

## Decision Analysis and Risk Analysis

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### Decision Making

Everybody is required to make decisions on a daily basis. They include decisions such as whether to get up in the morning and go to work or if it is safe to cross a busy road at a particular point in time. Decisions always have consequences and they can be very important. Decision problems become difficult if they are complex, require multiple successive decisions and each decision possibly has more than one outcome. In the presence of uncertainty about the outcome of a decision, the decision maker is in fact forced to gamble (Pratt, Raiffa, and Schlaifer 1995). In the case of veterinarians working in general practice, clinical decisions are continually made under conditions of uncertainty. The latter being caused by *errors* in clinical and lab data, *ambiguity* in clinical data and *variations* in interpretation, *uncertainty* about *relationships* between clinical information and presence of disease, *uncertainty* about *effects* and costs of treatment and *uncertainty* about *efficacy* of control procedures and medication. Other areas where decision problems are particularly complex include the planning of disease control policies. In this situation uncertainty is introduced for example through incomplete knowledge of the epidemiology of diseases or stochastic effects influencing disease spread. It is also not possible to predict the behaviour of individuals who are involved in handling and managing the disease vector or host.

Humans have attempted for a long time to develop systematic approaches to decision making which would allow them to reduce the uncertainty regarding the outcome of their decisions. Historically fortune tellers and high priests were used to provide information about the future. This was eventually developed into a business such as in the case of the Oracle at Delphi in ancient Greece. The Chinese had I Ching which was an integration of Chinese world views about yin and yang, cycles of the calendar and the interaction between water, earth and fire. All these approaches were based on guessing or sensing the outcome and did not involve systematic evaluations of choices. Throughout the middle ages the practice of prophecy was actively discouraged by the Roman Catholic Church, assuming that God's will ultimately affected every decision. Systematic approaches towards decision making were first introduced in the 16<sup>th</sup> century by Francis Bacon who developed the scientific method. In the 20<sup>th</sup> century the understanding of human decision making was much improved through psychological studies. The advent of the computer simplified the handling of large amounts of data used as the basis for decision making. But even today many decision makers view systematic logical approaches towards decision making with scepticism.

### Decision Analysis

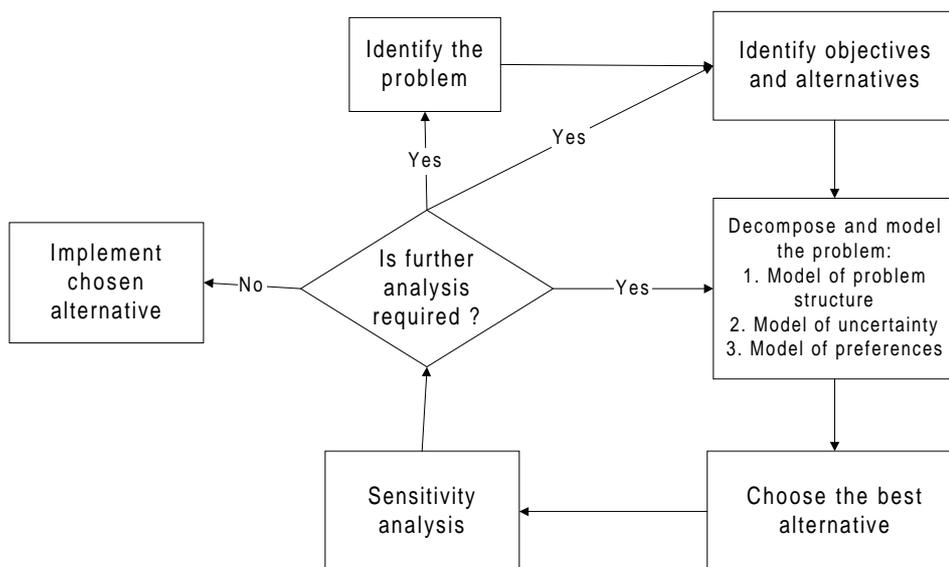
Howard (1988) describes the scientific discipline *decision analysis* as a systematic procedure for transforming *opaque* decision problems into *transparent* decision problems on the basis of a sequence of *transparent* steps. *Opaque* means "hard to understand, solve or explain; not simple, clear or lucid" and *transparent* means "readily understood, clear or obvious". It has also been defined as an approach to decision making under conditions of complexity, with inherent uncertainty, multiple objectives and different perspectives towards the decision problem (Clemen 1996). Decision analysis is used to make *effective* decisions more *consistently*. It should always be kept in mind that it does not provide solutions, but rather an *information source* providing insight into the situation, uncertainty, objectives and trade offs. Therefore, decision analysis is not intended to replace the decision maker's intuition, to relieve him/her of the obligations in facing

the problem, or to be a competitor to the decision-maker's personal style of analysis. The outcome of the analysis may yield recommended actions, or it can be used to justify a particular action. Petitti (1994) points out that while decision analysis in the medical field was initially mainly used to manage individual patients, it is now increasingly applied to development of policies for management of groups of individuals. It also forms the first step of cost-effectiveness analysis. Ngategize, Kaneene, and Harsh (1986) reviewed the usefulness of decision analysis in animal health programs. They acknowledge its advantages, but also point out, that it can be very time-consuming to perform and difficult to estimate the input parameters.

Howard (1988) emphasises that one of the most important distinctions required for decision analysis is the one between decisions and outcomes. He writes that a good outcome is a future state of the world that we prize relative to other possibilities and a good decision is an action we take which is logically consistent with alternatives we perceive, the information we have, and the preferences we feel. This distinction is important as in an uncertain world good decisions still have the potential of leading to bad outcomes.

