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On Temporal and Spatial Probabilistic Engineering Modeling

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ABSTRACT: The present paper addresses temporal and spatial modeling from the perspective of providing basis for societal decision making in regard to the further development, maintenance and safeguarding and societal infrastructure. Starting point is taken in the viewpoint that decisions concerning infrastructure projects should be optimized considering all potential benefits and losses which might arise during their entire life-cycle. For this purpose a systems representation in an intergenerational context is outlined which provides guidance on how risks may be consistently assessed considering benefits and losses caused by physical changes as well as perceived knowledge. The suggested systems representation is built up on three characteristics of the systems, namely; exposure, vulnerability and robustness. The detailed consideration of these in the modeling process as well as in the formulation of the decision problem provides aid in assessing direct and indirect consequences as well as on how these may efficiently be managed. The proposed modeling framework is illustrated and discussed taking basis in recent research on optimal engineering decision making considering maintenance planning of concrete structures, robustness assessment of structures and loss estimation for larger building stocks exposed to earthquake hazards.

1 INTRODUCTION

The services provided by the engineering community to society are of tremendous importance. Engineers in the past have created the societal infrastructure and thereby facilitated the societal development as we see it today. The societal infrastructure can be seen as the backbone of society without which there would be no civilization as we know it. Among significant engineering achievements count the numberless roadway bridges, tunnels, roadway systems, water, waste and energy distribution systems, structures for housing and industry as well as facilities for exploitation and distribution of various types of energy.

Until recently developments of society have been undertaken with only little or no concern in regard to the availability of the resources required for continued developments as well as the impact of societal activities on the qualities of our environment. The main focus has so far directed on the feasibility of various societal activities measured on the same scales as any other economical transaction in the free marked. Within the recent years the need for sustainable societal developments has become a general concern both at the political and the operational level in society, (Development 1987). Not least in the context of decision making in regard to the further development, maintenance and safeguarding of existing infrastructure decisions made at the present may have significant effect on the generations in the future.

Whenever decisions are made committing or using societal resources for development, maintenance and safeguarding infrastructure, society looses access to resources which in other ways might have been used to improve the life quality of the individuals of society. Therefore, societal decisions in this regard must be made such as to achieve an appropriate balance between investments and the benefit achieved through better performing infrastructure. This seemingly simple problem is, however, not so easy to frame in practice and comprises one of the main challenges in engineering decision making. How can we consistently assess the performance of societal infrastructure in such a way as to facilitate decisions which optimizes the benefit for society - now and in the future? The answer to this question is complicated due to the fact that the benefits are influenced by many uncertainties. Not only are there significant uncertainties and lack of knowledge associated with the modeling of the hazards to which the societal infrastructure is exposed but also the performance of the infrastructure for given hazard exposures is affected by uncertainties.

Typical engineering problems such as design, assessment, inspection and maintenance planning and decommissioning are consequently decision problems subject to a combination of natural inherent, modeling and statistical uncertainties. This fact was fully appreciated already some 30 – 40 years ago and since then the Bayesian decision theory together with Bayesian probabilistic modeling has formed the cornerstones of what is now commonly understood as modern methods of structural reliability see e.g. (Freudenthal 1947), (Turkstra, 1970) and (Ferry Borges and Castanheta, 1971). Within the recent years, taking basis in the theory of decision analysis see e.g. (Von Neumann and Morgenstern 1944; Raiffa and Schlaifer 1961), applied decision theory has been developed significantly for the support of a broad variety of engineering decisions, including structural design, assessment and maintenance of existing structures, planning of laboratory testing and on-site investigations as well as assessment and management of industrial and natural hazards.

In the present paper starting point is taken in the viewpoint that decisions concerning infrastructure projects should be optimized considering all potential benefits and losses which might arise during their entire life-cycle. For this purpose a systems representation in an intergenerational context is outlined which provides guidance on how risks may be consistently assessed considering benefits and losses caused by physical changes as well as perceived knowledge. The suggested systems representation is built up on three characteristics of the systems, namely; exposure, vulnerability and robustness. The detailed consideration of these in the modeling process as well as in the formulation of the decision problem provides aid in assessing direct and indirect consequences. The suggested modeling framework is illustrated and discussed taking basis in recent research on exposure modeling for the design of rock-fall protection galleries, vulnerability assessment of concrete structures subject to corrosion degradation, assessment of the robustness of structural systems and finally it is illustrated how the framework also strongly facilitates earthquake risk management through generic indicators based hierarchical Bayesian risk models incorporated in a GIS database.

2 BASIC CONSIDERATIONS IN ENGINEERING DECISION MAKING

2.1 *Time frame for life-cycle costing and engineering*

During especially the last decades great efforts have been invested into what is now commonly understood as life-cycle costing or life-cycle engineering, see e.g. (Frangopol and Maute 2003). However, whereas there is broad agreement in regard to the consideration that the life time for engineering facilities should be taken into account in the decision making there is still large differences in what is essentially understood by the term life-cycle.

