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# Towards flexible decision support in the control of animal epidemics

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**Summary**
Decision-making in the control of animal epidemics is a dynamic and flexible process. Facing uncertainties about the consequences of control options, flexible decision-making can avoid unnecessary control costs through learning and adjusting. While recognising the importance and complexity of decision-making, research has paid little attention to flexibility in deciding whether and when to use certain control options. The implicit assumption that control options are taken either immediately or never may lead to significant bias in selecting control strategies. This paper systematically analyses the elements in the decision-making process of animal epidemic control to illustrate the importance of flexibility. Also discussed are various ways of integrating flexibility into research on decision-making in animal epidemic control.

**Keywords**
Animal epidemic control – Decision analysis – Dynamic decision-making – Flexibility – Uncertainty.

# Introduction

The importance and complexity of decision-making in animal epidemic control have been frequently highlighted in the research literature (1, 9, 18). Since control strategies can greatly influence the course and consequences of an epidemic, the selection of an appropriate strategy is the focus of research on decision-making in this field. With increasing demand for socio-economic optimality besides veterinary effectiveness, economic analysis is widely used to evaluate potential control strategies (5, 10, 26, 29, 32).

Despite frequent reference to decision-making in the literature, little account has been given to *how* decisions are actually made in controlling an evolving or ongoing epidemic. Epidemics develop over time and the presence of uncertainties in their development is a well-known fact (23). In response to the actual development of an epidemic, practical decision-making in epidemic control is a dynamic process where the development of the epidemic is continuously assessed and monitored until the epidemic is considered to be over. The actual control strategy which brings the epidemic to an end is the result of a series of decisions on which control option(s) to use over the course of the epidemic. This is evident from contingency plans in many countries, for example, the Foot and Mouth Disease Contingency Plan drawn up by the Department for Environment, Food and Rural Affairs (DEFRA) in the United Kingdom (7).

Until now the dynamic nature of decision-making in epidemic control has received minor attention in research. When addressing decision-making about control strategies, researchers often refer to a single decision to use some predefined control strategies at the beginning of the epidemic (e.g. Tomassen *et al.* 2002 [35]). Models have been widely used to evaluate various control strategies on hypothetical epidemics (2, 3, 8, 30, 31, 32). These studies provided valuable insights into the possible consequences of control strategies when implemented immediately. However, reducing a decision-making process to a single decision-making step dramatically restricts the flexibility of the decision-maker in choosing the timing of the decision and responding to information gained during the process. The model used may not include all options, or may not correctly identify the costs or benefits of some options, so strategies selected using this rigid method of decision-making may not necessarily be the optimal choice.

Flexibility is an important issue in decision-making under uncertainty (36). Flexible decision-making recognises the importance of keeping options open when the future is uncertain. In uncertain dynamic situations, flexible decision-making has the potential to avoid unnecessary 'sunk costs' (costs that cannot be recovered) by postponing decisions with irreversible consequences in order to wait for better information and to respond adaptively to new situations. Since decisions in animal epidemic control, e.g. the slaughter or vaccination of animals, typically lead to irreversible consequences on a large scale, the role of flexibility in the decision-making process deserves careful investigation.

The intention of this paper is to connect current research on animal epidemic control to a flexible decision-making framework. To highlight the importance of flexibility in the decision-making process the paper begins with a decision analysis on the control of epidemics. Subsequently, possible ways to include flexibility in research are discussed, and an example follows as an illustration.

# Analysing decision-making in animal epidemic control

Scientific modelling of decision-making involves the transformation of a real-life situation into a decision framework which captures the key features of the decision problem in a structured way. Hammond *et al.* (16) demonstrated that even the most complex decisions can be analysed and resolved by considering the following eight key elements:

– Problem: what must be decided?

– Objectives: what are the goals in solving the problem?

– Alternatives: what are the available courses of action?

– Consequences: how well do the alternatives perform in terms of the objectives?

– Trade-offs: are there conflicting objectives? And how can a balance be struck among them?

– Uncertainty: what could happen in the future and how likely is it?

– Risk tolerance: how much risk is the decision-maker willing to take?

– Linked decisions: when there are many decisions to be made, how are decisions influenced by each other?

