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Decision making subject to aversion of low frequency high consequence events

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Abstract

The present paper focuses on the risk assessment of low frequency high consequence events. In current policies often risk aversion is introduced either to account for the behavior of the public or to include follow up consequences. It is discussed in detail whether the introduction of risk aversion in the context of normative decision making can lead to rational decisions. It is concluded that only a clear distinction between different kinds of consequences can lead to rational decisions which maximize the utility of the decision maker. A framework is presented that accounts for direct consequences and two different kind of indirect consequences. The framework facilitates a differentiated identification and treatment of risks and specifically addresses the modeling of possible consequences caused by the perception of adverse events by stakeholders.

1. Introduction

Depending on the situation at hand, decision makers may feel uneasy with the direct application of expected utility as basis for decision ranking. There are principally two reasons for this; the decision maker is uncertain about either the assessment of the consequences entering the utility function or the probabilistic modeling of the associated uncertainties. In order to account for the possible misjudgements of utility, decision makers feel inclined to behave risk averse – i.e. give more weight in the decision making to infrequent events of high consequences (typically events for which knowledge and experience is limited) compared to more frequent events with lower consequences (for which the knowledge and experience may be extensive).

Risks associated with low-probability high-consequence events, including events considered to lie outside the traditional design envelope represented by building codes, have become key issues in the design of complex structures such as offshore production facilities, industrial plants and high-exposure public structures. Additionally, following the occurrence of especially rare and/or high-consequence events, decision makers are often in the spotlight and as a consequences hereof may over-commit societal resources for reasons different to serving the general public. Due to this, the rational consideration of risk aversion has taken on renewed significance.

In applied risk based decision making the inclusion of risk aversion is often made by use of so-called risk aversion factors. In many applications risk aversion factors are introduced such that possible high consequences due to rare events are weighted stronger than more frequently occurring events with smaller consequences.

The present paper starts out with a discussion of the various reasons for risk averse behaviour of decision makers. Thereafter, based on a literature review, an overview of different approaches for use of risk aversion factors is provided. Based on this overview it is shown that the use of risk aversion factors may be related to one general and important issue in risk assessment, namely uncertainties associated with the system understanding and definition. Furthermore, it is shown that the use of risk aversion factors may introduce several problems associated with modeling consistency but also more ethical problems when life risks are concerned. Finally, a consequence model framework is introduced which by explicit representation of direct and indirect consequences associated with physical changes of a considered system as well as indirect consequences due to risk perception of the public may provide an improved basis for system understanding and representation in risk assessment. Examples are provided to illustrate problems and possible solutions.

2. Risk aversion in the context of decision making

2.1. System representation in risk assessment

The definition and modeling of the system determines which consequences are accounted for in risk assessment. In order to discuss aspects of risk aversion, the clear definition of the system is thus a basic prerequisite.

The system can be defined as the logical and causal physical representation of the interrelation between system components including all available knowledge concerning events, consequences and options which are of relevance for the decision making problem (Faber and Maes, 2005) The system refers to the context in which decision are made.

Different investments into measures which change the system can be performed to optimise the behaviour of the system and to maximize the benefit. Exogenous and/or endogenous processes and events might also cause system changes which in turn lead to different kinds of consequences.

A system can be modelled with different levels of detail; the basic principle being that the level of detail shall accommodate for the consistent ranking of available options for risk reducing measures. The detailing of a system shall thus provide for a representation of the mechanisms generating the consequences and facilitate for utilization of available and foreseeable achievable information (Faber et al. 2007). For engineered systems comprised by technical components and processes which are regulated by codes, standards and best practices the identification of possible options for risk reduction is greatly facilitated by system representations in terms of logically and/or causally interrelated components. Sub-sets of interrelated components may be considered as components themselves whereby a hierarchical aggregation of system risks is facilitated. A generic representation of a system is illustrated in Figure 1.

Different exposures can act on one or more components of the system. Exposures can be understood as all processes which might cause consequences. An exposure for a technical component of a system can be related to e.g. a load or a deterioration process. Individual components of a system can be seen as the first defence of the system in regard to the prevailing exposures. The damage of individual components of a system caused by exposures is a main descriptor of the vulnerability of the system. The consequences related to such damages are denoted by direct consequences (see Figure 1).

