Applications of Statistics and Probability in Civil Engineering – Kanda, Takada & Furuta (eds)
© 2007 Taylor & Francis Group, London, ISBN 978-0-415-45211-3

Principles of risk assessment of engineered systems

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ABSTRACT: The present paper summarizes recent work performed within the Joint Committee on Structural Safety (JCSS) on the development of general principles for risk assessment for engineered facilities. The JCSS principles are forming a part of the background for a new ISO Guideline on Risk Assessment presently in development. The approach presented utilizes to a high degree the hierarchical characteristics of typical engineered systems and introduces a quantitative definition of system characteristics such as exposure, vulnerability and robustness. The approach suggested puts special emphasis on the assessment of so-called indirect consequences associated with loss of system functionality and directly related to lack of robustness. The paper describes the general principles proposed by the JCSS and outlines how these may be applied and implemented in practical risk assessment and risk management contexts.

Keywords: Risk assessment, decision making, system representation, exposure, vulnerability, robustness, optimization, risk acceptance, sustainability.

1 INTRODUCTION

Ideally when engineering facilities and activities are planned and performed the risks should be managed from a holistic perspective considering all aspects of the considered activity for what concerns possible events which may lead to and/or influence consequences of any sort. In reality such a holistic and seamless assessment and management of risks is difficult to realize due to the way in which engineering facilities and activities are planned and organized. Typically when considering the process of planning and executing larger engineering facilities and/or activities, several different fields of engineering and different types of systems and components are involved. To facilitate efficient management, the process is traditionally sub-divided into a number of engineering decisions (and areas of responsibilities) concerning the individual components of the process. In practice there are numerous examples of this; considering structures regulations and codes individually specify the quality of materials, quality of workmanship, reliability of structural components, etc. In tunnel project as an example, several different types of systems and components including electrical systems, pumps, cameras, sensors, structural elements, drainage systems, etc. are put together to form a new joint functionality. Each of the components is designed according to regulations and/or codes which did not explicitly foresee that they would find application in a tunnel project. A complex project may in this way been considered as an assembly of standard components integrated in a specific and often unique context. Managing risks may be performed by selecting components which individually have an appropriate reliability and by assembling these such as to ensure an adequate reliable joint functionality. Realizing the characteristics of engineered systems such as the implicit hierarchical construct as outlined in the above may provide means of improving approaches for the assessment of risks of such systems.

In this light the Joint Committee on Structural Safety has established a guideline for risk assessment in engineering. The present paper provides an outline of the main contents and ideas contained in this guideline.

2 DECISIONS AND DECISION CONTEXT

If all aspects of a 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 aspects involved in the decision problems often is far less than perfect and that we are only able to model the involved physical processes as well as human interactions in rather uncertain terms the decision problems in engineering are subject to significant uncertainty. Due to this it is not possible to assess the result of decisions in certain terms. There is no way to assess with certainty the consequences resulting from the decisions we make. However, what can be assessed is the risk associated with the different decision alternatives. 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 (von Neumann and Morgenstern, 1943; Raiffa and Schlaifer, 1961) from the economical decision theory and a whole methodical framework is made available for the consistent identification of optimal decisions. This framework is considered to comprise the theoretical basis for risk based decision making and the following is concerned about the application of this for the purpose of risk based decision making in engineering.

2.1 *Decisions and decision maker*

Engineering decision making and risk assessment 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.

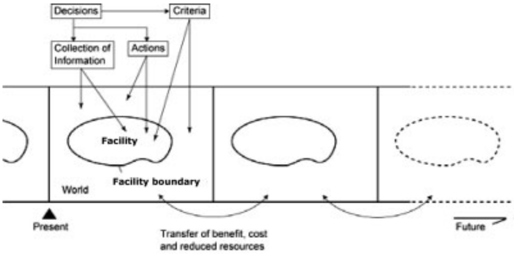

Figure 1. Main constituents of systems in risk based intra-/intergenerational decision analysis, Faber and Nishijima (2004).