Common interpretations of life-cycle include; the investment return period of a project, the service life specified in design codes, the time until a facility becomes obsolete and the time till failure. It is clear that optimal decisions will depend on the considered time frame and it is thus important that this issue is clarified. In addressing service-life engineering it is here proposed to take basis in the duration of the purpose which a given type of structure fulfills. Considering e.g. infrastructures such as bridges and tunnels it would be fair to assume that this type of structures will not only be needed in our own generation but also in the many subsequent generations. This is already reflected in common practice by typically specifying long service lives for such structures in most modern design codes; typically code specified design lives for bridges vary between 50-200 years. However, there are other types of structures where this is not the case, such as e.g. offshore facilities utilized for exploration and production of oil and gas. For such structures common practice assumes design lives in the order of 20-50 years. This is in consistency with the fact that one given structure of this type typically operates over such short durations of time, however, neglects that any specific structure is not the last to be constructed but merely one structure in a long sequence of structures to be constructed over time in fulfillment of a general long-term function.
By considering the duration of the purpose of a given type of structure facilitates that decisions are identified which optimize the benefit achieved by types of structures rather than just the benefit from any specific structure. Within the duration of the purpose any given structure may of course fail due to extreme events and or deterioration or simply become obsolete. These events and their associated risks provide the basis for the optimization of decisions concerning design and maintenance. It also opens up for a more conscious consideration of resource usage as it automatically points to potential benefits from re-use of parts of structures and re-cycling of structural materials. In a societal context for normative decision making such as e.g. writing codes and regulations this long term perspective is important.
In Figure 1 risk based decision making is illustrated in a societal context from an intergenerational perspective; see also (Nishijima et al. 2006), (Rackwitz et al. 2005) and Faber and Maes (2007). Within each generation decisions have to be made which will not only affect the concerned generation but all subsequent generations. At an intra-generational level the characteristics of the system consist of the knowledge about the considered engineered facility and the surrounding world, the available decision alternatives and criteria (preferences) for assessing the utility associated with the different decision alternatives. A very significant part of risk based decision making in practice is concerned about the identification and representation of the characteristics of the facility and the interrelations with the surrounding world as well as the identification of acceptance criteria, possible consequences and their probabilities of occurrence. Time and space plays significant roles in this regard. Managing risks is done by "buying" physical changes of the considered facility or "buying" knowledge about the facility and the surrounding world such that the objectives of the decision making are optimized.
The important issue when a system model is developed is that it should facilitate risk assessment and risk ranking of decision alternatives which in consistency with available knowledge and which facilitates that risks may be updated according to knowledge available at future times. A system representation can be performed in terms of logically interrelated constituents at various levels of detail or scale in time and space. Constituents may be physical components, procedural processes and human activities. The appropriate level of detail and/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.

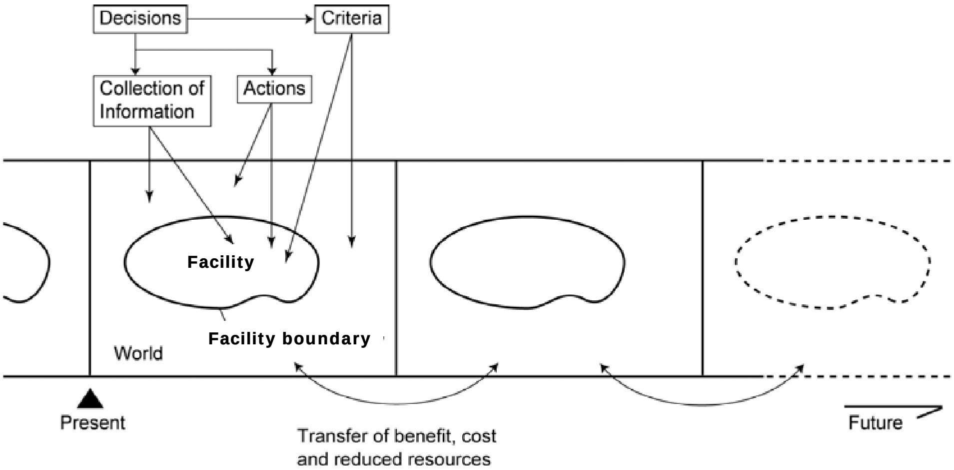

Figure 1 Main constituents of systems in risk based intra-/intergenerational decision analysis, (Nishijima et al. 2006).

2.2 *Consequences in societal decision making*

In an abstract sense risk is a characteristic of a system which indicates the potential of the system to generate consequences. For this reason it is necessary in risk based decision making to understand the details of how consequences might be generated. At a fundamental level consequences can be understood to be driven according to the second law of thermodynamics, i.e. through physical changes which all serve to maximize the entropy of the system. The effects hereof are typically material damages and associated monetary losses but also fatalities, injuries and damages to the qualities of the environment may follow. In addition information or knowledge plays an important role for consequences; knowledge facilitates taking actions and thereby to reduce risks, however information and knowledge may also trigger non-physical events associated with consequences; resource allocations forced by individual and public perception.

In Figure 2 a model framework for the assessment of consequences is proposed which address consequences due to physical changes and consequences due to perception individually. This in turn facilitates that focus can be directed to the different measures of risk reduction which are effective for the different types of consequences.

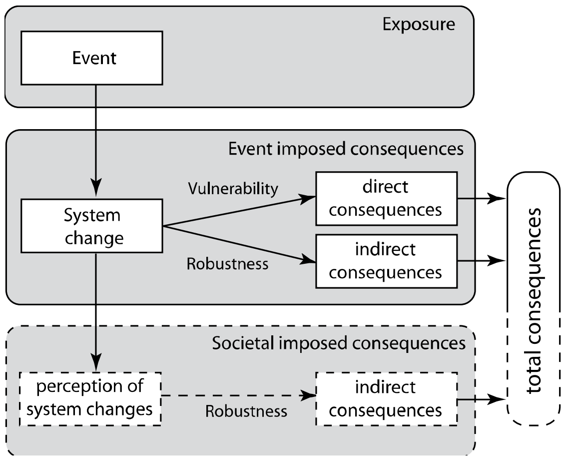

Figure 2 Representation of the mechanisms generating consequences (Faber and Maes 2007).

Following (Faber and Maes, 2007) the exposure to the facility is represented through different exposure events acting on the constituents of the facility. The constituents of the facility (see Figure 3) can be considered as the facility's first defense in regard to the exposures. The damages of the constituents are considered to be associated with direct consequences. Direct consequences may comprise different attributes such as monetary losses, loss of lives, damages to the qualities of the environment or just changed characteristics of the constituents.