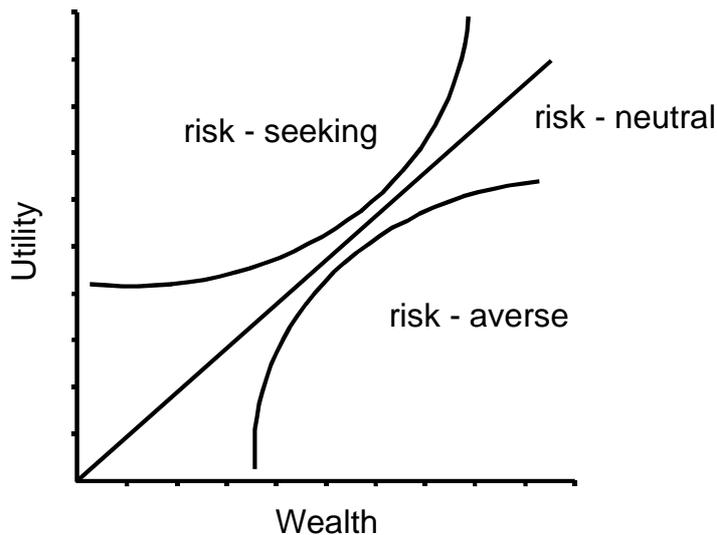
### Decision Analysis Process

Figure 1 shows a flow chart of the different steps involved in the decision analysis process as described by Clemen (1996). The first step requires the decision maker to identify the problem. This can already be quite a difficult process, as it is important not to target the wrong problem (*error of the third kind*). The second step has to be dealt with very carefully. Is the objective to minimise cost, risks or maximise profit? What is meant with risk? Is it monetary loss or potentially damaging conditions for health or the environment? During this phase it is likely that aspects of the decision problem are discovered which the decision-makers had not thought about previously. The next two steps involve decomposition of the problem to understand its structure, measure uncertainty and value. Decomposition is seen as the key to decision analysis. Decision analysis techniques are used to create *models* of the structure of the decision problem (alternatives or choices), they use probability to build models of the uncertainty and utility functions to model how the decision makers value outcomes and trade off competing objectives (preferences). During the sensitivity analysis aspects of the model are changed and the effect on the outcome is evaluated. This can result in reconsidering the whole decision problem or simple changes of the model structure. Decision analysis will typically be a process going through several iterations before a satisfactory alternative is found.



**Figure 1: Flow chart of decision analysis process (after Clemen 1996)**

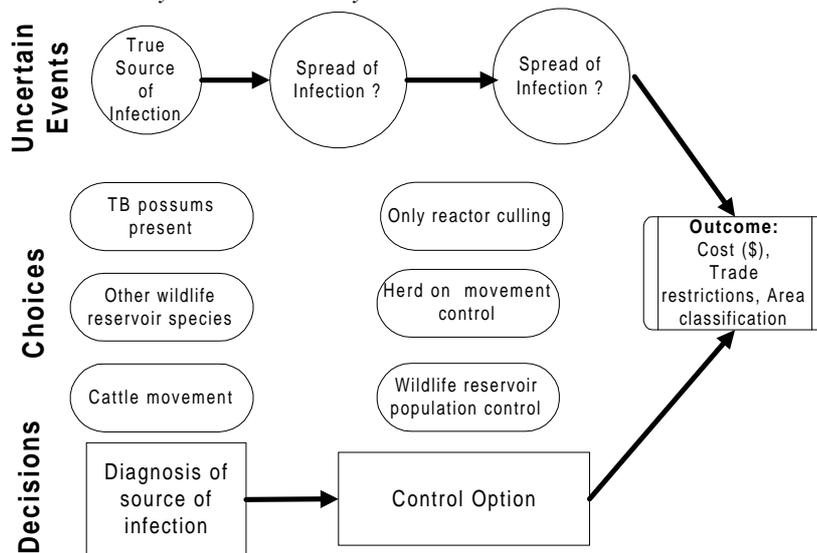
Defining appropriate utilities can become quite difficult, as there is only rarely a linear relationship between the risks that decision makers are prepared to take and the utilities expected from the different outcomes. These attitudes towards risk can be modelled using utility functions. Figure 2 presents the relationship between expected wealth and utility for different attitudes towards risk acceptance. The general assumption is that more is better than less wealth. Risk averse attitude results in curve with a concave shape (opening downward). These persons are prepared to take risks even if they can only expect small gains. Risk neutral behaviour is represented as a straight line, indicating a strong correlation between wealth and utility. A risk seeking attitude is shown as a curve with a convex shape (opening upward). Meaning that for these people there has to be a minimum gain before they are prepared to accept any risk.



**Figure 2: Utility functions representing different attitudes towards risk acceptance**

### Elements of Decisions

The first step in decision analysis should be to identify the elements of a decision problem which include the *decisions to make*, any *uncertain events* and *outcomes* and *values*. The example will be a situation where reactors to the tuberculin skin test have been detected in cattle in a geographical area which is considered free from *Mycobacterium bovis* infection. Some of the skin test reactors did show tuberculous lesions during meat inspection at the abattoir. It is known that infection is endemic in an area about 50 km away from this outbreak. Here, the *decisions to make* include for example the diagnosis decision regarding the source of infection and the decision about the control option. The latter includes for example whether to just cull the reactor cattle or to conduct a control operation in a wildlife species which is assumed to represent the main reservoir of infection in other areas. In this example the diagnosis and the control decisions are sequential decisions, and the choice or outcome of one will influence the subsequent. Whichever decision is made, there are *uncertain events* such as in this case the true source of infection which it may be difficult to identify (diagnose) correctly. The *outcomes* and *values* in this particular decision problem include a scenario with spread of infection from this outbreak which would be associated with costs and possibly trade restrictions or no recurrence of infection during future tests. Figure 3 presents a diagram of the elements in this decision problem. It is important to identify a *planning horizon* for the decision problem with respect to outcomes. In this example it could a period of two or more years may be appropriate, as the consequences of having infection in a wildlife population may take some time to show up as reactors in the cattle population.



