European Journal of Operations Research 75 (1994) 477-487
North Holland

Models, modelling and modellers; an application to risk analysis *

Björn Wahlström
Technical Research Centre of Finland, VTT / SÄH, PB 34, SF-02151 Espoo, Finland

Received April 1993; revised June 1993

Abstract: Risk analysis has become increasingly important with the emergence of new, unknown and potentially dangerous technologies. Risk analysis builds on the use of models. If the models are valid representations of reality, they can be used to predict and thus also to minimize the risks. Any model is, however, a simplification and a generalization which implies that it has only a limited region of validity. If a model in the risk analysis process is used outside its region of validity it can introduce serious flaws in the actions on different risks. The use of deficient models actually poses the most serious threat to the validity of risk assessments. To understand the origins of deficient models, it is necessary to consider the modelling process and the people involved in using the models. Models in risk analysis are based on many assumptions which have to be understood if erroneous interpretations are to be avoided. The paper considers theoretical foundations of risk analysis, models used in risk analysis and the modelling process leading to these models.

Keywords: Risk analysis; Modelling

1. Introduction

Man has always been searching nature for order and predictability. This search has triggered scientific discoveries and has thus also initiated the process of technological development. In this process, models and theories have been used for predicting outcomes of possible actions and they have served as tools for making better decisions. Models of many kinds are used more or less consciously in everyday choices. There are reasons to believe that heuristics people are using build on internal models of the outside world.

In spite of the importance of formulating and using models, astonishingly little has been written on the modelling process itself. Some authors have proposed that modelling is an art rather than a science, which would suggest that it cannot be described analytically. This view tends however to dilute the believability of the obtained predictions. Instead, modelling should be considered as an engineering science with the understanding that a useful model is a good model. Models carry the essence of human understanding and can therefore be seen as an important component of cognitive processes. Research in human decision making proposes that a major category of human errors is due to the use of erroneous or otherwise deficient models of reality. Decision support systems also contain more or less explicit models of their target systems.

The modelling process includes phases of model formulation, model validation and model use. A model is always both a simplification and a generalization which means that a model always is restricted to its region of validity. Any step outside this region may cause the model to produce completely misleading results. Models are developed during a process of continuing re-

---

* An early version of the paper was presented at the European Summer Institute VIII: Risk Management in Complex Production and Transportation Systems, Rosersberg Castle near Stockholm, Sweden, June 13-27, 1992.

Correspondence to: Prof. B. Wahlström, Technical Research Centre of Finland, VTT/SÄH, PB 34, SF-02151 Espoo, Finland.

finements and the control of this process can have a large influence on the quality of the resulting model.

Modellers play a crucial role in the modelling process (Rouse, 1982). If two teams take up the same modelling task, it is not likely that they will come up with the same model. Both teams may still have completely reasonable arguments for their own modelling approaches. Models are even sensitive to their users in that sense that two teams using the same model may come up with different predictions. Human learning is a process of modelling where many different models are formed in establishing an understanding of the outside world. In this process, the models, the modelling process and the modellers are sometimes interacting in a rather unpredictable way.

The discussion below aims at giving a general background of models and the modelling process to the extent they are used in risk analysis. Natural scientists have sometimes expressed a large faith in their models and have then forgotten that the real world always is much more complex than any model. Simplistic views on the applicability of risk analysis have found their proponents with claims that people are behaving irrationally towards risks (Zeckhauser and Viscousi, 1990). These claims do .not take into account the inherent complexity of the underlying models used in risk analysis.

Risk analysis has its foundations in different sciences. Models of different kinds have to be combined into a common framework in a risk analysis. Before claimed quantitative risk estimates can be regarded valid and reliable in an undisputable scientific sense. Far better models of both human: decision making and responses of nature will be needed. This insight does not however in any sense diminish the usability and benefit of risk analysis as it is exercised today. The argument that, some model is better than no model is still valid (Forrester, 1971).

2. Models in risk analysis

Risks are usually defined as a function of probability and costs. An enumeration of possible chains of unwanted events can be used to calculate the risks of a technical system. The probability of a chain of events can be calculated from the probabilities of single events using rules of probability calculus. The resulting probability can then be weighted with the cost of the consequences of the chain of events to give the risk. This straightforward consideration of risk is however only a model which has to be refined to encompass more detailed elaborations of risk.

