Using the predictive epistemic uncertainty approach to risk analysis in the design against catastrophic events

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Abstract
Preparation for managing future disasters includes a process for identifying scenarios and evaluation of the mitigation resources involved. We are uncertain about what kind of disasters that could occur, and we are also uncertain about the performance of the mitigating measures, given a specified disaster scenario. Risk analysis is a tool for dealing with uncertainties about the future, and the future can develop into a number of outcomes, of which some disastrous. The risk analysis is then inter alia used to reduce epistemic uncertainty. When applying the predictive epistemic uncertainty approach, the focus is placed on "observable" quantities, such as the number of fatalities, the number of accidental events of specific categories, the occurrence or non-occurrence of specific events, etc., and probability is used as a measure of uncertainty. This paper presents planned steps for the risk analysis in accordance with the predictive epistemic uncertainty approach. In order to illustrate important aspects of the approach, an example comprising the development of an accommodation building at a seafront, which is exposed to risk of ship collision, is chosen. Our conclusion is that the predictive epistemic uncertainty approach to risk analysis is a powerful design tool especially when risk of very remote catastrophic events threatening the disaster management is on stake.

Introduction
Design against catastrophic events often involves difficult decisions, in which project costs must be traded off with safety aspects. As an example, consider the planning phase of an accommodation project at the seafront next to a fairway carrying a great deal of traffic, mainly ferries (within the limits of 3000 dwt. and 500 passengers) and catamarans (within the limits of 250 dwt. and 200 passengers). Placing the building close to the sea is regarded as an important architectural value of the project. The provision of a quay has been limited for small recreational boats. The picture below illustrates the imagined situation.

Figure 1; Illustration of the accommodation buildings at the seafront

Is this situation acceptable with respect to the safety aspects? A ship collision is of course a potential disastrous scenario threatening the structural integrity of the accommodation building which could lead to a numerous fatalities involving people within the building as well as people onboard the ship or ferry. However, in Norway, a scenario like this has never occurred. Is the occurrence of a serious ship collision possible? What is the risk? How should we describe different scenarios, and which should be chosen for design purposes?

The traditional risk analysis approach, often referred to as classical approach to risk analysis, face serious problems as discussed in Aven and Pörn (1998). There are in most real life cases not available sufficient hard data to accurately measure risk, and quantification of uncertainties related to the true risk is difficult to carry out in practice and it gives a somewhat wrong focus. What should be highlighted is not a fictitious risk, but quantities of the "world", such as the number of fatalities, the occurrence of an event, etc. and risk analysis should be used as a tool for expressing uncertainty of these quantities. These are the main principles of the so-called predictive, epistemic uncertainty approach (hereafter called the predictive approach) to risk analysis as introduced by Aven (2000). In the present paper we discuss some key steps of the risk analysis when adopting this alternative approach, using an example comprising an accommodation building at a seafront.

The predictive epistemic uncertainty approach to risk analysis

The predictive approach to risk analysis represents a basis for developing a unifying set-up for dealing with risk and uncertainty for the many application areas, including design against remote catastrophic events. The predictive approach is illustrated in figure 2, below.

The figure is to be read as follows. A decision-maker or a decision making group (project management, local government, etc.) are to make a decision that affects system performance (the world). To support the decision-making a risk analyst (or a risk analyst team) conducts a risk analysis. The analysis is based on some background information, such as the system definition, provided by the decision-maker or his/her representative. The risk analyst presents his/her results, that is a risk picture covering predictions and uncertainty assessments, and an evaluation of this picture. Essential background information, such as key assumptions made in the analysis, is reported as well. The analysis as such is based on the development of a model (several models), that relate the overall system performance measure Y to a number of observable quantities $\mathbf{X} = (X_1, X_2, ..., X_n)$ on a more detailed level. The analyst assesses uncertainties of $\mathbf{X}$, and that could mean the need for simplifications in the assessments, for example using independence between the quantities X_i. Using probability calculus, the uncertainty assessments of $\mathbf{X}$ together with the model g, gives the results of the analysis, i.e. the assigned probability distribution of Y, with its mean and variance.