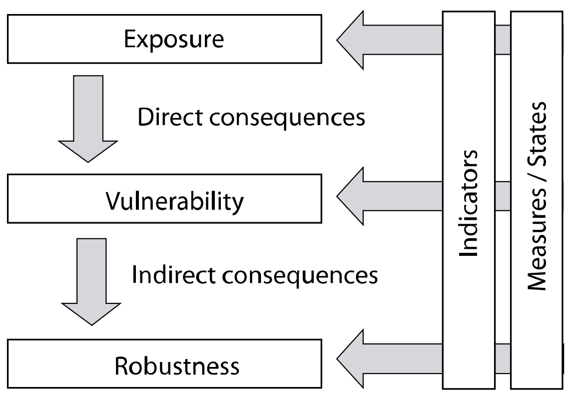

Figure 1: Generic representation of the system components

The damage of single components and/or the associated direct consequences can cause additional, indirect consequences. System robustness is here associated with the ability of a system to limit the possible consequences to direct consequences. The robustness of a system reflects aspects such as reliability, ductility and redundancy but also activities aiming to control and reduce indirect consequences by monitoring, control and intervention (Baker et al. 2006).

On all three levels (exposure, vulnerability and robustness) measures can be performed to reduce the risk. On each level, risk indicators can be identified. These risk indicators are quantities which contain information about the risk. They also provide information regarding which kind of measure could be performed in order to reduce the risk (see Figure 1).

The system model, in principle, must include a full inventory of all potentially occurring consequences as well as all possible scenarios of events which could lead to consequences. At an intra-generational level the characteristics of the system consist of the knowledge about the considered technical facility, the surrounding world, the available decision alternatives and criteria (preferences) for assessing the utility associated with the different decision alternatives {Faber, 2005 #165} (Faber and Maes, 2005).

Every decision involves an allocation or commitment of resources. The decision maker is either a person or an organization which can decide on the use of resources and which carries the responsibility of possible losses.

The optimal decision should provide an equilibrium between additional investments into risk reduction and the associated risk reduction. The resulting benefit of a decision is highly dependent on the preferences of a decision maker. Optimality is thus highly dependent on who will benefit from the decision. To provide a basis for decision making the expected utility corresponding to each decision alternative has to be assessed; the various attributes associated with the outcomes of decisions have to be transformed into comparable units, using utility functions.

2.2. Risk perception and risk aversion

In society, events associated with comparatively small consequences or for which the rate of occurrence is high are in general accepted by the public and indirect consequences due to the perception of the events are not important. To treat risks due to such events, the experience and the knowledge of experts is used and in general rational decisions are made the theoretical framework for risk based decision making based on the utility theory proposed by von Neumann and Morgenstern 1944, is generally accepted for rational and optimal decision making.

It is observed and widely discussed in the literature that adverse events which are unusual due to their consequences or rarity attract both public and media attention (see e.g. Kasperson et al. 1988, Slovic et al. 2004). In most cases such events implies high consequences. The attention of the public causes pressure to politicians and decision makers such that post-event actions are often undertaken without proper planning; in such cases axioms of the expected utility theory are thus often violated and the societal resources not optimally allocated.

In order to be able to describe the actual behaviour of people, *prospect theory* was developed by Kahneman and Tversky 1979. In surveys performed at different universities, they observed that people do not state their preferences in accordance with expected utility theory. In situations where people have to make decisions under risk with a positive outcome they tend to be risk averse, while in situations with an associated negative outcome they tend to be risk seeking. All observations from Kahneman and Tversky 1979 are based on stated preferences. It can not be presumed that stated preferences or stated rankings correspond to the preferences one can observe in society (Harsanyi 1997). In Diamond and Hausman 1994 the results from evaluation surveys are discussed in detail. They conclude that the absence of direct market parallels leads to a difference between the *stated* and the *real* preferences.

Both the findings in the prospect theory and the findings derived by sociological and psychological related research are useful to describe the behaviour of uninformed decision makers. The aim in engineering decision making is to provide normative tools for the decision maker to identify the optimal solution among different options which maximize her/his utility. The tools provide information regarding the outcome of decisions and thus primarily serve to avoid an uninformed and irrational decision making.