2.2 *System representation in risk assessment*

In Figure 1 risk based decision making is illustrated in a societal context from an intergenerational perspective; see also Faber and Maes (2004). 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 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 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. 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.

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 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.

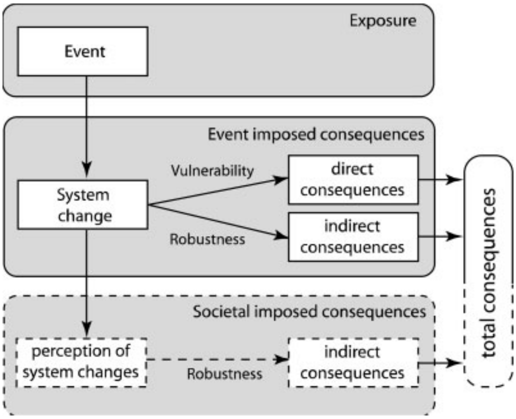

Figure 2. Representation of the mechanism generating consequences.

2.3 *Representation of knowledge*

The Bayesian statistics 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, model uncertainties and statistical uncertainties. However, 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. 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 (Faber, 2005; Faber and Maes, 2005a). For the purpose of decision making the differentiation is irrelevant and not coherent with formal decision analysis.

3 REPRESENTATION OF CONSEQUENCES

The risk assessment for a given system is facilitated by considering the generic representation of the development of consequences in Figures 2–3.

Following (Faber and Maes, 2005b) the exposure to the facility is represented as different exposure events acting on the constituents of the facility. The constituents of the facility 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 of the facility such as monetary losses, loss of lives, damages to the qualities of the environment or just changed characteristics of the constituents.

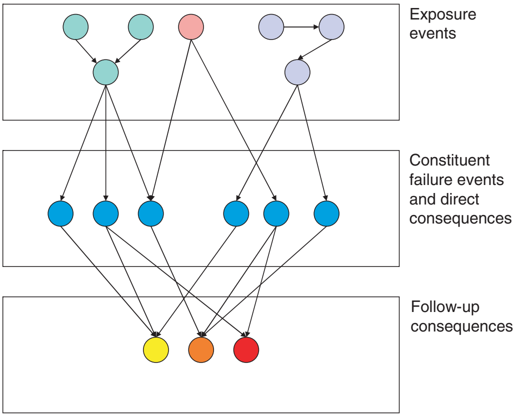

Figure 3. Logical representation of interrelation between exposures, constituent failures, sequences of constituent failures and consequences.

Based on the combination of events of constituent failures 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, 2004). Typically the indirect consequences evolve spatially beyond the boundaries of the facility and also have a certain 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 the total risk is increased beyond the direct consequences. These three characteristics (exposure, vulnerability and robustness) which will be defined in the following are only unambiguous subject to a definition of the system.

In consistency with (Haimes, 2004) it should be noted that very often the constituent in a facility can be modeled as a logical system comprised by its own constituents. A facility 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.

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

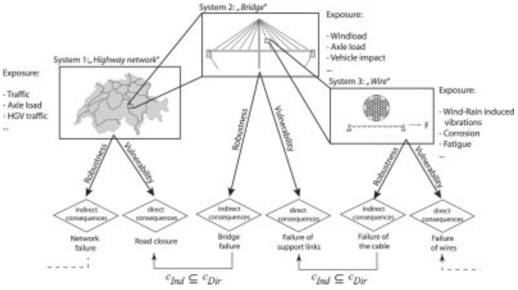

Figure 4. Generic system characterization at different scales in terms of exposure, vulnerability and robustness.

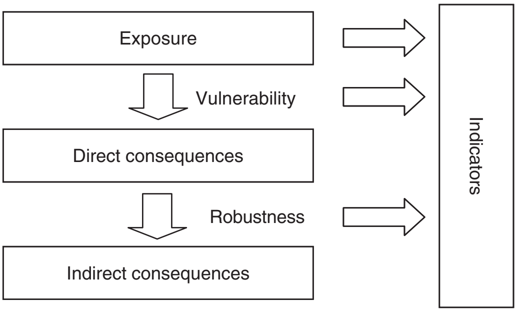

Figure 5. Risk indicators at different levels of the system representation.