**Figure 3: Elements of the example *Mycobacterium bovis* herd breakdown decision problem**

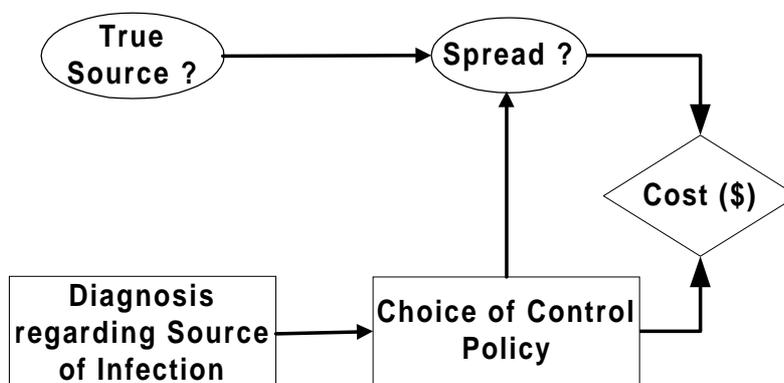
### Structuring of Decision Problems

There are two main approaches which are being used to describe and structure decision problems: *influence diagrams* and *decision trees*. Both complement each other, in fact modern computer software allows the decision problem to be designed as an *influence diagram* which subsequently can be converted automatically into a *decision tree*.

#### *Influence diagrams*

An influence diagram is basically a graphical representation of a decision problem. The elements of the decision problem are represented as different *shapes* linked by *arrows* indicating the relationship among elements. *Squares* represent decisions, *circles* represent chance events and *diamonds* represent values. The shapes are referred to as *nodes* (decision, chance and value nodes). The arrows are also called *arcs* with the *node* at the beginning of the *arc* being the predecessor and the one at the end of the *arc* the *successor*. Properly designed influence diagrams should not have any cycles. Information about detail as to outcomes, choices and payoffs are contained in tables associated with each node.

The decision problem relating to the *Mycobacterium bovis* outbreak is summarised as an influence diagram in Figure 4. The two sequential decisions are linked by arrows, as are the two uncertain events. Both, the chance node *Spread ?* and the decision node *Control Policy* influence the value node *Cost ?* which represents what will happen in the future as a consequence of this outbreak and any control measures taken.



**Figure 4: Influence diagram for the example *Mycobacterium bovis* herd breakdown decision problem**

Influence diagrams provide an excellent approach to displaying structure, but they can hide some of the detail. They are descriptive tools which it is usually easier to communicate to a non-technical audience than a decision tree. The relationships between the various elements of the decision problem are easier to display using an influence diagram compared with a decision tree. (Howard 1988) considers the influence diagram to be the greatest advance he has seen in communication, elicitation and detailed representation of human knowledge. He adds that they are the best tool for crossing the bridge from the original opaque situation in a person's mind to a clear and crisp decision.

Very often influence diagrams are mistakenly understood as flow charts. The latter are used to indicate the sequence of events and activities in a decision-analysis system. Influence diagrams on the other hand are structured displays of decisions, uncertain events and outcomes, and they provide a snapshot of the decision environment at a single point in time.

### *Decision tree analysis*

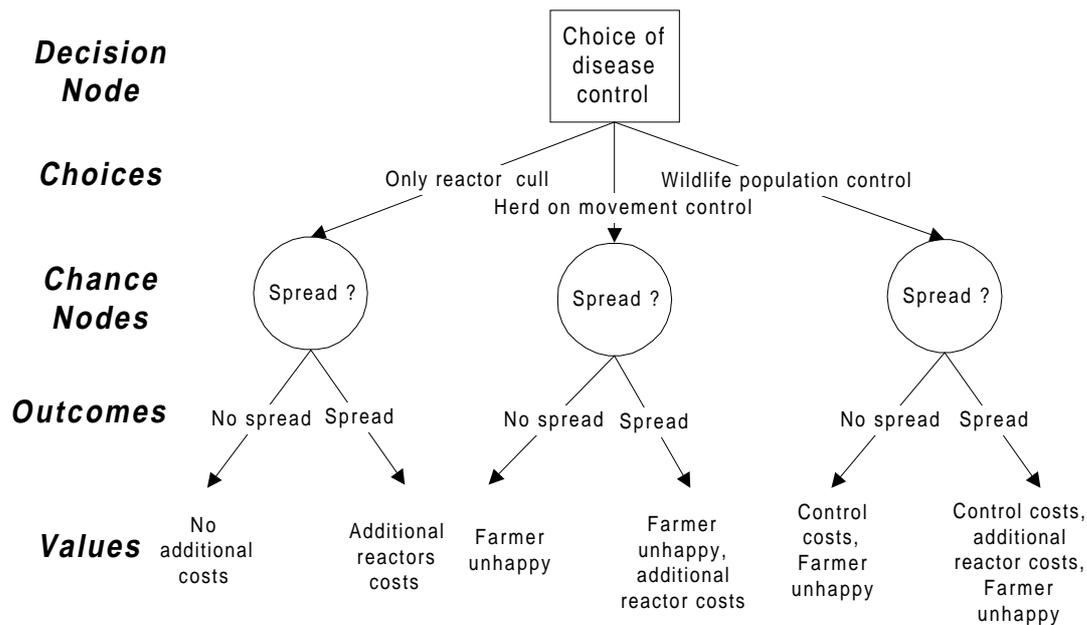
The decision tree is an approach which usually represents more detail than the influence diagram. The basic steps in decision tree analysis include first to specify the *decision context*, followed by the development of a *decision model* including management options, the consequences of each option and the likelihood and desirability of each outcome. The decision model is then represented as a *decision tree*.