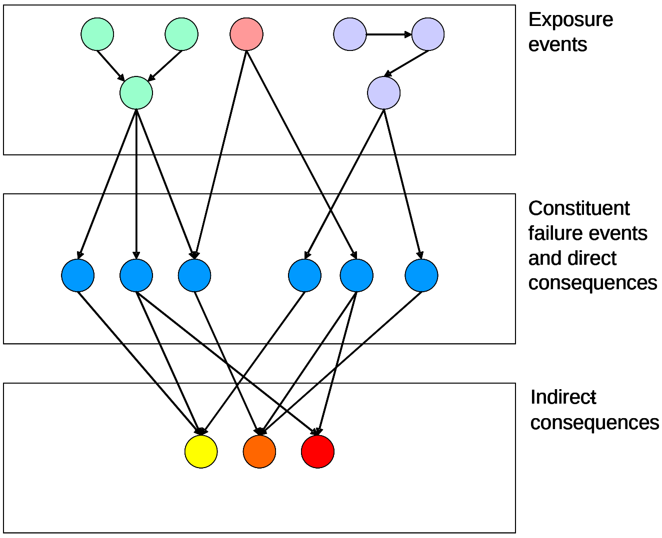

Figure 3 Logical representation of interrelation between exposures, constituent failures, sequences of constituent failures and consequences (Faber et al. 2007).

Based on the combination of events of constituent damages and the corresponding consequences indirect consequences may occur. Indirect consequences may be caused by e.g. the sum of monetary losses associated with the constituent failures and the physical changes of the facility as a whole caused by the combined effect of constituent failures. The indirect consequences in risk assessment play a major role, and the modeling of these should be given great emphasis (Faber and Maes 2005). Typically, the indirect consequences evolve spatially beyond the boundaries of the facility and also have a characteristic sometimes even postponed development in time.

The vulnerability of a give system (facility and the rest of the world) characterizes the risk associated with the direct consequences and the robustness characterizes the degree to which the total risk is increased beyond the direct consequences. It should be noticed that the three characteristics (exposure, vulnerability and robustness) which will be defined in a subsequent section are only unambiguous subject to the definition of the system.

Whereas it is obvious that any representation of a system should include any characteristic or aspect of relevance for assessing and managing risks the choice of time and space scale deserves a few added comments when consequences are discussed. First of all it is of tremendous significance that the considered spatial characterization of exposure events is consistent with available knowledge concerning occurrence frequencies, extents/intensities and also the spatial/temporal dependency between exposure events. A second issue relates to the spatial/temporal/causal interconnectivity of constituents of systems. A good representation

of these aspects is crucial for a realistic representation of system effects, i.e. indirect consequences and robustness.
The last comment to be made in this context concerns a criticism which is sometimes raised when societal consequences due to catastrophic events are discussed. The argument is that historically seen there appears to be, on a large scale in time and space, very small and sometimes even positive consequences associated with major events; as an effect of large societal losses there is often a substantial economical growth to be observed associated with reestablishing societal infrastructure. However, here it is argued that the perspective behind such arguments fails to appreciate that major catastrophic events in fact can be seen as forced renewals of societal infrastructure. It might be true that even a forced renewal can be associated with overall benefits; however, the important issue here is that this benefit in general would be much less compared to a well organized and planned strategic renewal, which in turn also would not involve loss of lives or damages to the qualities of the environment.

Finally in consistency with Haimes (2004) it should be noted that very often the system constituent can be modeled as logical systems themselves comprised by their own constituents. A system could be a road network with constituents being e.g. bridges (see Figure 4). The bridges in turn could be modeled by logical systems with constituents being 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.

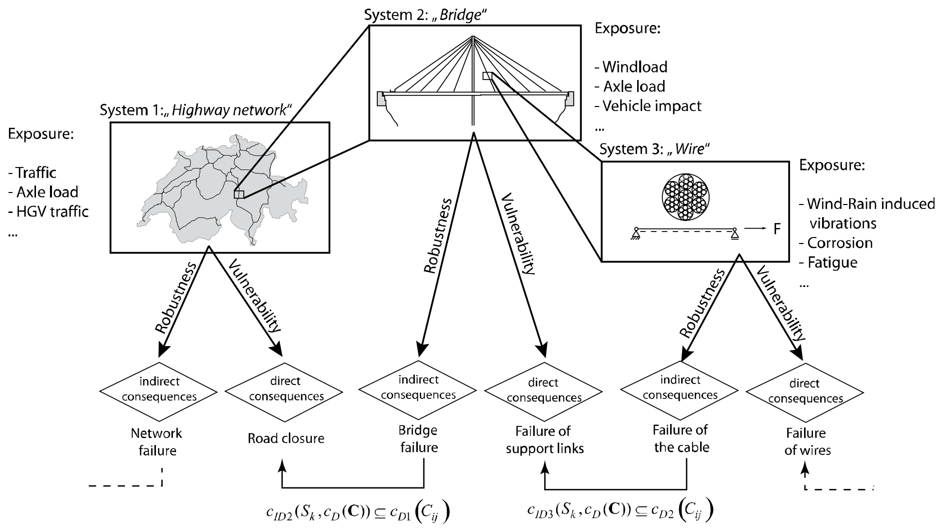

Figure 4 Generic system characterizations at different scales in terms of exposure, vulnerability and robustness (Faber et al. 2007).

The hierarchical risk assessment framework is applicable at any level of scale for the assessment of a given system. It may be applied to components, sub-systems and the system as a whole; thereby the framework also facilitates a hierarchical approach to risk assessment. The definition of the system in this context becomes of tremendous significance in the definition of exposure, vulnerability and robustness. 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, (Pearl 1988).

3 ASSESSMENT OF RISK FOR ENGINEERED SYSTEMS

3.1 *Representation of knowledge*

In the context of temporal and spatial modeling of uncertainty focus must be directed on consistently representing the prevailing dependencies. This is an important aspect not only for what concerns the modeling of exposure events, but equally important for the modeling of the vulnerability and robustness of systems (direct/indirect consequences). Hierarchical models for the representation of temporal and spatial dependencies form a convenient modeling framework (see e.g. (JCSS 2001)).

In general the Bayesian probability theory is suggested as basis for representation of knowledge as this facilitates the consistent representation of uncertainty independent of their source and type; purely subjectively assessed uncertainties, analytically assessed uncertainties and evidence as obtained through observations may be combined. It has become standard to differentiate between uncertainties due to inherent natural variability (aleatory/type I), model uncertainties and statistical uncertainties (epistemic/type II). This differentiation is useful for the purpose of setting focus on how uncertainty may be reduced but does not call for a differentiated treatment in the decision analysis, see (Faber 2005) and (Faber and Maes 2005). For the purpose of decision making the differentiation is irrelevant and not coherent with formal decision analysis.