In cases where the decision maker decides on behalf of a principal, the well known agency problem can be observed if the decision maker and the principle are not the same person (Grossman and Hart 1983). This applies especially for engineering decisions where the decision maker decides on behalf of the society and provides facilities and/or functionalities for third persons; she/he has to ensure a sufficient level of safety. Especially after high-consequence events, the decision makers are in the spotlight of the society and to prevent personal consequences they may tend to spend more societal resources for measures with low probability and high consequences. In such cases the resources of society are not used in an optimal way; the decision maker is buying a personal insurance by using resources of society. In principle the use of risk aversion factors, which contain a very high degree of subjectivism. This poses the problem that the basis for the decision making is not transparent and further that the modeling cannot be scrutinized nor verified – a basic prerequisite for any engineering model.

As already outlined, the descriptive modelling of the behaviour of decision makers (e.g. in terms of risk aversion) can help to understand how uninformed decision makers and stakeholders perceive and react in regard to different events, and in this way provides useful information also for normative decision making. Due to post-event societal reactions significant additional losses are often incurred. Understanding the mechanics of this process provides a means for improved risk communication between experts, decision makers and stakeholders, which if conducted efficiently might reduce or mitigate such losses.

Indirect consequences might not only depend on the event or the kind of direct consequences but also on the magnitude of the direct consequences. The loss of image (or reputation) is one example where the magnitude of the consequences of an event may cause indirect consequences. Events resulting in many fatalities may cause such a loss of image. Furthermore, consequences which exceed the budget of the decision maker may lead to a threat to existence of a company. These kinds of indirect consequences which are sometimes also denoted by *ripple effect* (Slovic 1987) or *side consequences* (Gethmann 2003) can be included in the decision making by an extension of the traditionally applied formulation of the loss function. Consider, as an example, two decision options with identical expected direct conesquences but where for the first option the uncertainty associated with the consequences are higher than for the second option; in effect, the probability of consequences larger than the expected value is larger for the first option. To include this effect in the identification of optimal decisions, the indirect consequences which may be associated with deviations from the mean must be added to the utility function (see e.g. Ditlevsen 2003 or Faber and Maes 2003).

2.3. Aversion factors in the context of decision making

The system for which a risk assessment is performed needs to be clearly defined when the issues of risk aversion and the use of risk aversion factors are discussed. Risk aversion factors are widely used in deriving acceptance criteria and for the planning of mitigation measures. Aversion factors are either used implicitly or explicitly.

One prominent example for an implicit use is the acceptance criteria used in *F-N* diagrams. Several publications have described and discussed applications of this concept (e.g. Kübler 2006; Ale 2005, Proske 2004 or Stuart 2000). The acceptance criterion is in general modeled by a power law:

$$F\left(N_{PE}\right) = m\, N_{PE}{}^{-b} \tag{1}$$

Herein N_{PE} denotes the number of fatalities, $F\left(N_{PE}\right)$ the accepted probability of occurrence in a defined time interval. The factor m can be interpreted as the acceptable frequency for a single fatality and b models the risk aversion for a higher number of fatalities. When b is equal to unity, no risk aversion is considered. In practical applications of this concept the factor b lies between one and two. Farmer 1967 proposed a factor of 1.5.

Explicit risk aversion factors are also used in the field of technical risk assessment. They are mainly applied for fatalities but also in some cases suggested for damages related to the qualities of the environment. In the explicit approach, the total risk R is directly calculated in terms of fatalities by multiplying the probability of occurrence p_i of the event i with number of potentially endangered people N_{PE} and an aversion factor φ as a function of N_{PE} ,and summing up over all possible events i:

$$R = \sum_{i=1}^{n} p_i\ N_{PE,i}\ \varphi\left(N_{PE,i}\right) \tag{2}$$

The risk aversion factor in Equation (2) is a function of the consequences (i.e., people endangered) and serves to amplify the magnitude of the consequences. In most applications of this framework only one risk indicator is used to represent the total risk. Different application of this framework can be found in BABS 2002, Kroon and Kampmann (2003) or Okrent et al. 1981.

2.4. *Discussion of the use of aversion factors*

The error introduced by using aversion factors either implicit or explicit is unknown. In some cases the aversion factors might dominate the analysis in a way that the assessment of probabilities plays a minor role. Especially for high consequence events, the focus should instead be set on the consistent assessment and modelling of the consequences.