The decision tree structure develops sequentially from *base* to *terminal* ends based on the components: *nodes*, *branches* and *outcomes*. There are three types of *nodes*: *decision* (choice) nodes, *chance* (probability) nodes and *terminal* nodes. The *branches* indicate the different *choices* if they are extending from a *decision* node and the different *outcomes* if they are extending from a *chance* node. Each of the *branches* emanating from a *chance* node has associated *probabilities* and each of the terminal ends has associated *utilities or values*.

It is important that the *branches* representing *choices* are mutually exclusive, meaning that only one branch can be chosen at a time. In the case of *chance* nodes, the *branches* have to correspond to mutually exclusive and collectively exhaustive *outcomes*. This means only one of them can happen and the different *branches* include all possible *outcomes*. *Chance* events placed in front of *decision* nodes indicate that the decision is made conditional on the chance *outcome*.

The following references can be used as examples of applications of decision tree analysis: Houe, Lloyd, and Baker (1994), Ruegg and Carpenter (1989), Salman *et al.* (1988) and White and Erb (1982).

An example of a decision tree for the decision problem example based on an outbreak of *Mycobacterium bovis* infection in a cattle herd is shown in Figure 5. The decision about the source of infection is not represented as it is directly represented in the choice of disease control program. A decision is required about the best disease control option. The alternative choices include reactor cull only, reactor cull plus placing herd on movement control and reactor cull and movement control plus conducting a wildlife population control operation. Each of the alternatives has a probability of being successful in achieving the objective of preventing spread of infection. Each of the terminal nodes has a *utility* or *value* associated with it calculated on the basis of the amount spent for the disease control option and the financial consequences of additional breakdowns of cattle herds in the same area.



**Figure 5: Decision tree for the example *Mycobacterium bovis* herd breakdown decision problem**

Among the disadvantages of decision trees is that they more quickly become very complex than do influence diagrams. If it is required to explain a decision problem to non-technical people it is advised to make use of influence diagrams. On the other hand, analyses of decision problems are conducted more easily with decision trees.

### Analysing Decision Problems

In the preceding paragraphs the emphasis was on structuring a decision problem so that it clearly and accurately represents all the elements of the decision problem. The next step will be to solve the decision tree or influence diagram to find the preferred choice. This section will focus on analysing decision trees. Techniques for solving influence diagrams are described in Clemen (1996).

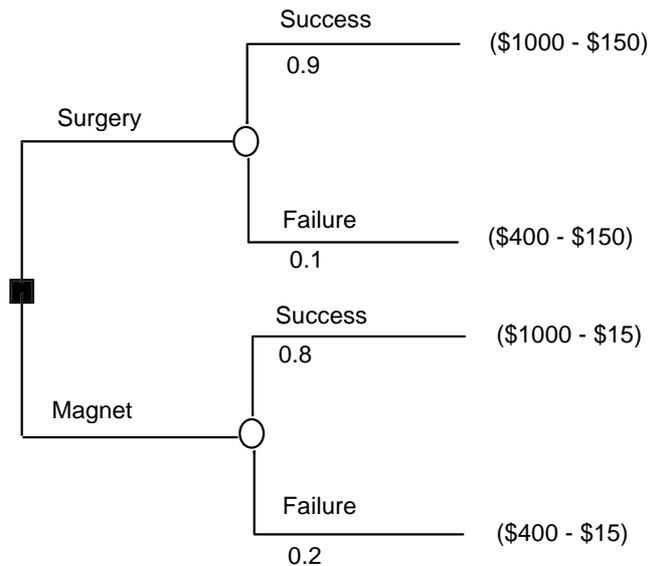
The quantitative information required to analyse a decision tree includes the utilities / values associated with the terminal nodes and the probabilities associated with each branch of a chance node. The utility or value is expressed relative to a numerical scale common to all terminal nodes in the decision tree. The utilities can represent subjective preferences as well as values generated on the basis of utility functions and monetary values. In the case of a monetary value the net benefit from a particular decision given a particular outcome after subtracting any costs incurred could be used. The quantitative parameters can be expressed as variables which can be varied during subsequent sensitivity analyses.

#### *Folding back*

In the case of decision trees a solution is typically obtained through choosing the alternative with the highest *expected* monetary value. This is done through *folding back the tree*. Starting from the terminal nodes and moving back to the root of the tree, expected values are calculated at each chance node as a weighted average of possible outcomes where the weights are the chance of outcome occurrence. At each decision node the branch with the highest expected value is chosen as the preferred alternative.

This approach is best illustrated using an example (after Smith 1995). This time the case of interest is a cow which is suffering from traumatic reticulitis. The cow has a value of \$1000 and the treatment choices are to perform surgery (\$150) or to use a magnet (\$15). The probability of recovery is 0.9 for surgical and 0.8 for magnet treatment. The salvage value of the cow

amounts to \$400. Figure 6 shows the decision tree describing the elements of this decision problem.