3.2 *Assessment of probabilities*

In the assessment of risk the probabilities of the different events associated with consequences must be evaluated. In principle if the consequence inducing events are well defined methods of probability analysis such as Monte Carlo simulation (Engelund and Rackwitz 1993), have been developed which in "theory" allow for the approximation of their probabilities; in "theory" because even though it might be possible, it might not be feasible in terms of computation time. However, for a very large class of problems methods of modern reliability theory such as FORM/SORM and various variance reduction schemes for Monte Carlo sampling may readily be applied with good efficiency (see e.g. (Rackwitz 1991) and (Rackwitz 2001). In the context of assessing probabilities for problems with temporal and/or spatial variability subject to both aleatory and epistemic uncertainty the appropriate probabilistic modeling necessitates that the assessment of probabilities is adapted accordingly. Probability assessment in temporally/spatially varying problems is discussed in e.g. (Schall et al. 1991), (Rackwitz 2001) and (Bryla et al. 1991). More recently (Der Kiureghian and Song 2007) have studied the probabilistic characteristics of complex systems and suggested approaches for achieving bounds of probabilities of events of interest for such systems.

3.3 *Risk updating and risk indicators*

The presented risk assessment framework facilitates a Bayesian approach to risk assessment and full utilization of risk indicators. 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 5.

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).

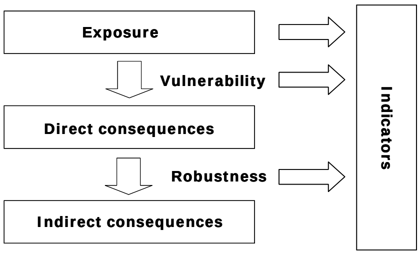

Figure 5 Risk indicators at different levels of the system representation (Faber and Maes, 2005)

3.4 *Quantification of risk*

Following (Faber et al. 2007) the facility 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. Generally exposure events should not be understood as individually occurring events such as snow loads, earthquakes and floods but rather as the effect of relevant combinations of these. It is assumed that there are n_{CON} individual constituents of the facility, each with a discrete set (can easily be generalized to the continuous case) of damage states C_{ij}, $i=1,2..n_{CON}$, $j=1,2..n_{C_i}$. The probability of direct consequences $c_D(\mathbf{C}_l)$ associated with the l^{th} of n_{CSTA} possible different state of damage of all constituents of the facility $\mathbf{C}_l$, 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 system is defined as the risk due to all direct consequences (for all n_{CON} constituents) and may be assessed through 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}:

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

The state of the facility as a system depends on the state of the constituents. It is assumed that there are n_{SSTA} possible different system states 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:

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l)) \times p(S_m | \mathbf{C}_l, EX_k) p(\mathbf{C}_l | EX_k) p(EX_k) \qquad (2)$$

The robustness of a system is an indicator of the ability of a system to limit total consequences to direct consequences and defined through the ratio of risks due to direct consequences to the total risk. This characteristic may readily be quantified though the index of robustness I_R (Baker et al., 2006, Schubert and Faber (2007)):

$$I_R = \frac{R_D}{R_{ID} + R_D} \tag{3}$$

which allows for a ranking 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 this is of course necessary as this will influence the decision making.

4 RECENT DEVELOPMENTS IN SYSTEMS MODELING

In the following the application of the suggested model framework for risk assessment will now be illustrated through different applications relating to the probabilistic modeling of exposure, vulnerability and robustness. These examples are taken from the authors own recent research.

4.1 *Exposure analysis in regard to rock-fall*

In (Schubert et al. 2005) a study is presented concerning the risk assessment in regard to rock-fall for the purpose of establishing design basis for the design of rock-fall protection structures. The exposure modeling comprises two main steps, namely the modeling of the detachment characteristics for a give site and the probabilistic modeling of the fall process. The probabilistic modeling of these two mechanisms leads to the joint cumulative distribution of the volume and energy of falling rocks at a give location where a rock-fall barrier is planned. In the probabilistic modeling of the detachment of rocks there is a substantial element of subjective expert judgment. Typically an expert visits a given site and his/her judgment combined with possible recordings of rock-falls from the location forms the basis for constructing a model as illustrated in Figure 6a, see (Schubert et al. 2005) for more details.

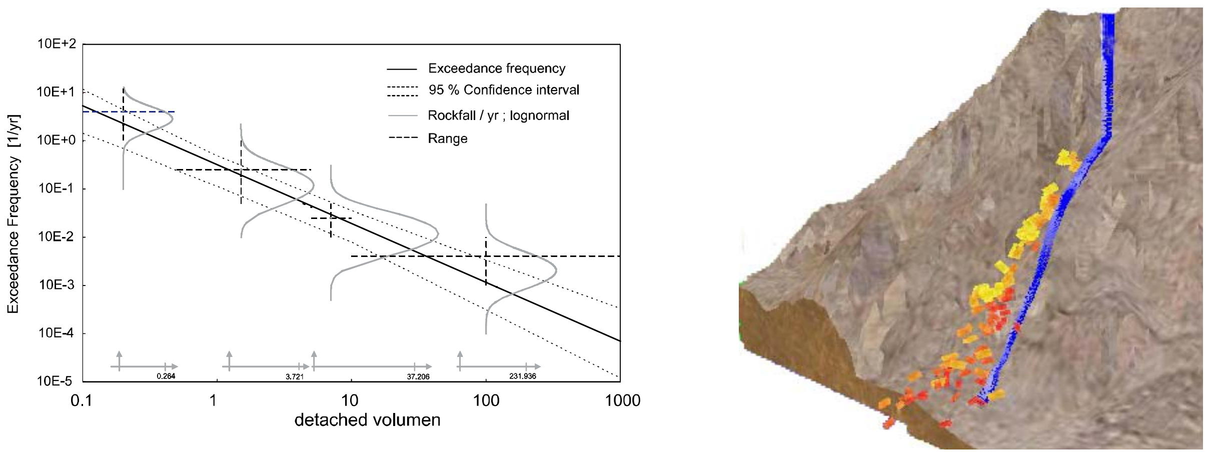

Figure 6 a) Exceedance probability of detachment volumes. b) Joint cumulative distribution of volume and velocity on the planned site of rock-fall barrier (Schubert et al., 2006).