Following this approach, the authors review these elements in order to set up a decision-making framework for the control of highly contagious animal diseases such as foot and mouth disease (FMD) and classical swine fever (CSF). (Due to the difficulty in assigning economic value to human health or human life, it can be difficult to directly apply the framework to epidemics of a disease with significant potential for human morbidity or mortality, such as avian influenza. Useful insights, however, can be derived.)

## Problem

A thorough understanding of the decision problem is the starting point of the decision analysis, as this provides a clear understanding of why the decision must be taken and of the difficulties that have to be faced in making the decision, and guides the decision analysis towards rational choices.

The problem of animal epidemics arises not only from the disease itself, but also from control activities. The fight against animal epidemics shares many features with fighting a war, where the term 'strategy' originated. A control strategy is a systematic plan of action to accomplish the goal of ending the epidemic in accordance with defined criteria. As in war, a control strategy, while stopping further spread of the disease, incurs considerable costs of its own. To prevent an epidemic from getting 'out of control', control activities of a pre-emptive nature are implemented, i.e. they are carried out without knowledge of how the epidemic will develop. These activities involve considerable upfront costs which can include more than just financial losses: the slaughtering and rendering of animals very often create social disruption as well as environmental problems (1).

Uncertainty about the effects of control activities adds another layer of difficulty to the problem. The considerable upfront costs incurred by control activities have to be justified by their efficacy in reducing the potential losses that may occur if the disease is not controlled. The efficacy of control strategies and potential losses are therefore the crucial factors in decision-making. Unfortunately, both are unknown at the onset of an epidemic since its size and pattern are highly uncertain due to many chance events in the disease spread process. Moreover, potential economic loss depends on, among other factors, the response of the market, which is difficult, if not impossible, to predict (35). This implies that it only becomes possible to determine the actual merits of any control strategy after it has been actually carried out. Consequently, decisions have to be largely based on expectations fraught with uncertainty.

An 'action' in a control strategy can itself be a strategy which consists of an organised set of control actions and which sometimes suffices for one epidemic when used alone. For example, the widely recognised 'stamping-out' strategy contains a series of actions such as the immediate slaughter of all susceptible animals on the infected and dangerous-contact premises, designation of infected zones, and livestock movement restrictions, etc. (12). To avoid the confusion between these sub-strategies and the specific control strategy for a particular epidemic, the authors refer to these sub-strategies as 'strategic options'. A strategic option, when considered as an alternative action in a strategy, is a predefined set of control actions that are used as a 'package'. Decisions within these 'packages' are often operational in nature and can usually be taken quite easily, while the decisions concerning the 'packages' are of strategic importance and attract the main attention in research into epidemic control.

The decision problem in controlling a particular epidemic is, therefore, how to construct the comprehensive control strategy with available strategic options over time; it is more complicated than simply selecting one or more strategic options in one step, even though the latter is the common problem formulation in research. Finding the rules for an optimal strategy is an obvious problem of multi-stage decision-making, i.e. when a series of decisions is made over time and later decisions are significantly influenced by the outcome of earlier decisions. A single-step formulation alone cannot capture this important feature and leaves many problems unaddressed, for example, the interaction of decisions over time (as linked decisions, see below), the effect of learning during the epidemic and the impact of uncertainty on the timing of decisions.

## Objectives

The objectives of the decision-maker provide the criteria for evaluating the alternatives that are available. Due to the 'public good' nature of disease-free status, animal epidemic control is still mostly undertaken by governments. The objectives of governments as decision-makers (primarily controlling, limiting or stopping the epidemic as recommended by the World Organisation for Animal Health [OIE] or other authorities) can be multifold and competing. Reflecting veterinary, economic and social requirements, the list of commonly addressed objectives (although not often explicitly stated) in research includes:

*a)* epidemiological effectiveness (e.g. minimising epidemic duration, number of animals infected, etc.)

*b)* economic efficiency (e.g. minimising direct control costs to the government, export loss, etc.)

*c)* social welfare (e.g. minimising emotional or psychological damage to owners of companion animals, disruptions to society caused by transport restrictions, etc).

## Alternatives

Identifying and understanding all of the alternatives is of central importance in decision-making, because an alternative cannot be chosen if it is not taken into consideration. The chosen alternative may be the best of those that are considered, but it will not give the optimal result if there exists a better alternative that is not considered (16).