The first refinement is to require that the risk model should cover different types of risks. 'A simple view is that high probability and small cost events should be considered to carry the same risk as low probability and high cost events. One example is to compare the risk of one thousand accidents each of which causing one death with the risk of one accident causing a total of one thousand deaths. Many arguments have been expressed to simply use the: product of probability and cost as an objective model of risks. The Dutch safety authorities have however decided to weigh high cost events more heavily (Ministry of Housing, Physical Planning and Environment, 1991). This argument is understandable, because large accidents often carry additional costs of fears and societal disruptions.

A second refinement of the simple model of risk is to consider different consequences such as losses of human life, injuries, environmental damages and economic losses. The consequences may also have different time constants, they may influence risk target groups differently, some risks can be acted on and other cannot, some risks are from natural sources and other are man made, some have their effects on a local level and others on a global level, etc. These different dimensions would require a multi-attribute framework, but the inherent difficulties of comparing very different risks make such approaches controversial.

The risk analysis methodology itself contains an implicit model of causation and control i.e. it is assumed that an unwanted outcome has a cause and that this outcome can be avoided by avoiding its cause. This assumption provides the rationality of risk analysis as an activity to identify and decrease risks which are connected to certain activities. Risk analysis is especially geared towards actions on low probability events, because high probability events can be reacted to in a direct feedback loop of improvements. The risk analysis actually enters a feedforward control loop where the risk causation models are used to predict a resulting risk level. The prediction is then used as an instrument to decrease the risk to an acceptable level. The risk analysis is a model which is used to simulate reality in a search for improvements until an acceptable solution is found (Wahlström, Laakso and Lehtinen, 1988).

The feedback and feedforward control loops actually provide a model of risk management (cf. Figure 1). The risk management process with its goals, practices and rules of conduct are setting acceptable borders for design and operation' of potentially hazardous systems. This model implies that a model of the hazardous system is used in the feedforward control. This model can provide a simulation of possible accident sequences to be studied which aim at constructing barriers against their occurrence. The feedback loops of operational experience provide the necessary corrections of the models used.

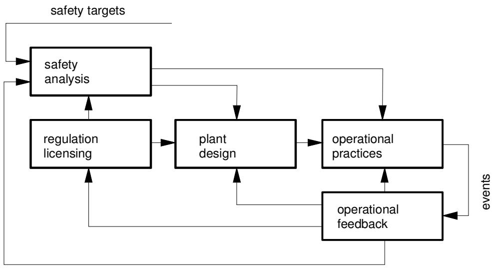

Figure 1. The feedforwards andfedback loops of safety management

3. What is a model?

According to a dictionary definition a model is "a simplified representation or description of a system or complex entity, especially-one designed to facilitate calculations and predictions" (Collins English Dictionary, 1986). In loose terms a. model can be said to be a counterfeit reality which can be used to test the outcome of possible actions to be taken. The model gives predictions and the predictions are used to choose between possible actions. The model provides a mapping of the reality to a modelled reality from which images can be interpreted as real sequences of` events. The model' also carries the target of attention by the separation between the *system* to be modelled and its *environment* (cf. Figure 2). This separation assumes that the interactions carried from the output of the system through the environment back to its input can be neglected as being small.

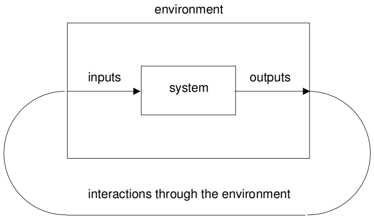

Figure 2. The separation between the system and its environment

A model can be separated into three parts the *logic engine*, the *structure* of the model and its *parameters* (cf. Figure 3). The logic engine consists of the computational rules by which the output is calculated from the input and the model. The model structure provides a script of how computational rules should be applied and, the parameters quantitative weighing factors used in the calculations. The logic engine and the structure of the model limit the richness of the input and output pairs that can be generated.

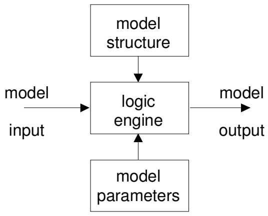

Figure 3. A model consists of a logic engine, model structure and model parameters

The search for a model of a system requires large amount of *data* i.e. collections of input and output pairs. There is an implicit relationship between data and the structure of the model, because any data collection relies on an implicit model. A change in this, implicit model engine and structure can easily make data collected earlier obsolete.