The next step is based on Monte Carlo simulations whereby a large ensemble of different volumes is detached and their trajectories during the falling process are calculated, see Figure 6b. This readily facilitates that the probabilistic characteristics of volume and energy of falling rocks at the location where the rock-fall barrier can be assessed as shown in Figure 7.

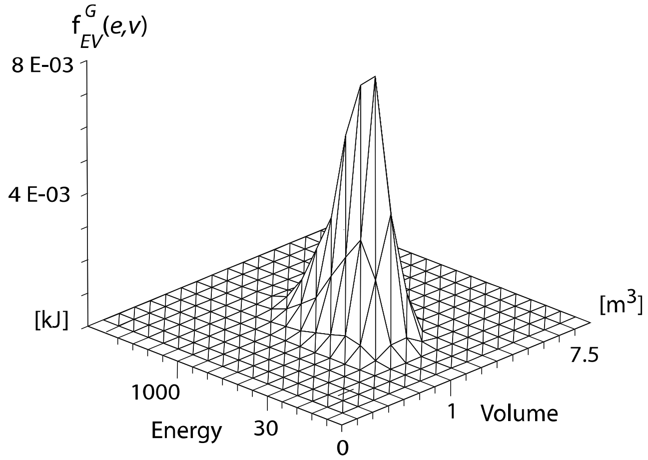

Figure 7 Joint probability density function of volume and energy at the location of the planned rock-fall barrier, (Schubert et al. 2005).

4.2 *Vulnerability of concrete structures*

In (Faber et al. 2006) the probabilistic modeling of deterioration of concrete structures subject to chloride exposure is addressed. In the modeling proposed there it is suggested to model concrete structures in terms of a subdivision of surfaces (zones) for which the deterioration process can be assumed to be homogeneous, see Figure 8a. This implies among others that the exposure to chlorides should be homogeneous and the characteristics of the structure should be homogeneous (concrete and concrete cover thickness). The deterioration is thereafter modeled for each individual zone by a further sub-division into segments for which it can be assumed that the deterioration occurs conditionally independently, see Figure 8b. The basis for this sub-division is a statistical assessment of the correlation structure of the diffusion coefficient based on measurements from representative structures ((Malioka and Faber 2004), (Malioka et al. 2006)). Based on these measurements the correlation length of the random field representing the spatial variability of the diffusion coefficient can be established. This then forms the basis for deciding on the length/height of the segments in the idealization. In the further probabilistic modeling of the deterioration over the surface it may now be assumed that the diffusion coefficients representing each segment are identically distributed. However, due to the fact that the distribution parameters of the distribution functions for the diffusion coefficients for all segments are estimated from data covering the entire zone the diffusion coefficients are dependent. As illustrated in Figure 8b this is modeled through a hierarchical Bayesian model, see (Faber et al. 2006) for more details.

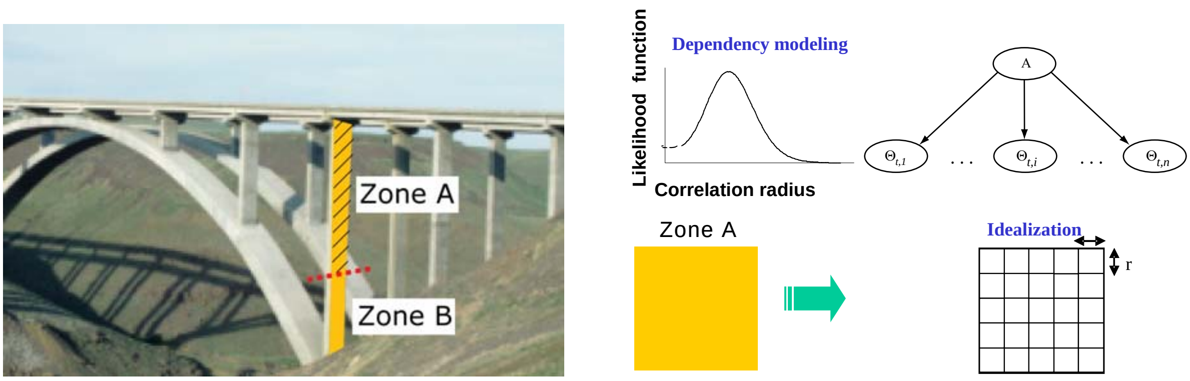

Figure 8 a) Illustration of zone sub-division of the surface of a concrete structure. b) Illustration of the principle for the sub-division of zones into segments.

With basis in the hierarchical modeling scheme illustrated in Figure 8 the performance of individual segments may now be assessed conditional on the outcome of the joint variables (e.g. the mean value of the diffusion coefficient). A typical result of a reliability assessment of one segment is illustrated in Figure 9.