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).

3.1 *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).

3.2 *Quantification of risk*

Following (Faber and Maes, 2005b) the facility which is considered subject to a risk assessment is assumed to be exposed to hazardous events (exposuresEX) 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:

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

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

$$I_R = \frac{R_D}{R_{ID} + R_D} \qquad (3)$$

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 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.

3.3 *Comparison of decision alternatives*

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

$$E\left[U(a_q)\right] = \sum_{i=1}^{n_{O_q}} p(O_i \left| a_q \right.) u(a_q, O_i) \tag{4}$$

where $E[\cdot]$ is the expectation operator, n_{o_j} is the number of possible outcomes O_i associated with alternative a_q, $p(O_i|a_q)$ is the probability that each of these outcomes will take place (given a_q) and $u(a_q, O_i)$ is the utility associated with the set (a_q, 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 3.2 Equation (4) can be rewritten as:

$$\begin{aligned} &E\left[U(a_q)\right] = \\ &\sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l \left| EX_k \right., a_q) c_D(\mathbf{C}_l, a_q) p(EX_k, a_q) + \\ &\sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l), a_q) \times \\ &p(S_m \left| \mathbf{C}_l, EX_k \right., a_q) p(\mathbf{C}_l \left| EX_k \right., a_q) p(EX_k, a_q) \end{aligned} \tag{5}$$

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. In prior and posterior decision analysis the optimal decision $a^* \in \mathbf{a}$ is identified from:

$$\max_{\mathbf{a}} \; U(a^*) = \max_{\mathbf{a}} E'_{\mathbf{X}} \left[U(a, \mathbf{X}) \right] \tag{6}$$

where $U(\cdot)$ is the utility and $\mathbf{X}$ is a vector of random variables representing all uncertainties influencing the decision problem. 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.

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:

$$\max_{\mathbf{a}} U(a^*) = \max_{\mathbf{a}} E'_{\mathbf{Z}} \left[E''_{\mathbf{X}|\mathbf{Z}} \left[U(d(\mathbf{Z}), \mathbf{X}) \right] \right] \tag{7}$$

“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. 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.

3.4 *Feasibility and optimality*

Different decision alternatives, e.g. in regard to damage prevention, damage reduction and rehabilitation will imply different potential losses and potential incomes. Risks associated with different decision alternatives may be understood as the expected utility associated with the same alternatives and this interpretation facilitates the application of the decision theory for the identification of optimal decisions (Rackwitz, 2002). In Figure 6 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.

Decisions which do not yield a positive benefit (utility) should clearly not be chosen. Optimally the decision yielding the largest utility is selected but there could be constraints on the decision alternatives which are not explicitly included in the formulation of the utility function, e.g. set outside of the risk assessment. In this case not all decisions with a positive utility may be acceptable. Such situations may occur due to the need to safeguard the individual in society from consequences of societal decision making.

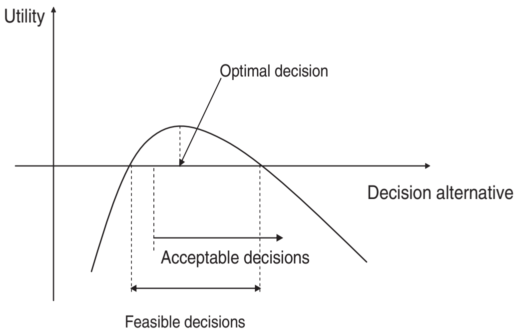

Figure 6. Illustration of variation of expected utility (benefit) as a function of different decision alternatives.

3.5 *Life safety and risk acceptability*

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 economical losses the decision maker has to take into account also the risk of fatalities and injuries as well as potential damages to the environment.

Rational risk acceptance criteria in the context of societal decision making may be derived on the basis of socio-economical 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 economical resources. In the context of societal infrastructure with a life time typically in the order of decades or centuries it is expedient that such economical 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 economical 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 forms 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 (Nathwani et al., 1997). 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 per capita g, the expected life at birth l and the proportion of life spend for earning a living w.