Using the language of systems theory one can say that a real system S is modelled by a system S' if there exists a mapping f from the space of inputs of S to the space of inputs of S' and a mapping g from the space of outputs of S' to the space of outputs of S such that

$$u' = f(u), \quad y' = S'(u'), \quad y = g(y') \quad \text{and} \quad y = S(u). \tag{1}$$

The mappings f and g determine how the system S is represented by its model S'. Given a certain representation f and g then the input x' and the output y' can be calculated. The modelling problem is then to calculate the model S' of the system S. When u' and S' are given the calculation of y' could be called the simulation problem. These two problems suggest a third type of problem, the control problem. The model S' and a wanted output y' are given and the input u' giving that output should be calculated. These three problems are summarized in Figure 4.

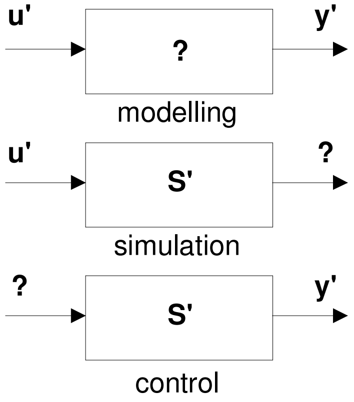

Figure 4. The three problems of systems analysis

The mappings f and g are in a sense defining the model S' when the real system S is given and they are selected at the discretion of the modeller. For a certain system there are many different mappings that can be selected. The selection can often determine the usefulness of the model. The mappings f and g are not independent, but they have no fixed relationship.

A modelling exercise is often implicitly a control problem. The model is built with an ultimate intent of obtaining better decisions, i.e., better control of the system. A modelling exercise is thus governed by the intent of the control problem. The control problem is connected to a specific goal, because, the modeller wants to accomplish something by a more favourable output from the real system. The goals are connected to, values functions which define order relations on the set of possible outcomes of the system. A control problem therefore bears a close connection to an optimization problem.

The most essential concept in the modelling process is *causality*. The input u applied to the real system S is causing the output y. Another input u_l would cause another output y_l. The cause and effect relationship between input and output provides the main reason for modelling a system. An unwanted output w can be avoided by avoiding the input v which causes it. The optimal outcome y^* can similarly be obtained by selecting the optimal causing input u^*. A model offers the possibility of doing experimentation with the model instead of the system. A commitment to action can be postponed until an acceptable input output pair has been found.

4. Different types of models

Models can be divided into the general categories: *Verbal*, *symbolic* and *numeric*. A verbal model uses spoken language and its inherent logics as the logic engine. A verbal model is often defined using *if-then* statements. A symbolic model consists of a set of symbols and a set of rules for how these symbols can be combined. Symbolic models are often used to express relationships between entities. Numeric models are used to calculate quantitative answers. Numeric models use mathematics as their logic engine. Risk analysis studies often combine all these models and special attention should then be given to ensuring compatibility of the models.

Static models do not contain time dependent behaviour, which means that the transfer of information between causes and effects is considered to be instantaneous. Time dependent behaviour is included in *dynamic models* and time constants have to be considered in the transfer of information between inputs and outputs of the system. Many models are *deterministic* in the sense that they always give the same output when a specific input is applied. A chance mechanism is included in *stochastic* models. Stochastic models can be used to calculate estimates of probability distributions by repeated simulations of system responses. Risk analysis models are stochastic as they are concerned with probabilities. A typical probabilistic safety analysis model is static, because time dependence is usually omitted in favour of a more accurate modelling of components and sequences of events. More refined models take into account risks as a function of time, but the dynamic modelling of probability distributions requires more efforts and simplifications in other aspects.

Models are used for *understanding* the causal mechanisms of a real system. This understanding makes it easier to select inputs for influencing outputs in a favourable way. Models are used to make *predictions* for future outcomes of real systems. The predictions make it possible to systematically select actions which give wanted outcomes. In this way models are used as tools for *optimizing* control strategies. Models can also be used for *training* of human decision makers to make better decisions. There is often a need to combine many models into an integrated framework to provide users with diverse views of the system.

Linear models have a special position, because an extensive analytical apparatus is available for predicting responses directly from the structure of the model. Nonlinear systems can sometimes be modelled by linear models in a small operational regime around a certain operational point. When the deviations from the operational point are small and the nonlinearities are smooth the linearized model can give all the essential dynamics of the system. *Nonlinear models* are usually not simple enough to allow elaborate analytical calculations and the equations therefore have to be solved numerically. Models used in risk analysis often contain nonlinearities such as multiplication, division, trigger functions, saturation, hysteresis, etc. which implies that there is no assurance that a linearized model is valid.