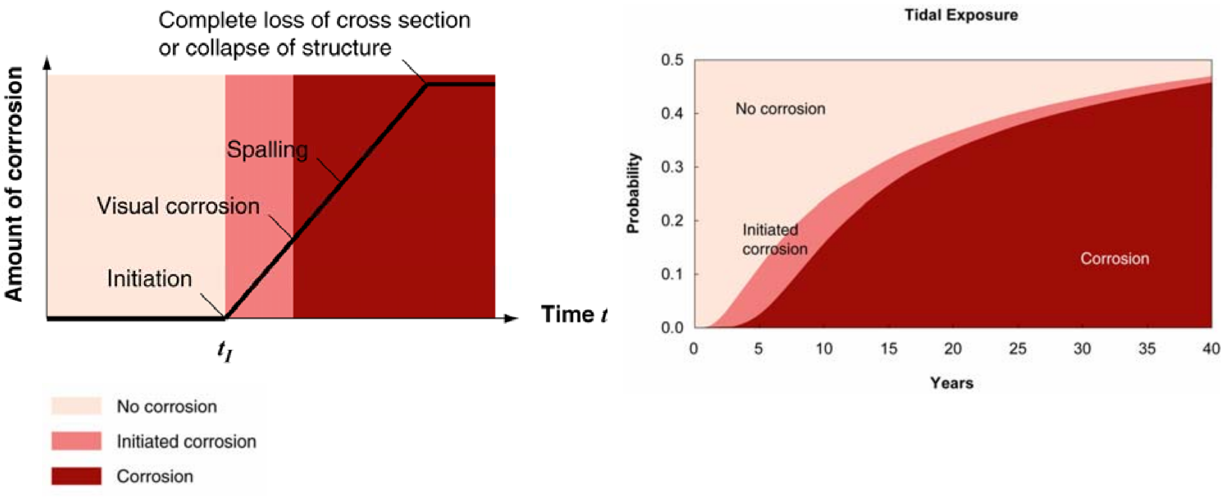

Figure 9 **a) Illustration of different states considered in the vulnerability assessment. b) Illustration of the probability of different states as a function of time.**

Based on the probabilities of the different condition states for the individual segments the probability that any number of segments belong to a certain condition state (system performance) is readily assessed through the binomial distribution. However, it must be remembered the performance of the individual segments are dependent. Thus the conditional probability of system performance as assessed through the binomial distribution must be integrated out over the possible realizations of the joint variables, see (Faber et al. 2006)

Finally based on the joint performance of the individual segments in the zones, defined criteria for repairs of different types and corresponding costs and by considering all zones an assessment of the total direct consequences can be performed resulting in e.g. the distribution of costs for different types of repairs over time. This is illustrated in Figure 10.

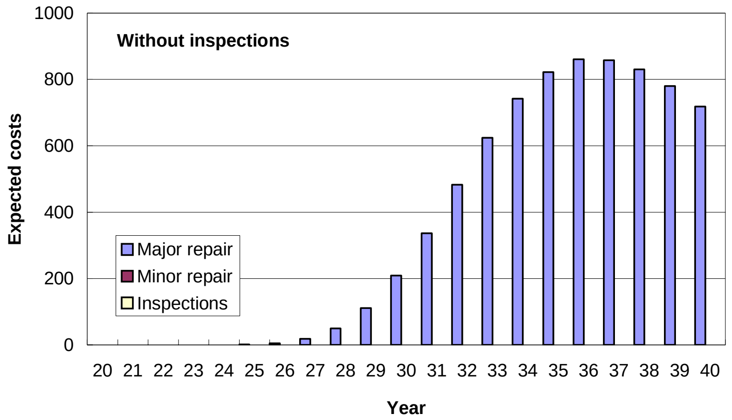

Figure 10 **Illustration of direct consequences as a function of time.**

4.3 *Robustness of structures*

The proposed risk assessment framework might also be applied for the assessment of structural systems robustness. For a structural system the characteristics of exposures, vulnerabilities and robustness may be considered as illustrated in Figure 11.

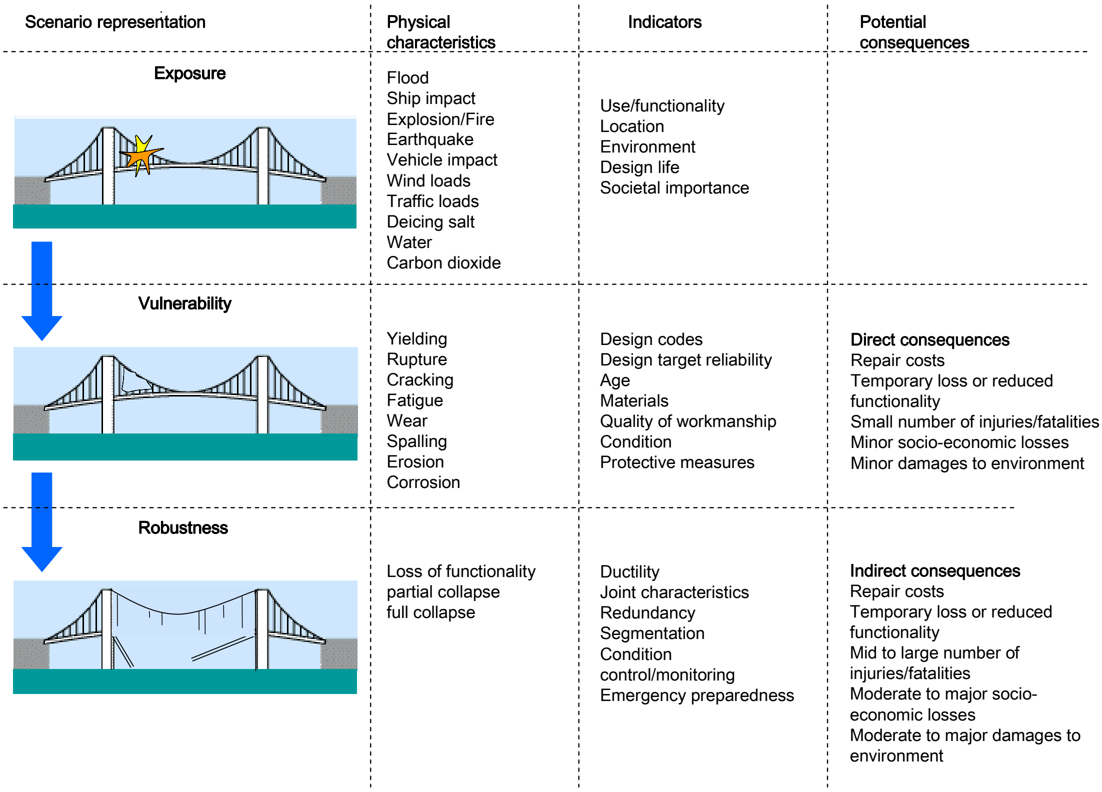

Figure 11 **Systems representation in terms of exposure, vulnerability and robustness for a structural system.**

Following (Baker et al. 2007) the assessment of the robustness can be illustrated by considering the event tree in Figure 12 together with Equation (3).