**Figure 6: Decision tree for cow reticulitis treatment example**

The expected monetary values for the two treatments are calculated as follows:

- expected value for surgery

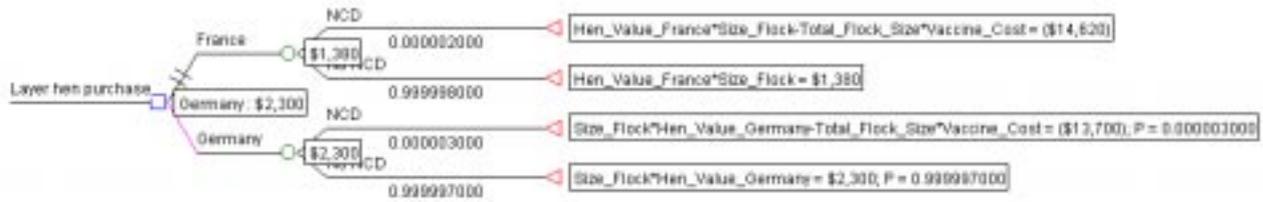
$$EV_{surgery} = 0.9 \times (\$1000 - \$150) + 0.1 \times (\$400 - \$150) = \$790$$

- expected value for magnet treatment

$$EV_{magnet} = 0.8 \times (\$1000 - \$15) + 0.2 \times (\$400 - \$15) = \$865$$

The interpretation of these results is that *in the long run* the magnet treatment is more profitable assuming that the values and probabilities are chosen correctly.

A decision analysis could also be applied to the following decision problem. Please keep in mind that the data is fictitious and the structure of the problem was deliberately kept simple. A Swiss poultry farmer has to make a decision if he should purchase young layer hens from France or Germany. He is specifically concerned about the risk of introduction of Newcastle disease (NCD) into his flock. The flocks to be considered for purchase would be tested for presence of NCD infection. Based on disease reporting information from the two countries it is assumed that 10% and 6% of imported flocks from Germany and France respectively. The sensitivity of the haemagglutination inhibition test of 76% in combination with the prescribed sample size suggests that the risk of undetected infection in flocks from Germany and France amounts to about  $3.0^{-6}$  and  $2.0^{-6}$  respectively. Layer hens from Germany and France are assumed to be worth about US\$5 and US\$ 3 per hen, which is used as an estimate of added herd value. The imported flock size could be about 460 hens. It is assumed that in case of introduction of NCD, the only consequence would be that the farmer would have to vaccinate his flock consisting of 16000 hens using a vaccine costing about US\$ 1 per hen. The decision tree for this problem is presented in Figure 7. Given these parameter settings the results of the roll-back suggest that if the farmer had to make this decision 100 times and every time would choose to purchase from Germany, on average he would gain \$2300 rather than \$1380 for always having purchased from France.

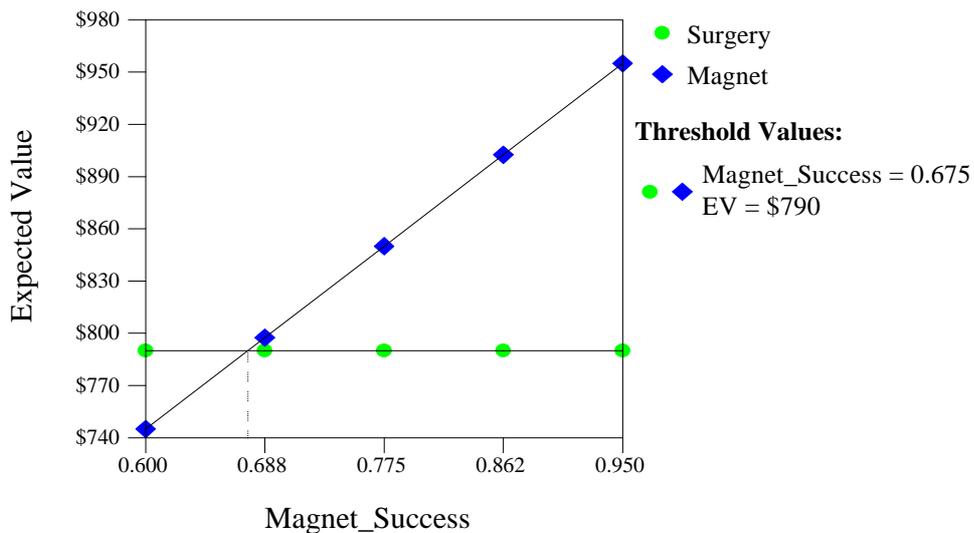


**Figure 7: Rolled back decision tree for NCD problem**

*Sensitivity analysis*

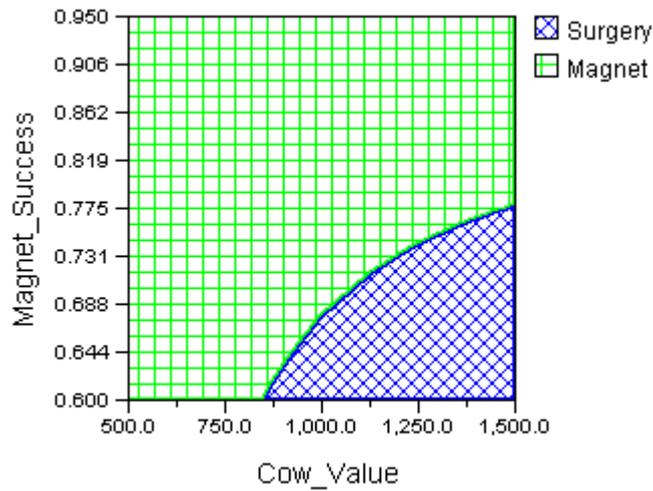
Sensitivity analysis is a modelling approach which allows identification of the parameters which are important in the decision tree. As a consequence of the results from a sensitivity analysis the decision maker may have to reconsider the structure of the decision problem or obtain more precise information about individual parameters.