Control structures of the modelled systems have to be included in the same way as in the system itself. Controls are sometimes making the dynamics of a system simpler because certain variables can be assumed to stay within defined intervals. The possibility that the controller can have a failure will however make a more refined model necessary. An incorrect model of the control structures can easily offset the dynamics of the model to yield a completely incorrect response.

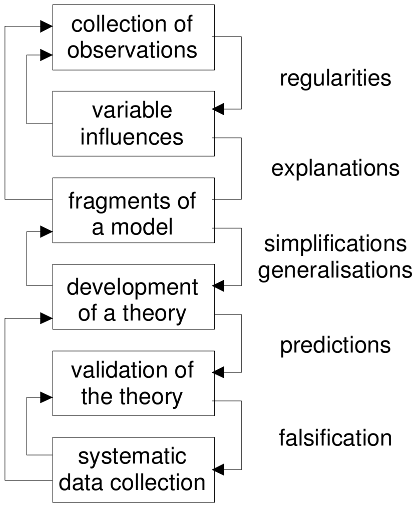

Figure 5. Modelling is an interative process where new observations may force the modeller to step back to earlier stages

5. Building a model

Building a model is a rather pragmatic exercise which contains iterations between a large number of different tasks (cf. Figure 5). There are no fixed rules for what a model should look like. The purpose of the modelling exercise will determine the logic engine to be used. Qualitative predictions of relationships and directions of influence are often sufficient and in these cases verbal or symbolic models can be useful enough. Sometimes it is advantageous to use quantitative models to calculate responses to different actions although qualitative results would be sufficient.

The mapping f by which an image of the reality is created and the mapping g which recreates the reality from simulated results are determined in the modelling process. A model should be refined enough not to be trivial, but simple enough to bring forward only the essential characteristics of the real system. The first step in building a model is to distinguish between the system to be modelled and its environment. The second step in the modelling process is a *simplification*. This means that characteristics of the real system which are not relevant are not taken into consideration. A third step is a *generalization* over a large number of similar components into one lumped component which gives an average behaviour. This generalization often takes place as a renormalization in a transfer from a micro view of system parts to a macro view of system behaviour.

When the appropriate simplifications and generalizations have been made causal relationships between variables in the model can be determined. The causal relationships can be established either qualitatively, i.e., there exist a relationship between two variables such that the first is influencing the second, or, quantitatively, i.e., also giving the size of the influence. In physical systems causal relationships often are two-directional, i.e. there is an interaction and not only an influence between the variables.

Building a model progresses from a definition of a model structure where a micro behaviour is used for explaining observed macro behaviour. The micro behaviour can sometimes be hidden in the system and inaccessible from the macro considerations. In these cases, the model can provide access to internal interaction mechanisms of the system by tuning model parameters to give observed macro behaviour.

When the structure of the model has been defined then the parameters of the model can be sought. By collecting data from the real system and converting the data into parameters the model is finally created. Different methodologies have been designed for bridging this step. When a physical relationship exists between certain parts of the system it is often possible to find model parameters from separate measurements. This possibility to construct the model and find model parameters in multiple independent experiments is extremely valuable in ensuring a large region of validity for the model.

Any model created has to be verified and validated. The verification and validation should be done by exercising the model in its whole range of validity. Verification means that a check is made that the model has been implemented correctly according to the specifications of the modelling exercise. The validation means that a check is made that the model is a correct representation of the real system. A validation can be done only by using data sets which have not been used in constructing the model.

6. The dilemma of modelling

The validation process aims at checking that a model is a good representation of reality. Model predictions are compared with real system responses. If there is a good agreement the model can be accepted and used. The validation procedure contains one catch, however, because deviations between model predictions and reality are needed to force the modeller to inspect the model closer. Therefore there is always a possibility that the model gives good predictions for old data, but bad predictions when exposed to new data.

A similar dilemma is hidden in the predictions given. If the model generates only expected results there is not much information in them and the actual benefit of the modelling exercise remains poor. A good model should therefore always generate surprises. However, if the results deviate too much from what is expected, then these results tend not to be believed, regardless of their validity. A model, when it is as best, should therefore generate only mild surprises which can be believed or at least supported with common sense reasoning from the model assumptions. A model can generate believable predictions only when it has been developed in an evolutionary process of gradual refinements.