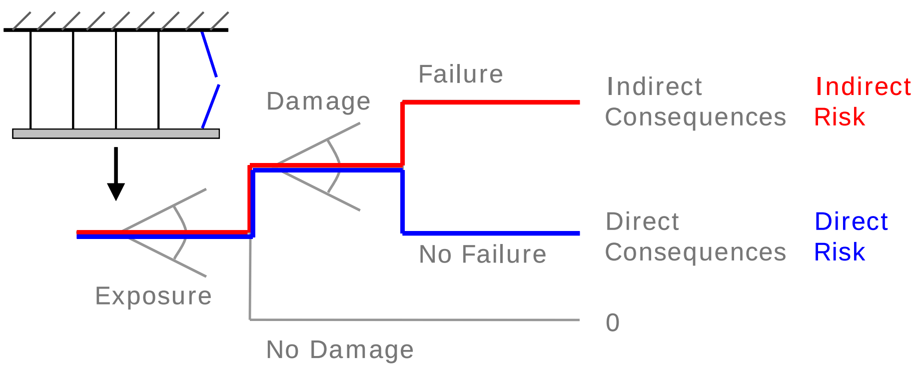

Figure 12 **A simple event tree illustrating the principle for assessing the robustness of structural systems (Baker et al, 2007).**

Based on the analysis of event trees of the type illustrated in Figure 12 principal studies have been performed in regard to the robustness of parallel systems as a function of the number of components, dependency between the resistances of the components, the uncertainty

associated with loads and finally also the costs of component failures relative to costs of system failure, see (Baker et al. 2007). In (Faber et al. 2006) and (Schubert and Faber accepted) robustness assessments of offshore steel jackets and bridges are illustrated.
The event tree from Figure 12 can easily be extended to include the effect of decisions regarding design, inspection and maintenance planning, see Figure 13.

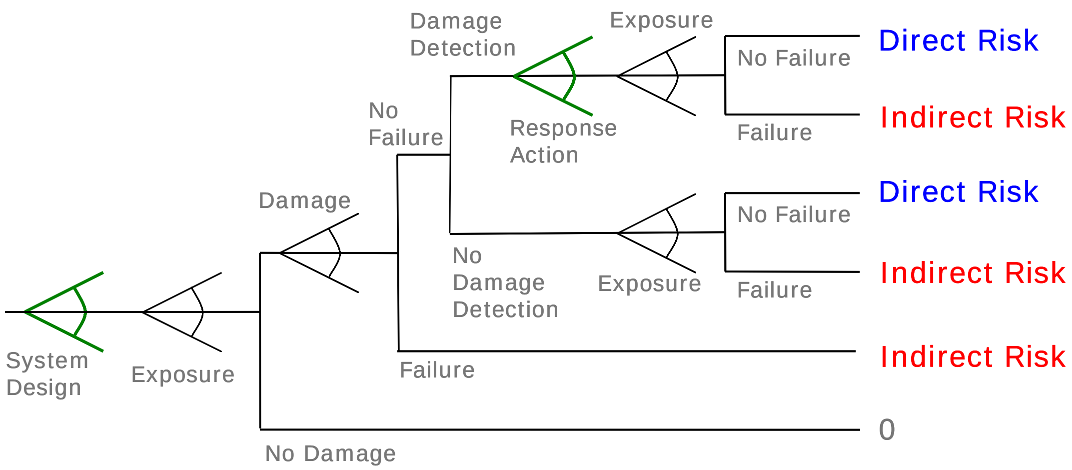

Figure 13 Decision event tree for the optimization of robustness of structures (Baker et al., 2007).

From Figure 13 it becomes clear that structural robustness within the proposed risk assessment framework is not only a characteristic of the structural system in terms of redundancy, ductility and joint performance but that the robustness may also be managed through human intervention aiming to detect damage and to reduce the consequences of damages.

4.4 *Large scale earthquake risk management*

Management of risks due to earthquakes is a research topic which has attracted broad attention from many different engineering disciplines and for very good reasons also the insurance industry. Whereas the treatment of this problem complex necessitates in depth knowledge of several disciplines of natural science and engineering an additional challenge lies in the interdisciplinary understanding required to interface these disciplines consistently for the assessment and the management of risks. Within the MERCI project (Bayraktarli et al. 2004) management of earthquake risks is approached by considering the tree different decision situations; before, during and after the event of an earthquake, see Figure 14.

The methodical idea in the MERCI project is to utilize the Bayesian decision theory in conjunction with generic risk assessment models; including important model components ranging from the modeling of the seismic event itself, over the behavior of the soil to the response of structure categories and the further development of different types of consequences. Indicators of risk in terms of observations and data are achieved from satellite and aerial photographs and utilized by the generic risk models. The whole set of modules and data are managed by a Geographical Information System (GIS) which in the end is used for the optimization of strategies for the management of risks before, during and after an earthquake event, see Figure 14.

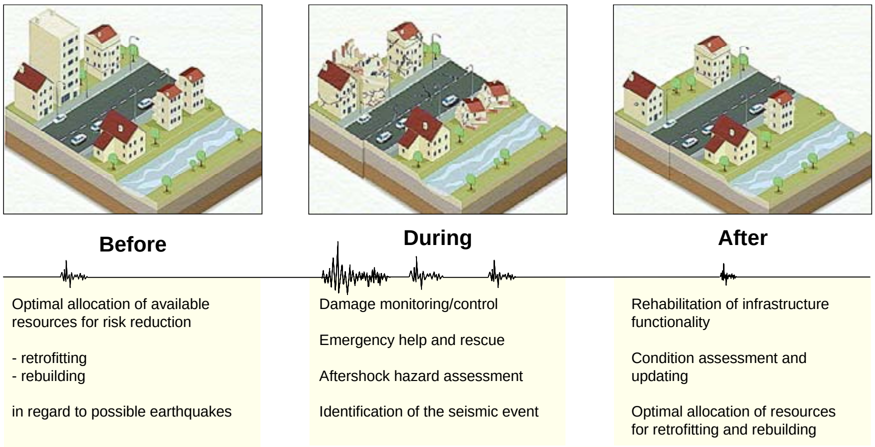

Figure 14 **Illustration of the different decision situations before, during and after an earthquake.**