Over the years, various strategic options in animal epidemic control have been developed based on the removal of diseased or potentially diseased animals, movement restrictions and vaccination. Because of the shared interest in disease-free status at the country, regional or compartment level, the occurrence of many contagious diseases must be reported to the OIE and controlled following its guidelines. In the European Union (EU) context, there are legal obligations on governments to control epidemics of highly contagious diseases such as FMD, CSF and avian influenza (AI). EU regulations lay out the basic control actions that must be taken immediately, known as the 'stamping-out' approach. Besides compulsory measures, the Member States are allowed to use additional strategic options such as national stand-still (movement restriction), pre-emptive culling of animals, and the use of emergency vaccination (7).

With the choice set expanded, the possibility of using these strategic options greatly increases governments' flexibility to direct the control strategy in any epidemic. Unfortunately, the same possibility also dramatically increases the complexity of the decision-making: since these options do not have to be immediately taken, but may be considered again in a later stage, the number of possible strategic combinations increases indefinitely. Ignoring the optional nature of the strategic options would dramatically reduce the set of alternatives, possibly excluding many better strategies.

## Consequences

Although some alternatives can be easily eliminated after specification of the objectives – because they can in no way satisfy the objectives – most control alternatives cannot be dismissed quite so easily and have to be selected or rejected based on the basis of their consequences in relation to the objectives of the decision-maker. For example, if the objective of epidemic control is to minimise the direct control costs to the government, the consequences to be considered will be the costs caused by the control option. If the objective is to minimise the indirect loss from an export ban, the duration of the epidemic becomes the main consequence of concern, together with other factors contributing to export loss.

Given a certain control objective, the corresponding consequence of an alternative determines its desirability. If the decision-maker has only a single objective and the consequence can be measured with certainty, alternatives can easily be ranked and the best choice would manifest itself. Unfortunately, neither of these two conditions is fulfilled in decision-making in epidemic control, which necessitates subsequent analysis of trade-offs, consequences and uncertainty.

## Trade-offs

No strategy can be ideal for every possible objective of the decision-maker. Logically, what constitutes the best control strategy will depend on the chosen objectives. When multiple objectives are involved, trade-offs must be made based on the relative weight the decision-maker gives to each objective (21). The presence of multiple and often conflicting objectives makes it a formidable task to find one optimal strategy which satisfies all objectives. To strike a balance between different objectives, the relative weights of the objectives must be assigned by the decision-maker. Making decisions with multiple objectives has been an increasingly important topic in animal epidemic control (19).

## Uncertainty

Uncertainty reflects the decision-maker's lack of information about, and/or incomplete control over, the process under consideration. When uncertainty exists, there is often no guarantee that the best decision (as judged at the time it was taken) will ultimately have the best outcome (17). The quality of decisions should then be judged by *how* they are made rather than their actual outcome. In this sense, the presence of uncertainty in a decision problem underscores the need for a consistent decision-making framework which represents and deals with the uncertainty in defendable ways.

Uncertainty permeates many aspects of epidemic control. The main sources of uncertainty in decision-making in epidemic control are the lack of information on the exact development of the disease, and the lack of certainty about the consequences of control alternatives which depend on socio-economic factors such as the reaction of market or public opinion, as well as epidemiological factors. Below, the authors analyse both issues to identify their impact on the decision-making process.

### Uncertainty about the epidemic

To understand uncertainty in an epidemic, it should be kept in mind that the observed development of the epidemic and the number of diseased animals or herds detected over time are only part of the picture. Underlying this development is a chain of stochastic processes not directly observable and influenced by many social and biological factors (23). Figure 1 illustrates the transmission chain at the herd level. During the development of an epidemic, contact between infectious herds and susceptible ones (process $p_0$ and $p_1$), direct or indirect, can lead to the exposure of susceptible herds to the disease (process $p_2$). Whether the exposure results in infection (process $p_3$) depends, among other things, on the immunity of the exposed herd and the infectivity of the infectious herd. The process in which the infected herd becomes infectious (process $p_5$) is influenced by factors such as length of incubation period, which varies among animals. If detected, the infected herd is normally removed immediately from the transmission chain; however, the infected herd can remain undetected, which is due to factors such as individual differences in the animals and the alertness or transparency of farmers or veterinary staff, which makes process $p_4$ again highly uncertain.