An important question in any modelling exercise is to what extent it is necessary to require that the structure of the model is similar or equal to the structure of the real system. A careful representation of the structure of the real system has a larger chance of giving a robust model, i.e., a model which is valid in a large region and which will not give completely ridiculous predictions anywhere. Simon (1982a) argues for the importance of models in the economic sciences, which describe the microbehavior of the system correctly, i.e., models that are true causal models with a structure mimicking the structure of the real system. A black box model making blind predictions of observed past behaviour can seldom provide the necessary internal robustness and explainability needed in a good model.

The use of microbehavior as an explanation for macro-observations is actually the most important principle in modelling. The transition from the microworld to the macroworld is in carried out as a summation of all the small particles contributing to observable macro-behaviour. A model, which does not correctly describe the microworld can never provide but a very restricted description of the macroworld. With a metaphor one could say that a model of a snowflake should build on the choices of the interacting water molecules.

A further dilemma is connected to the inherent unpredictability of non-linear systems. Systems exhibiting chaos, bifurcation and catastrophes have little prospect of being possible to model accurately. The possibility that two neighbouring initial values are giving qualitatively different responses for the same system equations implies that the responses are infinitely sensitive to small parameter fluctuations. The complexity of large scale systems can also make the modelling task an impossible one. Crucial interactions between variables can also be unknown.

7. Decision making under uncertainty

A formal treatment of risk analysis and risk management relies on the more general problem of decision making under uncertainty which has traditionally been approached with the expected utility theory. The formal theory is, however, too restricted to handle practical applications, but it can still provide important insights by directing attention to the validity of underlying assumptions. Decision making relies on models to predict outcomes of certain actions and models are used to describe the decision making problem itself. Uncertainty implies that outcomes can be predicted only in terms of probability distributions. Research in decision making has proposed a division into descriptive, normative and prescriptive models of decision making (Bell, Raiffa and Tversky, 1988).

Decision making is often viewed as an optimization problem. Four major components of an optimization problem should be considered. An *objective* defines an order relation on a *set of outcomes*. There is a set of *allowed actions* which can be restricted in different ways. Finally there is the *model of the system* which connects the given input to a calculated output. The objective and the set of allowed actions set the rules for rationality.

The transfer from preferences to order relations is not straightforward. One attempt has been to search for a natural set of axioms describing rationality. Table 1 is summarizing the essence of axioms proposed. Experiments have shown, however, that the formulation of a decision problem can result in different decisions (Tversky and Kahneman, 1988). The problem with these axioms is that, in spite of their intuitive appeal, they are violated systematically by human decision makers. This experimental finding makes it dubious to use them as a base for a normative theory.

Table 1
The axioms of rationality

Invariance. The preference of an alternative A over an alternative B should be independent of how it is presented for the decision maker.

Cancellation. If an alternative A is preferred to an alternative B then it shall be preferred also in the combined alternative $A\&C$ to the combined alternative $B\&C$, where C is an arbitrary addition to the alternatives not depending on them.

Transitivity. If an alternative A is preferred over an alternative B and B is preferred over C then A is preferred also over C.

Dominance. If an alternative $A=\{a_1,\_., a_n\}$ is dominating an alternative $B=\{b_1,...,b_n\}$ in such a way that each a_i is preferred to each b_i, then A should be preferred over B.

A practical approach to decision making is to consider costs and benefits. A complication of the straightforward optimization problem is that costs and benefits often are related to utility by a nonlinear function. Another complication is incurred when the costs and benefits are distributed in time. Models for calculating discounted values of future costs and benefits are used to make them comparable, but these models again contain parameters which are both subjective and situation dependent.

A complication of the simple optimization problem is connected to multiple values. A typical problem in risk analysis is to determine if a certain risk decreasing action which has a certain cost, can be considered worth wile to implement. If the decision is influencing several output variables simultaneously and gains in one variable are compensated for by losses in some other variable, there are many additional difficulties to solve. A weighted sum or other combinations of the values can sometimes provide a model of a common objective. This has been tried in deciding on risks by assigning a monetary value to different risks. The assignment of such weighing factors has, however, proved to be controversial especially when a calculation of the value of human life has been attempted.