The management of earthquake risks involves a long series of challenges in which the temporal and spatial representation of uncertainties play important roles. This concern not least the modeling of the earthquakes themselves, the propagation of the earthquake waves through the stratum, the characteristics and the behavior of the soil, buildings and infrastructures subjected to the earthquake excitation. The uncertainties involved in any model of these phenomena include model and statistical uncertainties as well as inherent natural variability. Information can be obtained in regard to the parameters which have influence on the assessment of risks; however, this information, whether it is achieved from visual surveys, by testing of building performance or soil samples or achieved through aerial or satellite photographs is also associated with often significant uncertainty. As the assessment of risks must take all these uncertainties into account the data are conveniently managed in GIS systems as illustrated in Figure 15.

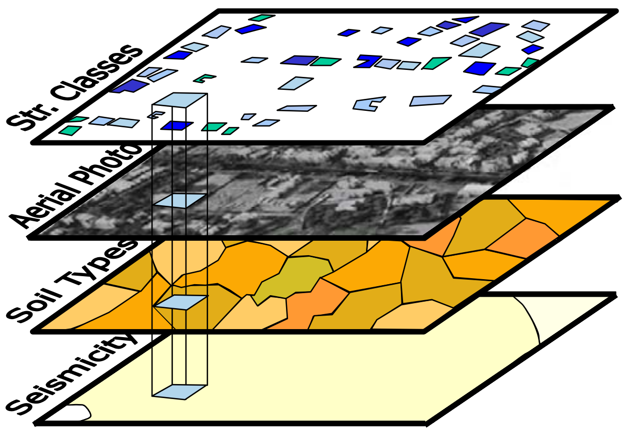

Figure 15 **Illustration of the hierarchical storage of information in the GIS system.**

As outlined in (Bayraktarli et al. 2005) the risks as well as optimal decision options are identified through generic risk models utilizing hierarchical Bayesian probabilistic networks. Available information which has influence on the risks is represented through indicators. Indicators might be information characterizing the class of structures, the characteristics of the soils, the distance to the known fault lines, etc, see Figure 15.

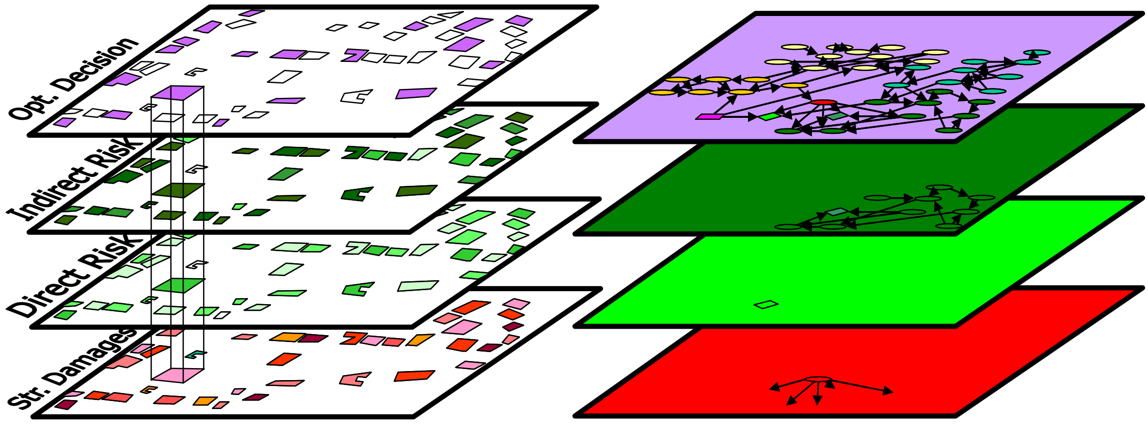

Figure 16 Illustration of the organization of the generic hiearchical Bayesian risk modeling in the GIS system.

The use of indicators based risk models facilitates that generic risk models are developed which through the indicators can be made specific for each individual building in e.g. a large city. In this way only a few risk models need to be developed to assess e.g. the expected losses due to damages of buildings; the same net can be applied for all buildings using the indicators which are stored in the GIS database for each building, see Figure 16.

Integral risk assessment and management utilizing a system where all available information is represented in terms of indicators provides not only the basis for identifying in which way earthquake risks might be reduced most efficiently in terms of soil improvements or retrofitting of different classes of structures in accordance to different schemes. Moreover, such an integral framework facilitates that optimal decisions can be identified for the cost efficient improvement of knowledge, see (Bayraktarli et al., 2007).

5 DISCUSSION AND CONCLUSIONS

The present paper addresses risk assessment of engineered facilities with a special emphasis on the consistent representation of expected consequences or risks taking into account the temporal and spatial variability of prevailing uncertainties.
A framework is proposed which represents the mechanism of how consequences occur in terms of consequences due to physical changes and consequences due to perceived knowledge. The framework furthermore suggests representing the considered systems in terms of exposures, vulnerability and robustness, where vulnerability is linked to the magnitude of direct risks and robustness the degree to which direct risks are amplified.

The framework is illustrated on a few selected examples from recently performed research considering the exposure modeling for the design of rock-fall protection galleries, vulnerability assessment of concrete structures subject to corrosion degradation, assessment of the robustness of structural systems. Finally it is illustrated how the framework also strongly facilitates earthquake risk management through generic indicator based hierarchical Bayesian risk models incorporated into a GIS database.

The consistent representation of uncertainty in time and space in all steps of the risk assessment constitutes a major challenge in bringing the methods of the modern structural reliability theory, risk assessment and decision analysis into practice. Each practical problem has its own specifics, but it is also important to realize the similarities. Over time it would be a great benefit for the engineering profession to establish as certain level of standardization in the probabilistic modeling of events and their consequences. Significant contributions in this direction are collected in (JCSS, 2001) but there are still many important amendments and improvement to be made.

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