It can be doubted if a simple power law as used in the *FN*-curves can model complex causal relations of systems. Furthermore, the choice of the risk aversion factor is either purely subjective or empirical if a descriptive approach is used. In addition to the broad criticism of the general concept of *F-N* diagrams (see. e.g. Ball and Golob 1999 or Kroon and Hoej 2001), by using this concept a transparent and rational decision making is not facilitated.

The approximation of the total risk through an aversion factor implies that all risks are lumped together. This is associated with a violation of a fundamental principle in risk based decision making requiring that the system modeling should facilitate for a differentiation (ranking according to risks/utility) of alternatives for risk reduction; using risk aversion factors does not accommodate for such a differentiation. Thereby it is not possible to judge which measures can reduce which kind of risk in the most efficient way and an optimal combination of measures in order to minimize the total risk can not be identified.

Optimal allocation of societal resources necessitates that assessed risks are comparable and universal (Gethmann 2003). This can only be done if risks are assessed on the same basis. If the total risk is modelled by only *one* amplification indicator, e.g. fatalities, they are not well suited to model events with high property losses or substantial environmental consequences. In applications where e.g. property losses dominate, the risk could be substantially underestimated and thereby the aim of the use of the risk aversion factor, namely to model the total consequences, is not achieved. The weighting of risks, furthermore, leads to an uneven distribution of risks to the stakeholders of society and also implies an uneven allocation of resources for e.g. life saving activities; such a concept is unjustifiable in accordance to the first article of the the UN's universal declaration of human rights, "all human beings are born free and equal in dignity and rights" (UNHCR 1948).

If the expected utility theory is not applied for decisions regarding life safety, more resources are spend for averting fatalities when more persons are affected. For decision making regarding life safety the first article of human rights is violated. Societal decision making is concerned about decisions regarding allocation of societal resources for the purpose of life saving for an anonymous statistical person. The allocated resources should lead to an equal reduction of the risk for all persons in society independent of age, gender, health or living conditions. Society cannot provide an equal safety for everybody in absolute terms since the risk of dying is changing over lifetime and still no measure can prevent the ultimate effects of age.

Risk aversion factors may appropriately be assessed if the system is clearly defined and well understood. In such cases risk aversion factors can be used as an approximation of the indirect consequences. Such factors might be useful and reasonable for an initial simplified risk assessment. Detailed knowledge of the system behaviour, the probabilities and the consequences are, however, necessary to determine such factors. A comparative analysis and calibration might be performed and possible limitations for the application established. In order to develop such approximations two principles of engineering modelling should be fulfilled, namely the knowledge should not be extrapolated beyond the experience.

Even though only the normative decision theory should be applied in societal decision making, it is often not clearly distinguished between the normative and the descriptive approach nor is it clearly defined which kind of consequences are accounted for in the modeling. As discussed before the use of risk aversion factors or functions may lead to over, but also underestimation of the total risk and thereby to sub-optimal decisions; this is illustrated in the following through two cases.

The ICE train disaster in Eschede on 3rd June 1998 was caused by a failure of one wheel. The train derailed and collided with the piers of an overpass. 101 people were killed and 88 injured. Additionally to the fatalities, the overpass and the train were destroyed. After the event in the Netherlands all wheels of high speed trains have been exchanged and a detailed investigation of all overpasses on the railway system was performed. The total finance loss estimated by the German railway company was Euro 150 Mio.

In July and August, 1997 floods of the rivers Oder and March caused high consequences in Czechia, Poland and Germany; 114 persons were killed and material damages amounted to Euro 4.1 billion. A large area was affected; hundreds of kilometres of dikes were destroyed and aid organizations as well as the army were in service for several weeks.

Assuming that both events have a similar rate of occurrence, the magnitude of the risk due to fatalities is similar. Taking basis in a modeling where the total risk is approximately estimated by multiplying the fatalities with an aversion factor, the total risk in both cases is nearly the same independent of the risk aversion factor. However, it is obvious that in comparing these cases the number of fatalities is not a consistent indicator of total consequences

Another problem related to the use of risk aversion factors can be illustrated using the flood example from the above. If decision making in regard to risk reduction is made at a national level it is clear that the assessment of total consequences through the use of risk aversion factors added up over the affected countries would lead to significantly different risks as compared to an assessment of risks for all three affected countries as a whole. The aggregation of risks assessed using risk aversion factors is thus not obvious and any assessment of risk aversion factors has to be fixed in relation with the definition of the considered system. This will be an important consideration for events of a large geographical scale, such as global warming and all side effects, only a methodology that explicitly accounts for all consequences can assure a fair and effective allocation of the resources of society.