The basis of sensitivity analysis is that one or more parameters are varied and the effect on the decision tree solution is being examined. One of the outcomes of the analysis will be a set of threshold values for which the optimal decision would change. Figure 8 shows the results of a sensitivity analysis for the success probability of magnet treatment from the traumatic reticulitis example. It suggests that magnet treatment reaches the same value as surgery if the success probability drops to 0.68. Meaning, once the success probability for the magnet treatment is lower than 0.68, surgery becomes the preferred treatment option.

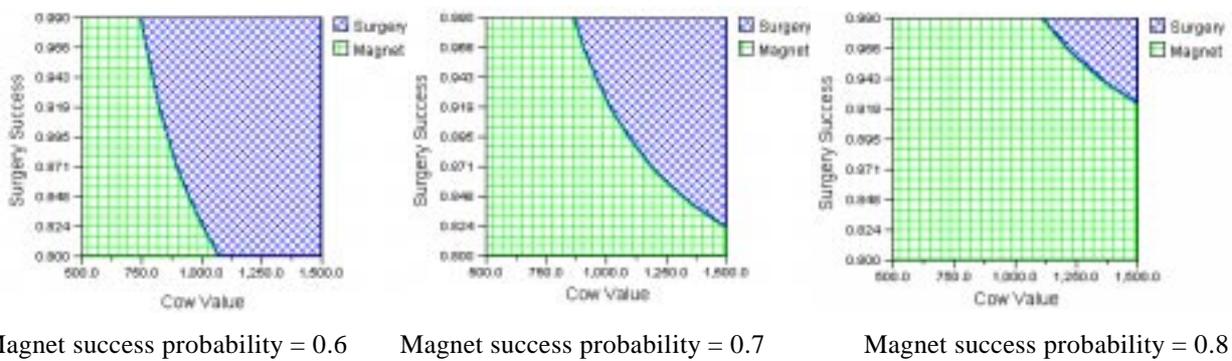


**Figure 8: Sensitivity analysis for magnet treatment success probability in cow reticulitis example (change in expected value of magnet treatment chance with varying magnet success probability)**

The sensitivity analysis can be extended to include two or three variables. Figure 9 shows the result of a two-way sensitivity analysis for the reticulitis example. It suggests that surgery becomes the preferred option once the cow value goes up and the magnet treatment success probability decreases. Figure 10 extends the analysis to a three-way sensitivity analysis where separate graphs of the relationship between cow value and surgery treatment success probability are produced for three different magnet treatment success probabilities. For low magnet success probabilities and increased cow values surgical treatment may become a more interesting treatment option.

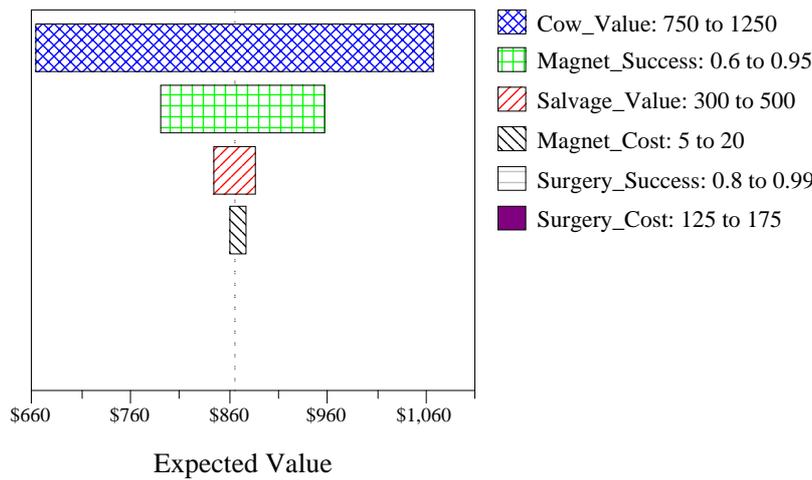


**Figure 9: Two-way sensitivity analysis varying cow value and magnet treatment success probability in the cow reticulitis example (shading indicates preferred treatment option)**



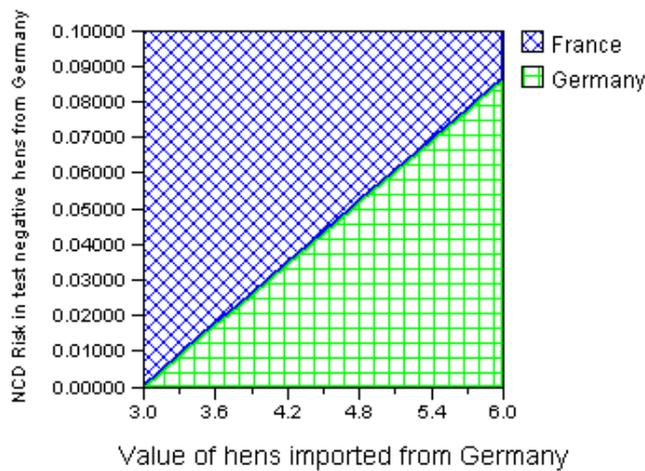
**Figure 10: Three-way sensitivity analysis varying cow value and surgery success as well as treatment success probability for the reticulitis decision problem (shading indicates preferred treatment option)**

Another approach allowing a quick examination of the sensitivity of the decision problem to the various parameters in the model is the tornado diagram. The horizontal axis displays the expected value, each bar represents the range of expected values resulting from changing this particular variable within a given range. The variable with the widest bar is listed at the top. The wider the bar the more uncertain the effect of this parameter assuming that it may vary along the indicated range. Figure 11 shows that varying cow values results in significant variation in expected value for the surgery treatment.