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

$$L(g,\ell)=g^{q}\ell \tag{8}$$

The parameter q is a measure of the trade-off between the resources available for consumption and the value of the time of healthy life. It depends on the fraction of life allocated for economical activity and furthermore accounts for the fact that a part of the GDP is realized through work and the other part through returns of investments. The constant $q$is assessed as:

$$q=\frac{w}{1-w} \tag{9}$$

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 (Rackwitz, 2002):

$$\frac{dg}{g}+\frac{1}{q}\frac{\partial\ell}{\ell}\geq 0 \tag{10}$$

based on which the societal willingness to invest into life saving activities (societal willingness to pay) is assessed as:

$$SWTP=dg=-\frac{g}{q}\frac{\partial\ell}{\ell} \tag{11}$$

A given measure with the purpose of reducing risks of life implies an allocation of $dg$and a corresponding increase of life expectancy dl. Based on Equation (10) the relationships between dg and dl which lead to increases in the LQI may be determined which in turn can be utilized for assessing the acceptable probability of different types of failures of relevance for a considered system.

Considering structural reliability applications the relative change in life expectancy $\frac{\partial\ell}{\ell}$ may be exchanged by a change in mortality $d\mu$as (Rackwitz, 2005):

$$\frac{\partial\ell}{\ell}\approx C_x d\mu=C_x kdm \tag{12}$$

where dm is the failure rate and C_x is a demographical economical constant corresponding to a given scheme x for mortality reduction and k is the probability of dying given a failure. Finally there is:

$$dC_y=\frac{g}{q}C_x N_{PE}kdm \tag{13}$$

where dC_y are the annual investments which should be invested into life safety and N_{PE} is the number of persons exposed to the failure.

3.6 *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 a risk free investment. In the public sector the discounting rate, also in the context of life saving investments should correspond to the real rate of economical growth per capita (Rackwitz et al., 2005). This corresponds to the rate at which the wealth of an average member of society increases over time.

3.7 *Risk treatment*

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 or options. Risk treatment is decided upon for the purpose of optimize the expected utility to be 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. 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).

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). Depending on the budget limitations of decision makers it may be relevant to consider transferring risk due to extreme losses to a third party. This risk treatment approach transfers a possible small risk associated with potential large losses in return for a payment which under normal conditions exceeds the actual risk.

Finally as indicated in Figure 2 indirect consequences due to the perception of the public in connection with events gaining the interest of the media can be associated with very severe socio-economical losses; such losses may be due to political pressures to react to disasters or severe accidents in contradiction to optimal decisions or before a decision basis has/can be established at all. 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.

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.

4 CONCLUSIONS

Engineering decision making is a complex issue due to often very significant potential consequences and substantial uncertainties. In addition engineering decision making increasingly necessitates a holistic and integral consideration of technical, environmental and social aspects and thus requires the involvement of expertise across disciplines of very diverse background. The continued successful development of society as well as the general competitiveness in engineering depends on the efficiency of identified options for the management of risks as well as for the communication of the basis for decision making to all stakeholders. This situation calls for the development of a unified framework for risk based decision making which is general enough to accommodate for the special needs of different application areas but at the same time specific enough to ensure a sufficient degree of consistency in modeling and theoretical basis.

The present paper presents an outline of such a framework, recently developed by the Joint Committee on Structural Safety. The presented framework should be seen as a general philosophy and a set of principles for risk based decision making rather that an operational tool box. It is implicitly understood that the user of such a framework will appreciate the need for engaging experts and or appropriate tools in the implementation of the proposed framework.

ACKNOWLEDGEMENT

The presented framework is the result of work and discussions performed within the Joint Committee on Structural Safety (JCSS) over the last 4 years. All members of the JCSS contribution are greatly acknowledged for their valuable contributions. In addition the first author greatly acknowledges the financial support from ASTRA (Swiss Federal Roadway Authorities) through the project: Development of a Homogeneous Basis for Assessment of Risks.

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