the risk in regard to different types of hazards, the significance of categories of objects, etc., the aggregated recorded losses are factual, though historical, and may and shall be utilized for the purpose of calibration of modeled risks.

The aggregation of risks may be performed at object/segment level as well as over object categories, geographical areas and hazard types. For all aggregations it is suggested to use a one year period as standard reference period. However, the temporal variations within a one year period can also be of interest.

Aggregation should be undertaken individually for the risk categories: persons, costs and environment, with an appropriate differentiation, e.g. for persons: Injuries and fatalities, for costs: User costs, compensation costs and material losses, for environment: CO_2 emissions, toxic releases and energy use.

At the level of individual assets the aggregation is made over risks due to different types of hazards, which for various reasons might be evaluated individually. The result of such an aggregation at asset level is illustrated in Figure 16, where only one risk type is illustrated for each object, differentiated into direct and indirect risks. However, in the aggregation all relevant risk components must be considered, i.e. including all relevant risks to persons, environment and costs.
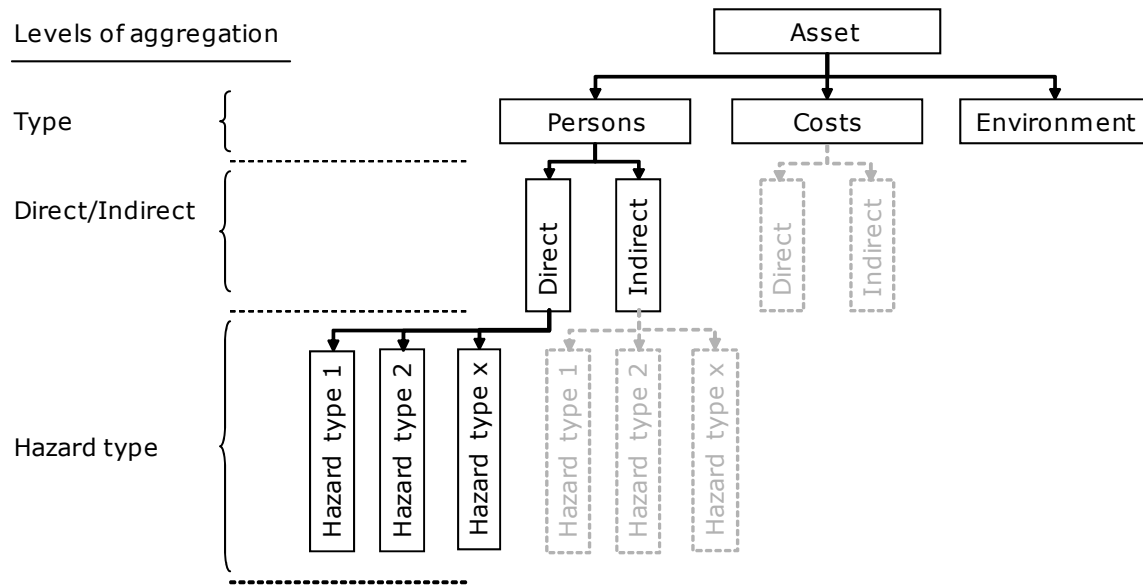

Figure 16. Possible representation of aggregated risks.

The differentiation of direct and indirect risks (in the different categories) at the level of assets is useful in the aggregation over different types of hazards. This aggregation provides insight on how robust the considered asset is and thus points to a possible need to upgrade its performance in relation to its function in the context of the system. The robustness assessed for one object/segment or activity based on the risk aggregated over the different relevant hazards may be expressed through the asset robustness index I_{AR}:

$$I_{AR} = \frac{R_{AD}}{R_{AD} + R_{AID}}$$
(23)

Where R_{AD} and R_{AID} are the direct and indirect risks for the considered object/segment or activity aggregated over the relevant hazards.

At higher levels of aggregation, e.g. over object type or geographical areas the direct/indirect differentiation at object level is no longer relevant.

Knowledge in regard to the temporal variation of risks is useful for the purpose of budget planning, but also necessary as a means for decision making in regard to the focusing on risk reduction activities which may not be very critical for individual objects/segments and

activities but due to their effect on the overall portfolio have a large aggregated effect. This could e.g. relate to activities such as de-icing and planning of roadway maintenance.