**Figure 11: Tornado graph of the reticulitis decision problem**

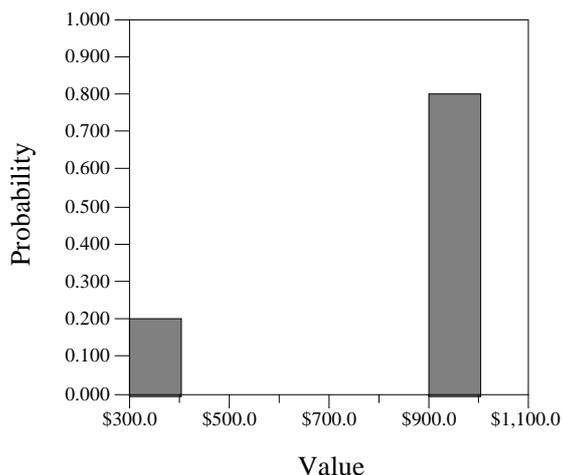
In the case of the NCD example a two-way sensitivity analysis was conducted to assess the effect changes in hen value and risk of undetected NCD infection for Germany. It suggests that France does become the recommended decision if the risk of infection increases considerably and / or the value of hens from Germany decreases substantially.



**Figure 12: Two-way sensitivity analysis for layer hen purchase decision problem for the parameters hen value and risk of introduction**

*Risk profiles*

While expected value provides an estimate of the average value of a particular decision, it does not provide information about individual outcomes. A risk profile shows the probability of occurrence for each outcome. This allows selection of the decisions associated with for example a low-risk outcome. A risk profile is constructed by collapsing the decision tree through multiplying out each chance branch and it can be displayed as a graph. It is useful when the decision problem contains successive chance nodes. Figure 13 shows an example of a risk profile for the magnet treatment option in the reticulitis example. It indicates that the outcome of \$300 will occur with a probability of 0.2 and \$900 with 0.8 probability.



**Figure 13: Risk profile for the magnet treatment option in the reticulitis example**

### Advanced Decision Analysis Techniques

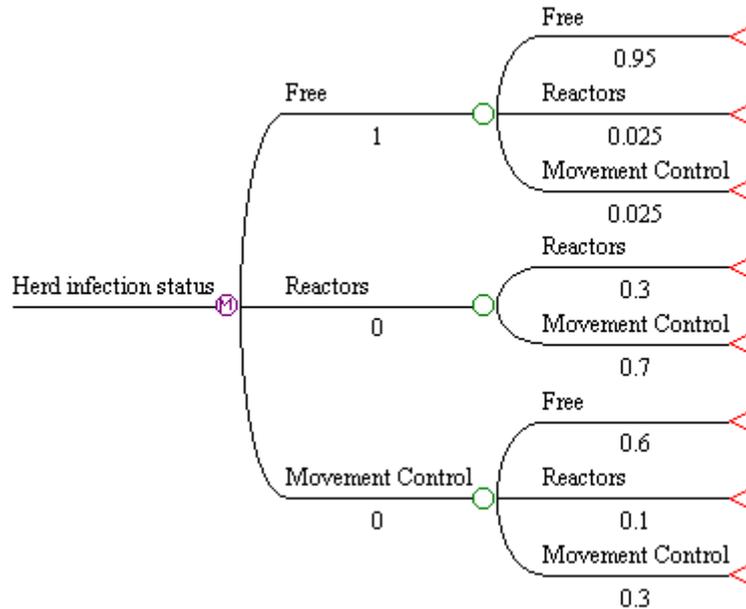
One of the major criticisms of decision tree analysis in particular has been its emphasis on making decisions on the basis of a weighted average which is a statistical measure not necessarily appropriate for this kind of data. Decision analysis attempts to describe the pattern of thinking of the decision maker which very often is rather fuzzy. In fact, it is very difficult to define patterns on the basis of a weighted average alone. Also, the objective of the analysis can be to optimise multiple competing objectives, one of them could be to maximise monetary value and the other to minimise damage to the environment. Cost-effectiveness analysis is the most appropriate technique for this kind of problem (see Petitti 1994).

Markov models and Monte Carlo simulation are two techniques which are now easily accessible through decision analysis computer software.

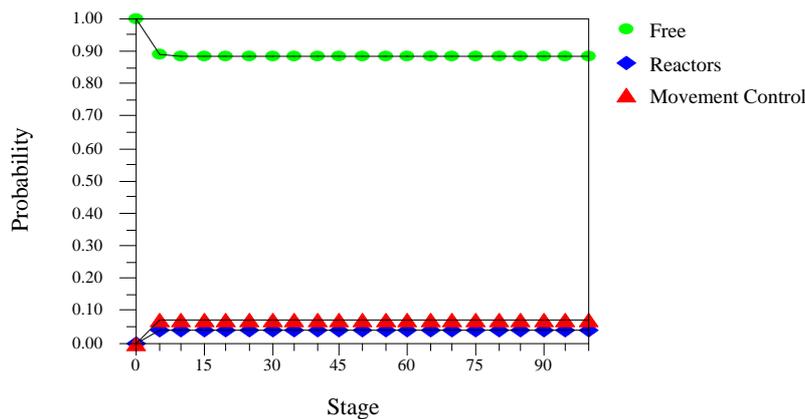
#### *Markov modelling*

Markov models can be used to replace decision trees in situations where the tree contains events which occur repeatedly or over extended periods of time (Beck and Pauker 1983). The basic components of a Markov process are called *states* which are for example the possible states of health an animal can be in. *Transitions* between *states* allow the animal to move from one *state* to another over time depending on a *transition probability*. An assumption of Markov processes is that they do not have a memory about past *states*. Markov chains are used when it can be assumed that the transition probabilities are constant, otherwise a more general Markov process has to be used. Examples of applications of Markov models are presented in Hillner and Smith (1991), Hillner, Hollenberg, and Pauker (1986) and Siegel, Weinstein, and Fineberg (1991).