3. Consequence model

For a rational and consistent risk assessment it is crucial, especially for events with potentially high consequences, that *all* relevant consequences and their associated uncertainties are accounted for and transparently documented in the basis for the decision making.
In Figure 2 a consequence model is proposed that includes direct consequences and indirect consequences; it is consistent with the generic system modeling from Figure 1. A possible event leads to a physical change of the considered system. This system change can cause direct consequences and indirect consequences. The direct consequences themselves can also cause indirect consequences. All consequences related to the physical system change are denoted by *event imposed consequences*.

Due to risk perception or perception of the system changes, the society causes additional indirect consequences. These *societal imposed consequences* occur as a result of uninformed decision making by societal decision makers, who typically perceive a pressure from stakeholders to undertake some sort of action; to take action is often considered more important that to take the correct action. Since measures of risk reduction can be performed at all levels (Figure 2), this part of the consequences can in principle be avoided. Efficient risk communication and the development of a risk culture in society could help to reduce and theoretically even avoid such consequences.

To illustrate the difference between *event imposed indirect consequences* and *societal imposed indirect consequences* the following example is considered. After an event such as the derailment of a train there are many different kinds of indirect consequences such as additional costs due to delays of other trains or necessary replacments of parts of other trains (see 2.3). These costs can be considered as event imposed indirect consequences. But also the fact that fewer passengers might want to use train transport after such events is associated with losses. There is no rational reason for such behaviour, since the risk did not increase after the event – it will actually decrease due to the performed measures.

Risk communication in society is rarely practiced in a targeted manner (Vrouwenfelder et al. 2001) and a common understanding of risks in the general public is not available. In addition to risk communication also regulations and guidelines can help to build a basis for societal decision making. Appropriate reactions in the aftermath of adverse events could effectively help to limit societal losses. Both risk communication and regulations are clearly directed to the future; such measures of risk reduction can be seen as long term objectives. Of course, the modelling of societal imposed consequences is not straightforward. The investigation and observation of past events can help identify and understand the main indicators for these consequences. This would also provide a basis for decision making in regard to the type and amount of communication that is most efficient to reduce these consequences.

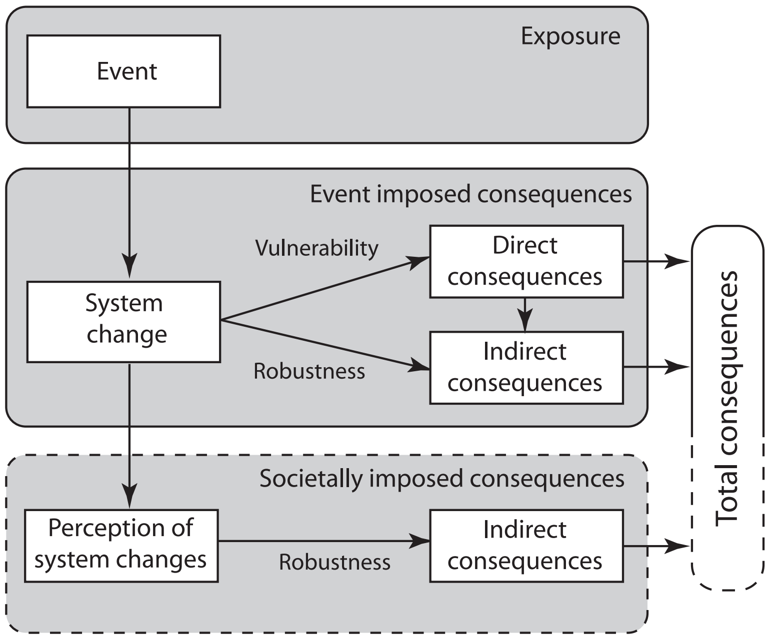

Figure 2: Representation of the different components of total consequences.