If risks are aggregated for which the uncertainty associated with the risk is known, the aggregated risk should be assessed, such that these uncertainties are reflected in the result. This necessitates that dependencies between the risks subject for aggregation are accounted for; a task which is generally non-trivial and necessitates careful modeling. However, hierarchical probabilistic models as illustrated in Figure 17 greatly facilitate such aggregation.
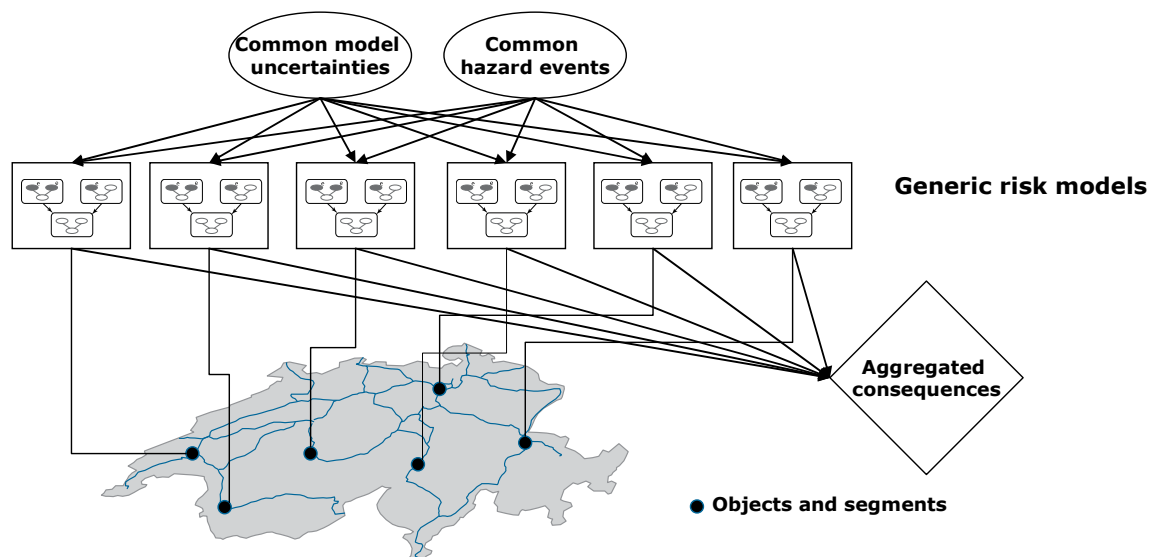

Figure 17. Illustration of how dependencies may be accounted for in the aggregation of risks.

To assess the benefit of refining the level of knowledge in the overall management of risks, an assessment of the aggregated risk in regard to its dependency of knowledge uncertainties is a very strong means. Therefore, as a general rule, it shall be evaluated to what degree knowledge uncertainties influence the uncertainty associated with the aggregated risk. Such an evaluation may be performed qualitatively; however, in the process of refining risk aggregation models, a quantitative assessment is generally required. Quantitative evaluations necessitate that the uncertainty associated with the risks subject to aggregation are subdivided into their two components, knowledge uncertainty and inherent natural variability. Furthermore, such evaluations also require that the sources of the knowledge uncertainties are known and included in the risk models. This is greatly facilitated by the use of indicators in the formulation of the risk models as outlined in Section 4.2.

In the assessment of the portfolio risks, the value or significance of information may be conducted by artificially reducing the uncertainty associated with the uncertain parameters entering the various risk models. By doing this, the significance of the different parameters for the portfolio risk may be assessed in qualitative terms, providing an idea on the most important parameters. However, in the assessment of the efficiency of collection of information as a means of reducing portfolio risk uncertainty, it is necessary to account for the accuracy of various means of collecting information, as well as the costs of collecting information.

4.9 Risk transfer

Risk transfer may be considered as a special case of risk treatment. A decision maker who is responsible for the management of risk may optimize his/her decision making with the purpose to reduce risks and/or maximize benefits as outlined in the foregoing. However, as emphasized previously; the outcome of the decision making is generally associated with uncertainty. For a decision maker with limited economic capabilities this uncertainty might be a problem, in the sense that losses could result from the decision making even though this, in expected value, is optimal. Such losses might be in excess of the economic capabilities of the decision maker and it is thus a central issue to take budget constraints into account directly in the decision making. The consequences of such event can be included into the formulation of the decision problem by using the concept of follow-up consequences outlined in Chapter 4. However, the risks associated with the event of excessive economic losses may also be managed by transferring this risk to a third party. Such risk transfers must generally be bought and this is typically the concept followed in the insurance and the re-insurance industry.

4.10 Risk communication

Risk communication may just as risk transfer, be seen as one special means of treating risks. Different individuals and different groups of individuals in society perceive risks differently, depending on their own situation in terms of to what degree they may be affected by the exposures, to what degree they are able to influence the risks and to what degree the risks are voluntary. Generally risk are perceived more negatively when stake holders feel more exposed, when they feel they have no influence and they feel they are exposed to risks involuntary.

Another aspect is related to how adverse events are perceived by individuals and groups of individuals in society when and after such events take place. Again, this depends on the perspective of the affected individuals and groups of individuals. Furthermore, the occurrence of adverse events and the way the information about such events is made available will affect the perception of risks in general but also in many cases trigger actions which have no rational basis and only adds to the societal consequences of such event, see also Figure 8. To the extent possible such behavior should be included in the consequence assessment as a follow-up consequence.

Due to the effects of the perception of risk it is generally observed that different individuals and groups of individuals have different attitudes in regard to what risks can be accepted, moreover this attitude to a high degree is affected by the characteristics of the associated adverse events . Risk averse and risk prone attitudes are observed, which simply refers to the effect that risks are assigned different tastes depending these characteristics. Whereas such behavior is a private matter for individuals of society, it leads to an uneven distribution of risks, if exercised in the context of societal decision making and this is clearly unethical and from that perspective also not rational.

The perception of risks may be significantly influenced by information about the risks themselves. Information can and should be used as a targeted means of reducing potential losses caused by reactions to events beyond what is rational, seen in the perspective of normative decision making. Being provided with transparent information in regard to the nature of exposures, possible precautionary actions, information on how risks are being

managed and the societal consequences of irrational behavior reduces uncertainties associated with the understanding of risks of individuals. This, in turn, adds to rational behavior and thereby reduces follow-up consequences. For this reason; schemes for targeted, transparent and objective information of the stakeholders is a highly valuable means of risk treatment.