The Markov model presented in Figure 14 describes the possible infection states for a cattle herd from an area with endemic *Mycobacterium bovis* infection and the associated state transition probabilities. Using this particular model the average time a herd spends in each of the three different states (free from infection, presence of reactors and movement control status without presence of reactors) can be modelled. Given the probabilities used a herd would over a period of 20 years spend 18 years declared as free from infection, 1 year with reactors and another year without reactors present but on movement control. Figure 15 presents the probability of being in any of the three different states, on the basis of a Monte-Carlo simulation with 100 trials.



**Figure 14: Markov model of infection status of a cattle herd in an area with endemic *Mycobacterium bovis* infection**

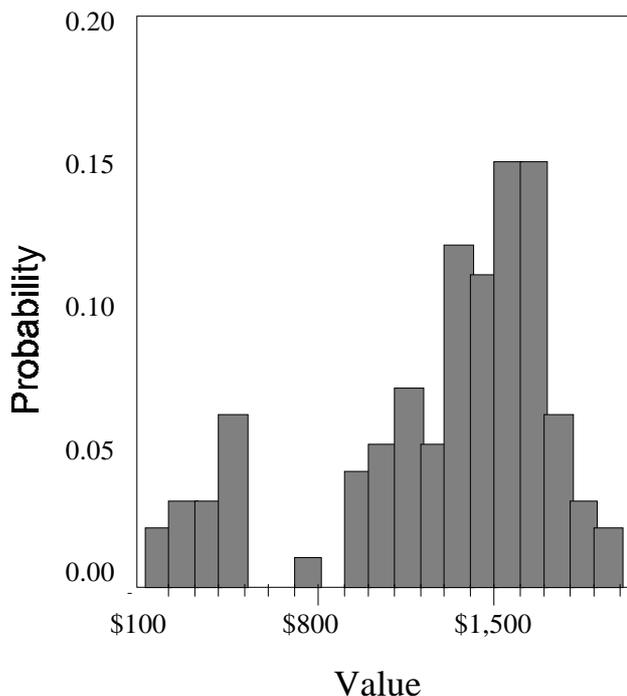


**Figure 15: Probability analysis based on Monte Carlo simulation of Markov model for tuberculosis cattle herd infection status**

*Monte Carlo simulation*

Incorporation of Monte Carlo simulation into a decision tree allows examination of probability distributions rather than of single expected values or ranges of expected values. This provides more detailed information about the uncertainty in the decision problem. Slenning (1994) describes the use of a Monte Carlo simulation approach for a decision tree analysis choice between different reproductive programmes for breeding dairy cattle.

The decision tree for the reticulitis problem was changed such that the monetary values involved were replaced with normal distribution functions. The cow value for example was represented through a normal distribution with a mean of \$1000 and a standard deviation of \$250. Figure 16 presents the distribution of results for the expected value after a Monte Carlo simulation with 100 trials. Table 1 lists the outcome and sampled values for each of the four value distributions for the first 10 trials. The results for the whole 100 trials indicate that in 29% of the trials surgery was the optimal treatment. In 17 out of 100 trials the treatment strategy chosen resulted in failure.



**Figure 16: Results of Monte Carlo simulation using the reticulitis treatment example**

**Table 1: Output from the first 10 trials of a Monte Carlo simulation of reticulitis example**

Trial	Outcome	Value	Optimal	Surgery	Magnet	Cow Value	Salvage Value	Surgery Cost	Magnet Cost
1	Failure	481.11	Magnet	1054.57	1130.95	1314.5	502.2	178.7	21.09
2	Success	1443.45	Surgery	1309.09	1290.795	1570	226.4	126.55	10.485
3	Success	1451.925	Magnet	1171.365	1220.305	1468.5	310.4	181.325	16.575
4	Failure	240.2	Surgery	1529.135	1519.695	1837.75	405.6	165.4	31.625
5	Success	1654.5	Surgery	1526.615	1509.09	1778.25	499.4	123.75	13.39
6	Success	1244.13	Magnet	1028.985	1110.65	1262	594.6	166.275	17.87
7	Success	1573.2	Magnet	1316.615	1352.43	1592.75	488.9	165.75	19.55
8	Failure	346.605	Magnet	1357.95	1368.005	1645.25	368.5	159.625	21.895
9	Success	1035.075	Magnet	834.84	922.455	1038	474.9	146.85	2.925
10	Success	1434.215	Magnet	1149.245	1204.205	1449.25	299.2	185	15.035

**Conclusions**

Decision analysis offers significant advantages to the decision maker. It encourages to break down complex problems into simpler components - choices, probabilistic events and alternative outcomes. The decision maker can weigh risks and benefits and is forced to introduce a logical sequencing of components. The requirement of explicit estimates of probabilities which it sometimes may be difficult to obtain is very important. Decision analysis encourages concern about utilities through the need of placing values on them, it identifies critical determinants of a decision problem and may indicate areas of insufficient knowledge.

## Resources

There are a number of computer software packages available, which can be used to perform decision analysis and decision tree analysis in particular. Just to name two packages, the software DATA™ (TreeAge Software, Fax: 413 458-0104, <http://www.treeage.com>) which was used to perform the analyses in this manuscript and the spreadsheet add-in software PrecisionTree (Palisade Corporation, FAX: 607-277-8001, <http://www.palisade.com>). It is also possible to conduct simple decision tree analyses using computer spreadsheet software. A range of text books are available which are useful for learning more about the techniques discussed in this manuscript, for example Clemen (1996), Petitti (1994), Pratt, Raiffa, and Schlaifer (1995), Ragsdale (1995) and Weinstein and Fineberg (1980).

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