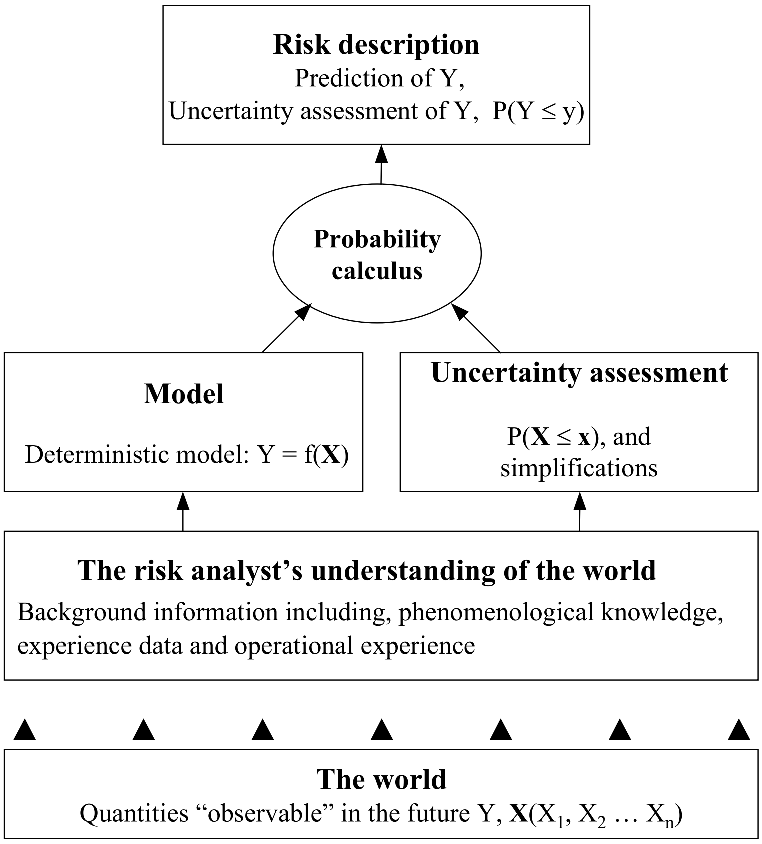

Figure 2; The predictive approach to risk analysis (Nilsen & Aven, 2001)

The main steps of an analysis in accordance with the predictive approach can be described as follows:

1. Identify the overall system performance measures (quantities expressing the state of the "world" on a high level). These are typically associated with the objective of the system performance.

2. Develop a deterministic model of the system linking the system performance measures and "observable" quantities on a more detailed level.
3. Collect and systematise information about these low-level quantities.
4. Use probabilities to assess uncertainty of the low-level quantities
5. Calculate the uncertainty distributions of the performance measures and determine suitable predictions from these distributions.

In the rest of this paper these steps are discussed in more detail, and some guidelines are outlined.

Overall system performance measures

Every risk analysis is carried out to provide decision support in a specific context. Normally safety risk analysis is subjected to planned physical or organisational changes such as a construction project, enterprise development, new plans for a public infrastructure, etc. where safety issues are sought. The risk analysis could also be subjected to reveal new information about existing systems.

The interesting quantities in the future relate to the performance of the considered activity or system, hereafter denoted as the system. Overall system performance is a multiple term that could contain aspects of human health (psychosocial and physical), the environment (e.g. amount of pollution), safety (e.g. number of fatalities, the occurrence of an accident), economy (e.g. profit, production, production loss) emergency preparedness (e.g. capacity, execution time, vulnerability of emergency measures), aesthetics and so on, i.e. every aspect deemed as important for the actual decision-making. In a safety risk analysis the system performance are normally restricted to safety and emergency preparedness quantities.