An additional complication is introduced when real decision making situations have to be modelled. Including several decision makers with partly competing objectives leads to the consideration of non-zero sum games. Real decision making situations where it is possible to manipulate the information given and the rules of the game are also far richer than any artificial decision making situation in the form of a simple game. The way human decision makers are acting should also be taken into account, because internal models, beliefs and attitudes may introduce preferences for certain options.

8. Models of human decision making

The human and social systems enter the risk management process at several points. Design and operation of technical systems always involves humans. The risk analysis process is carried out by humans and the results are interpreted by humans. There are certain costs and benefits involved in using the hazardous processes which may influence the interpretations of the results. This means that any model of a hazardous process in some way has, to account for the humans involved.

Research in human decision has shown that people generally make good decisions when they are well trained and are given enough time. It is however also well known that humans make errors. The definition of a human error implies, however, that there is a way to tell what the correct decision is, i.e., there is a normative theory for decision making. The observation that humans systematically tend to violate the axioms of rationality therefore implies either that there are certain tasks where humans behave irrationally or that the normative theory is too simplified. The expected utility theory does not, however, account for several of the influences which are important for human decision making in a more realistic situation.

A model of human decision making has to cover many different characteristics. An optimization problem used as a model of human decision making can cover only a few of them. Actual objectives are difficult to assess and understand, outcomes are viewed differently, it can be difficult to get an agreement on allowed actions, etc. Decision makers also carry different internal models of how systems behave. Humans use heuristics in their decisions. Heuristic rules are used to break down the problem into subproblems, to set priorities and to ensure that some decision will be generated within the time frame given. The benefit of using heuristics is that the decision maker can decrease his cognitive load in familiar situations.

A framework of models of human decision making has been proposed by Jens Rasmussen (1976). His recognition that there are different mechanisms of human data processing which is depending on the familiarity of the task led to the separation between skill, rule and knowledge based behaviour (Rasmussen, 1983). This model is closely related to the cognitive, the associative and the autonomous stage described in connection with skill learning in the psychological literature (Anderson, 1980). A decision making task can be broken down into: detection of a need for a decision, collection of necessary information, identification of system state, evaluation of decision alternatives, selection of decision, formulation of implementation procedure, and execution and collection of feedback. These subtasks actually represent decision making situations of their own which again can be further subdivided. Many models are used in these decision making subtasks. Models can give rapid answers to priorities and can be assumed to control the allocation of attention. Many of the models are tacit and based on preferences, attitudes and beliefs.

A complication of modelling human decision makers is connected to the behaviour of people in groups as compared with the behaviour of single persons. People in a group seem to use a broader social rationality. Group interactions sometimes make collaboration important, while at other times competition is more important. There is a dynamics of interacting views in the search for a group decision. Organizations seem to emerge as entities of their own. Rewards and punishments have an overriding influence on the whole organization for better or for worse. A manipulation of individual utility functions can provide the balance between selfishness and altruism. Leadership is one of the essential characteristics in a search for common themes aligning individual ambitions and desires. In a risk analysis framework these mechanisms enter the interpretations of the results and their applicability on the underlying decision making problem.

Social rationality contains a cautious attitude to change which is rational taking into account the large number of unexpected problems with new technologies. Suboptimal solutions are often preferable to a tedious search for an optimal decision, but in other cases any change can be preferable to the status quo. There is a difference between the ways an idea is expressed on the enthusiasm and support it gets. This means that very subtle interference on a social level can have a large influence on actual development. Multiple and changing goals have their own influence on the dynamics of decisions. In this process of change, goals and priorities are subjected to continuous re-evaluation. The evaluation of costs and benefits has to be considered both spatially and temporally. Equity differences in risk contribution can have a large influence especially if weak social groups are the target. A pitiable victim of some risk can obtain support from influential decision makers. In reality there is a balance between individual and societal goals in the decisions which may be difficult to model.

Learning is a process of forming and using increasingly refined models. Experience has the benefit of making the use of models automatic and therefore more rapid and less resource demanding. Making the decisions more automatic has however the danger of hiding important clues to important information behind a set of familiar cues. The balance between the pragmatics of suboptimality and the dangers of a too simplistic reasoning provides the essence of this dilemma of bounded rationality (Simon, 1982a,b). The emergence and refinement of internal world models of human decision makers are one of the most interesting mechanisms in modelling. Models of human intuition and understanding are however still far from any practical application.