4. Rational acceptance criteria regarding life safety

Decisions on behalf of society in regard to investments into life saving should reflect the preferences of society. Fundamentally this is a difficult pursuit; first of all the question arises concerning how such preferences may be established and secondly it may be questioned whether such preferences are indeed optimal. In aiming to solve this problem (Nathwani et al. 1997) proposed the concept of the Life Quality Index (*LQI*) as an indicator for societal preferences regarding investments into life safety. The *LQI* concept takes basis in the three demographical indicators; life expectancy at birth l, gross domestic product per capita g and the average fraction of life spend to earn a living w. During the last decade several researchers (see e.g. Rackwitz 2002 and Ditlevsen 2003) have scrutinized this concept, undertaken empirical verifications and proposed various extensions. In regard to whether the *LQI* reflects optimal societal allocation in regard to life safety investments it should be noted that this is implicitly ensured through the so-called universality principle, which takes the perspective that all individuals have optimized their own personal allocation of time use between paid work and leisure time.

The *LQI* can be expressed in the following principal form:

$$L(g,\ell)=\frac{g^q}{q}\ell\left(1-w\right) \tag{3}$$

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:

$$q=\frac{1}{\beta}\frac{w}{1-w} \tag{4}$$

The factor β arises from the description of the *GDP* using the Cobb Douglas Production function (Pandey et al. 2006). β describes the part of the income produced by labour. The other part of the income is produced by the capital. The *LQI* is based on the *revealed preference method* (*rpm*) and can be interpreted as a societal utility function. The theory of the revealed preferences was developed by Paul Samuelson (Samuelson 1938) and is an indirect method to model the value of goods which are not traded on the market. The concept of the *rpm* is to model the preferences of the society by observing its behaviour. The behaviour has to follow the real market conditions and budget constraints.

Every risk reduction measure will affect the value of the *LQI*. The *LQI* is not directly used as a nonlinear utility function in the decision making process but provides a basis to determine what is affordable for society to invest into life saving activities. Since it is assumed that the individuals of society already have optimized their work time – leisure time relation w, the *LQI* can be seen a societal weighing of *g* and *l*. The indifference curve provides a societal trade off relation between these two goods. The slope of the indifference curve equals the marginal rate of substitution between life expectancy and wealth:

$$-\frac{q\ell}{g}=\frac{\partial\ell}{dg} \tag{5}$$

The acceptance criteria is derived by the consideration that any investment into life risk reduction should lead to an increase of the *LQI* results in the following risk acceptance criteria (Rackwitz 2002) :

$$\frac{dg}{g}+\frac{1}{q}\frac{\partial\ell}{\ell}\geq 0 \tag{6}$$

If the change in the income dg is interpreted as the cost of a measure to reduce the risk and $\partial\ell$ is a measure for the risk reduction; Equation (6) can be used to assess whether a measure is affordable and effective (Rackwitz 2006). This criterion sets a societal boundary condition for decisions that might maximize the benefit for a decision maker at the expense of society. A sufficient level of safety is provided by this criterion. To model the consequences and to establish the utility function for systems including aspects of life safety the assessment of the so called *societal value of the statistical life* (*svsl*) may serve as a guideline for the assessment of compensation costs associated with loss of lives. The *svsl* can also readily be established based on the *LQI*.

Conclusions

This paper outlines two common reasons of implementing aversion in risk analysis. Firstly, risk aversion are utilized for the purpose of describing the behaviour of uninformed decision makers. Secondly, risk aversion is introduced to model total consequences in terms of a risk amplification factors as a function of one risk indicator. The effects of aversion, however, can be represented in the decision making by carefully accounting for all consequences, direct as well as indirect.

Especially for low frequency and high consequence events, a detailed assessment of the risk including all inherent uncertainties is of utmost importance. Approximations in such cases through risk aversion factors are not appropriate; they rely on extrapolation and do not facilitate the identification of risk reduction measures. Furthermore, they do not facilitate transparency and communication.

It is concluded that the level of detail for assessing the probability of occurrence and the consequences should facilitate a ranking of different decision alternatives and assessed risk should be comparable and additive. By using aversion factors the risk assessment is not performed on an appropriate level of detail.

For well understood systems and frequent events with low associated consequences, however, risk aversion factors may be useful if used with care. Under such conditions, risk aversion can support the decision maker to get a first approximation of risks and directions for more detailed investigations.

In the light of the reviews and the discussions of the present paper it is suggested to differentiate between three general types of consequences - namely the *direct event imposed consequences*, the *indirect event imposed consequences* and the *societal imposed indirect consequences* - when consequence models are developed for the purpose of normative decision making.

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