Consider the building project example. The project management evaluates safety against catastrophic events caused by vessel collision from the seaside. Prior to choose the strategy for the provision of safety barriers against ship collisions, the project management needs an analysis covering possible catastrophic scenarios. In this case the performance measure is limited to the occurrence of a collision between building structures and a maritime vessel. The site structure, the ship lane, the ships (traffic) and the immediate surroundings thus define the system. Note that no evaluation of safety barriers is made at this stage, since it is the design strategy that is focused. We are only interested in the characteristics of the vessel impacting the border of the building.

In the selection of which performance measures to be chosen for the risk assessment, the major concerns are:

What negative conditions or consequences could be associated with the system?
How can we observe and measure these conditions or consequences?

In the predictive approach the quantities focused are observable, expressing a state of the "world". This means that the notion observable quantity is to be interpreted as a *potentially* observable quantity - for example, we may not actually observe the number of injuries (suitably defined) in a process plant although it is clearly expressing a state of the "world". The quantities are observable meaning per definition that they can be accurately measured in the future. The value of an observable quantity is well defined as conventions and procedures exist expressing how to measure it. There can not be any ambiguity present. Thus an observable quantity has a true, objective value. For example, the number of fatalities in a company during a specific period of time would clearly be an observable quantity. If we consider the number of injuries, it is not so obvious. We need to define precisely what an injury mean. According to such a definition, we would have one correct value. The fact that there could be measuring problems in this case – some injuries are not reported – does not change this. The point is that the true number exists according to the definition and if sufficient resources were made available that number can be found.

Navigational error is a causal factor of ship collision. Human error as such needs to be thoroughly explained in order to avoid ambiguity and interpretation problems. Lack of competence related to navigation and the navigation equipment is one of the causal explanations for a navigation error. However, this explanation is not sufficiently precise. The setting of the situation must be described, for example a normal situation with respect to traffic load (not more than one boat in each lane) and weather conditions (within acceptable limits – wind, waves, current, fog). The navigation error is then either a wrong action or not to commit a necessary action, and the navigator afterwards explain that he/she did not know how to interpret the situation (on the bridge) and/or to operate the navigation equipment.

Modelling and simplifications

A model is a simplified representation of a real world system. In typical risk analyses the focus is normally related to isolated incidents. The incidents are part of cause-consequence chains, where the focus is either placed on lack of control, loss of control, energy exposure onto structures (human bodies and material) and the ceasing of the energy exposure. Fault trees and event trees are basic models used in risk analysis, made of logical connections (AND-gates, OR-gates). Occasionally, sub models are applied to form the input to the events. Such models could become constructed with physical quantities such as pressure, volume, temperature etc. Note that events as well as physical quantities are observable in accordance with the discussion above. Strict focus should be on the events and quantities in the modelling without associating any probabilities.

A ship collision with the building would actually mean that a vessel has made an *unrecoverable mistake* in the *vicinity* of the building site. An unrecoverable mistake means that an undesired consequence will occur, that could either be grounding/ collision with onshore structures or collisions with other ships. The vicinity is defined as critical nearness to the border of the building structures in which the different types of vessels are unable to stop (varies between 70 – 200 m). This is the first step modelling. The next step or the starting point for the detailed modelling is thus:

What can lead to an unrecoverable mistake?
Given the unrecoverable mistake, where will the vessel end up (including type of vessel and speed)?

The first situation is modelled by applying the fault tree technique. The second topic is modelled by defining angular deviations from specified ship lanes.

The models are by definition simplifications of the real world. Only factors regarded important for the system's performance is included in the models. Important assumptions or conditions, for example critical nearness of 100 m given a specific type of vessel, must be clarified and properly communicated in the analysis. The assumptions and models constitute an important part of the actual knowledge brought to the analysis. The users' confidence in the analysis could be influenced by for example the analyst having judged quantities of the models independent, by inaccuracies in the real world descriptions, by deliberate simplifications introduced by the analyst or by phenomenological limitations.