9. Models in risk analysis revisited

There are several limitations of the risk analysis methodology which are connected to limitations in the models used. In the modelling process, the modellers can also introduce important restrictions in the validity of the models. Models have their own regions of validity and a step outside of that region may render important conclusions invalid. The interpretation of the results of a risk analysis relies on a true account of all the limiting assumptions of the used models. It is very easy but dangerous to consider the results of the analysis without the context of these assumptions.

Even the concept of probability carries an inherent model which is based either on a subjective or an objective model of the world. According to the first model the probability is a result of uncertainties in measurements, parameters, initial values, etc. According to the second the uncertainty is a property of the world where a mechanism of chance is generating different realizations at different instants of time. This distinction in the interpretation of -probability can sometimes be important, because it sets a limit for useful efforts in collecting additional information.

A problem related to modelling is connected to a proof of causality. Causality between two events A and B such that A is the cause for B or written $A \Rightarrow B$ means also that the negation $\neg B \Rightarrow \neg A$ should hold. From observations it may be relatively easy to conclude that one of these conditions is true, but to show that both are true involves a considerable larger effort. Another complication is that the causal mechanism is only influencing the probability distributions involved. The existence (or non-existence) of a small influence from a certain variable on a probability distribution can be very difficult to prove when the distribution is influenced by other similar variables. A typical example in this connection is to assess the influence of the Chernobyl accidents on cancer frequencies when they are confounded by many other variables without control.

The intent of a safety analysis is to prove that the system is safe. This means that it should be proved that no safety threats exist. This is a proof of non-existence which always is more difficult than a proof of existence. A proof of existence can be given by an example, but a proof of nonexistence has to be given using structural evidence. In a model used in risk analysis there is always place for some yet unknown relationship which may enter a sequence of events with disastrous consequences.

When a model response has been calculated the question is how this solution is influenced by inaccuracies in the models. Analyzing the sensitivity of the solution with respect to changes in model parameters gives a possibility to address these questions. A great sensitivity of the solution to a specific parameter indicates that this has to be calculated very accurately not to make errors in the decision. The calculation of sensitivities provides one way for extracting additional information from the models. The sensitivity coefficient of an output i to changes in an input j can be calculated as the quotient between change in output and change in input. A sensitive parameter has to be identified accurately to make modelling results accurate. The sensitivities therefore provide importance measures for setting priorities for additional refinements of the models.

A specific dilemma in connection with the models used for risk analysis is brought forward by the complexity of the systems (Wahlström, 1992a). Different mechanisms contribute to an increasing size and complexity of technical systems. A better predictability is needed, but cannot be achieved. The errors in the results from a risk analysis are often indicative of deficiencies in the control structures of the systems. The control structures are containing an implicit model of the controlled system and deficiencies in the controls could therefore often be traced back to errors in the models and the modelling process.

There are many actors in the process of risk analysis and these actors can have both expressed and hidden goals. The risk analysis and the responses for decreasing certain risks are parts of a societal decision making process (Wahlström, 1992b). Policies, societal values and cultural habits interact in this process which forms a part of political decision making. Industrial practices, tasks of safety authorities, the educational system, etc. are determined in this process, which thereby sets the general level of safety in the society. Many different institutional and individual parties such as companies operating hazardous facilities, vendor organizations, designers, constructors, operators, maintainers, and safety analysts are interacting in this process. Additional influence is obtained from subject matter experts, lobbying groups, media, local communities, single issue movements, etc.

Actions based on the risk analysis will always be considered in a negotiation between stakeholders. Induced risks often are compensated with payments and therefore there is often a direct gain of being the victim of some incident or risk. These interactions which have a direct interest tend to obstruct a scientific interpretation of results obtained from the risk analysis models (Huber, 1991).

10. Conclusions

Models enter a risk analysis exercise in several ways. For the results to be applicable the models should be used in a region where they are valid. There are many implicit models used by the different actors in the risk analysis process. It is not an easy task to ensure that these models are valid representations of their corresponding real world systems. This validity requirement- can to some extent be ensured by making the models very transparent and thus at least to some extent separately verifiable.

A risk analysis and actually any modelling exercise should aim for quantification, because it is often necessary to place results in a context. Qualitative models depend on the use of language which means that results are easily interpreted differently by different people. Quantitative models can, however, still be useful for structuring the risk analysis and as a basis for later quantifications. Sensitivity analysis can be used to generate qualitative results from a quantitative model in studying how small changes in parameters influence the results. A sensitivity analysis can be extended to consider switching surfaces in a decision space and how these surfaces move in response to changes in important parameters.

Formal models of risk analysis and decision making under uncertainty have been proposed, but these models are simplified to an extent where their applicability for real world problems is challenged. Simplified models can provide a basis for possible extensions along the paths of multiple competing objectives and multiple decision makers. Models of human decision makers both alone and in a group need very much more work before they can be used in the same way as models for physical systems. One can even argue that models which are able predict the complete richness of human and societal behaviour will remain an utopia. Risk analysis can, however, be intelligently applied also without such models provided that the modellers have a sufficient understanding both for the mathematics of decision making and the psychology of human beings.

Several general requirements can be placed on model performance. The responses should be repeatable, the model should have predictive power, the model should be based on scientific consensus, applied theories should be general, the models should be based on a mechanism of cause and effect, used theories should not be contradictory and only a minimal number of assumptions should be used. Models can in principle be seen as an instance or an application of a theory. A theory is therefore more a general explanation of cause consequence relationships than a model. A model is actually geared very much towards simple predictions of outputs in response to inputs.

A model takes a specific view in a transfer from micro to macro. The microstructure of one model can be the required macrostructure of another model and vice versa. The models can actually be seen as a Russian doll where a consideration of more details always opens up new views. A discussion of models, the modelling process and modellers involves models of models. This gives a type of self-reference (Hofstadter, 1979) where the model of a system has to contain a model of that model. Models are the essence of human cognition with which an understanding of the world is reached. Models of cognitive processes should therefore also include a model of how the modelling process is progressing. Models, analogies and metaphors are ingenious mechanisms of the human mind in managing the complexity of the real world.

References

Anderson, J.R. (1980), *Cognitive Psychology and its Implications*, Freeman, San Francisco, CA.

Bell, D.E., Raiffa, H., and Tversky, A. (eds.), *Decision Making; Descriptive, Normative and Prescriptive Interactions*, Cambridge University Press, Cambridge, MA.

Collins English Dictionary (1986), second edition, William Collins Sons and Co. Ltd., London, 1986.

Forrester, J.W. (1971), *World Dynamics*, Wright-Allen Press, Cambridge, MA.

Hofstadter, D.R. (1979), *Gödel, Escher, Bach: An Eternal Golden Band*, Basic Books, New York.

Huber, P.W. (1991), *Galileos Revenge; Junk Science in the Courtroom*, Basic Books, New York.

Ministry of Housing, Physical Planning and Environment (1991), "*Premises for risk management*" VROM 00526/291, Department for Information and International Relations, The Hague, Netherlands.

Rasmussen, J. (1976), "Outlines of a hybrid model of the process plant operator", in: T. Sheridan and G. Johannesen (eds.), *Monitoring behavior and supervisory control*, Plenum Press, New York.

Rasmussen, J. (1983), "Skills, rules, knowledge: Signals, signs and symbols", *IEEE Transactions on Systems, Man, and Cybernetics*, 13, 257-267.

Rouse, W.B. (1982), "On models and modellers: N cultures", *IEEE Transactions on Systems, Man, and Cybernetics*, 12, 605-610.

Simon, H.A. (1982a), *Models of Bounded Rationality: Behavioral Economics and Business Organizations. Vol. 2*, MIT Press, Cambridge, MA, 1982.

Simon, H.A. (1982b) *Models of Bounded Rationality: Economic Analysis and Public Policy, Vol. 1*, MIT Press, Cambridge, MA.

Tversky, A., and Kahneman, D. (1988), "Rational choice and the framing of decisions", in: D.E. Bell, H. Raiffa and A. Tversky (eds.), *Decision making; Descriptive, Normative and Prescriptive Interactions*, Cambridge University Press, Cambridge, MA, 167-192.

Wahlström, B. (1992a), "Avoiding technological risks; the dilemma of complexity", *Technological Forecasting and Social Change* 42, 351-365.

Wahlström, B. (19926), "Risk analysis as a social process; supporting societal responses to hazardous technologies", Paper presented at the conference of the European Section of the Society for Risk Analysis, December 16-18, 1992, Paris, France.

Wahlström, B., Laakso, K., and Lehtinen E. (1988), "Feedback of experience for avoiding the low-probability disaster", IAEA International Symposium on the feedback of operational experience from nuclear power plants, IAEA-SM-302/23, Paris, May 16-20, 1988.

Zeckhauser, R.J., and Viscousi, W.K. (1990), "Risks within reason", *Science* 248, 559-564.