Background information and data gathering

All probabilities are conditioned on the background information (and knowledge) that we have at the time we quantify our uncertainty. This information covers historical system performance data, system performance characteristics (such as policies, goal and strategies of a company, type of equipment to be used etc.) and knowledge about the phenomena in question (such as fire and explosions, human behaviour etc.), as well as decisions made. We may assume for example in a safety risk analysis that no major changes in the safety regulations will take place for the time period considered, the plant will be built as planned, the capacity of a emergency preparedness system will be so and so, and equipment of a certain type will be used etc. These assumptions can be viewed as frame conditions of the analysis and the produced probabilities must always be seen in relation to these conditions. If one or more assumptions were dropped, this would introduce new elements of uncertainty to be reflected in the probabilities.

Recapturing the fundamental issue – what is the risk of a catastrophic ship collision? There exist no directly relevant accident data in Norway. However, the Bright Field Riverwalk Accident (Bright Field, 1996) December 14th 1996 in New Orleans, LA, showed incredible forces of the ship collision, damaging vital structures of the shopping mall. Accident reports from this accident and other accidents can be retrieved as background information, but are the reports relevant? Yes, to some extent, since organisational similarities onboard ships could exist, technical equipment could be related, international regulation and so on. However, a specific Norwegian harbour is different from other harbours, due to its operational aspects (type of traffic, weather conditions, geography, seabed topography, services, enterprises etc.) as well as prevailing sociological and cultural conditions. The latter relates to for example unwritten traffic rules and behaviour (such as the largest boat proceed anyway), maintenance routines, roles of seamen, relationship between seamen and other actors (owners, clients, passengers), harbour authority activity and routines, seasonal happenings, accident reporting routines, etc. The traditional conflict between leisure traffic and commercial traffic (see for example Booth, 1994) could also have its distinctive character in the specific harbour. A serious attempt to express the risk must include these considerations, and experts are normally required.

It is a basic principle of the predictive approach to risk analysis that the analyst is ultimately responsible for the assessment, and as such, the analyst is obliged to make the final call on the probability distribution. "Experts" have advanced knowledge in rather narrow disciplines and they are unlikely to devote the time necessary (even with training) to become as familiar with the unique demands of the assessment question as the analyst. A formal expert elicitation is recommended, when little relevant data can be made available and when it is likely that the judgement of the analyst will be subject to scrutiny, resulting for example in costly project delays.

Since little data of marine incidents are available, the challenge is to identify sufficient expertise (covering all aspects) that can give good predictions. More than one expert is recommended and an expert elicitation process is to be carried out (Njå, Aven and Rettedal, 1998, present an example of an expert elicitation procedure). The experts make their uncertainty assessments of the low-level quantities of the fault-trees and the angular deviations (scenario development) from the predefined ship lane.

Uncertainty assessment of low-level quantities
To assess uncertainties and specify probabilities for low-level quantities, different approaches can be used (cf. Hoffman and Kaplan, 1999 and Aven, 2001):

Classical statistics. If we are to assign a probability of A, and we have some observations of which 20 % is "success", we may use a subjective probability of 20 %. This method is appropriate when the analyst judges the observational data to be relevant for the uncertainty assessment and the number of observations is large. Unfortunately this is not the case in most practical cases. For the ship collision example we cannot apply this method.

Analyst judgement using all sources of information. This is a method commonly adopted when data are absent or when data are only partially relevant to the assessment endpoint. A number of uncertain exposure and risk assessment situations are in this category. The responsibility for summarising the state of knowledge, producing the written rationale, and specifying the probability distribution rests with the analyst. Consider the problem of specifying P(A). The starting point is that the analyst is experienced in assigning probabilities expressing uncertainty, so that he/she has a number of reference points – he/she has a feeling for what 0.5 means in contrast to 0.1, for example. A probability for 0.1 means that his/her uncertainty related to the occurrence of A is the same as when drawing a favourable ball from an urn with 10 % favourable balls under standard experimental conditions. To facilitate the specification he/she may also think of some type of replication of similar events as generating A, and think of the probability as corresponding to the portion of "successes" that he would predict among these events. For example, say that he/she predicts 1 "success" out of ten, then he/she would assign a probability 0.1 to A. Note that this type of reasoning does not mean that the analyst presume the existence of a true probability, it is just a tool for simplifying the specification of the probability.

Say that a navigation error has occurred. The analyst is to assign his/her uncertainty that corrective measure will not be taken by the co-navigator. The analyst evaluates the possibility of distraction inside the bridge (telephones, misunderstandings, stress and weather conditions) and predicts that corrective measures will not be taken in 1 time out of 100 occurred errors, the probability is then 0.01 as described above.

Other techniques that can be used for uncertainty assessment and probability specifications are formal expert elicitation and Bayesian analysis.

Calculation of uncertainty distributions and determination of suitable predictions

The tool for the calculations of the uncertainty distributions, given the uncertainty distributions on the low-level and the models, is probability calculus. Reference is made to textbooks. From the uncertainty distributions we establish predictions, in most cases the mean would be the natural candidate, in other cases the median or modal point would be preferred, depending on which value that best represent the distribution.

Summary and discussion

In this paper some principles for the predictive approach to risk analysis has been demonstrated by a simple example. The aim of the analysis was to identify different accident scenarios threatening the structural integrity of the building structure. Based on the analysis one can for example choose a design criteria as a ferry collision, specified as a typical ferry (1500 tons and related geometry), 2 knots speed in an angle of 30° tangential to the building structure. The analyst's calculated probability that a scenario worse than this would occur is also of interest in the design process, say that it is 9.0 x 10^{-5} (annual probability), i.e. less than 0.01%. In practice, the design process should be an iteration process. Say that an embankment below sea level is chosen as a safety barrier in front of the building structure. Its capacity could be sufficient for heavy vessels with draught exceeding say 2.8 metres. Lighter vessels, for example catamarans could then represent a worse scenario. Assessing the impact from such factors is easy when the risk models are in place. Then finally iterated, the risk of a catastrophe, given the selected safety barriers could be calculated.

The analysis is based on reported incidents, reported experiences and silent knowledge, not accessible when sticking to traditional deterministic design approach. Lack of hard data is not seen as a problem to the approach, because the local characteristics of the harbour play such an important role, and the probability assignments must reflect those characteristics. Enforcing the risk modelling to focus on "observable" and measurable quantities, ambiguity is avoided and a common platform is obtained. Expert judgements are especially vulnerable to ambiguity and misunderstandings.

Catastrophes occur rarely. Assessing risk of catastrophes necessitates use of low probabilities. It is not easy to distinguish between probabilities of the occurrence of a specific event, say 10^{-5} and 10^{-7}, even though it is a factor of 100. Modelling is one way to deal with this problem, i.e. to break the event in question further down in more frequent sub events. This would of course require more analysis effort, which increases the analysis expenses (see Nilsen and Aven, 2001 for a further discussion about use of model and model uncertainty).

Presently, the construction industry is not used to probabilistic design approaches, at least in Norway. The authorities lack routines for enforcing requirements to design against disasters, unless it is specified in the standards and codes. The local authorities and the harbour authorities, in particular, should be more eager to obtain knowledge about risk and vulnerability in and around their inshore waters. Unless an improved practise of the supervising authorities becomes implemented, the quality and distribution of safety barriers against ship collision will remain variable and probably in most cases designed to optimise short-termed economic interests.

Some scientists, for example the sociologist Charles Perrow (1984), are critical to the use of risk analyses. Firstly they claim that the risk analyses are inaccurate, and not efficient in the prediction of accidents. Secondly, they claim that risk analysts obscure the decision arena by complex analyses no one besides themselves understand. They become shamans with unlimited power to direct decision processes. By use of the predictive approach to risk analysis, Perrow's objections need to be reconsidered. In accordance with the predictive approach true risk does not exist – it is a subjective judgement – and complexity is not highlighted. The risk analysis is simply a structured sampling of experiences and knowledge, basing predictions and uncertainty assessment of the risk analyst's (analysis team's).

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