Uncertainty in epidemics has been the focus of research on decision support. Although transmission mechanisms are often known, none of the processes $p_0$ to $p_5$ is directly or immediately measurable or observable. To gain knowledge of the possible development of animal epidemics, many epidemiological models have been developed (8, 20). With numbers and charts the outputs of mathematical models can appear deceptively 'correct'. But epidemiological models, like all models, are open to question when used without regard to their limitations (15, 34). As simplifications of reality, mathematical models represent the underlying process with well-defined stochastic processes described by parameters. In reality, these parameters are hardly known and must be estimated or even guessed from veterinary knowledge. The use of mathematical models may therefore introduce additional epistemic uncertainty into the decision-making process (27).

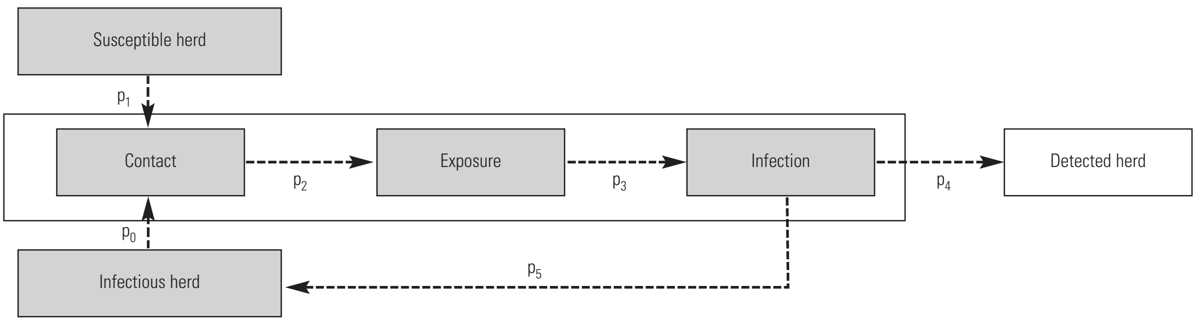


**Fig. 1**
**The transmission chain before the disease is detected**

When striving for the accurate estimation of parameters, another important fact can be easily overlooked in epidemic modelling: if the parameters are to describe a stochastic process, the outcome of the epidemic will still be uncertain even if the parameters are perfectly known. The inherent randomness in any epidemic is often masked by deterministic interpretations of model results in terms of expected (average) values such as the basic herd reproduction ratio ($R_h$), defined as the average number of outbreaks caused by one initially infected herd in a wholly susceptible population (35). An $R_h$ that is smaller than one is usually interpreted as a sign that the epidemic will automatically fade out, and an $R_h$ greater than one is taken as an indication that the epidemic may grow. However, the actual developments of the epidemic can show similar patterns even when the parameters are significantly different. An eventually declining epidemic ($R_h$ <1) may still appear to be growing for a short period of time. Similarly, even with an $R_h$ much greater than one, it is still possible that the epidemic could become self-limiting very quickly due to many 'unfortunate' events in the transmission process. With all the uncontrollable factors in force, any long-term prediction regarding the epidemic beforehand is subject to serious error.

Much remains to be known about the development of animal epidemics. However, from a decision-making point of view, information is only of interest when it can lead to a change of decision. Some information, which may be of great interest for the study of epidemiology, might be of little importance to the decision-making of epidemic control because it does not change the relative desirability of the alternatives. Therefore, the analysis of uncertainty should focus on the impact of uncertainty on the desirability of the alternatives, i.e. on how uncertainty will influence the consequences of control strategies.

### Uncertainty about the consequences

As demonstrated by simulation studies, different control strategies can greatly alter the final size and pattern of an epidemic and result in significantly different socio-economic consequences (2, 13, 26). Epidemiological models have greatly assisted the assessment of epidemics and the evaluation of control strategies in 'peace time'. The quantification of potential consequences of the alternatives is based on the outcomes of epidemiological models which simulate epidemics. This means that if an epidemic cannot be precisely predicted due to uncertain factors, neither can the consequences of control options.

In the absence of certainty, the consequences of control alternatives are often presented as a risk profile which consists of the values of the consequence and their likelihoods based on various outcomes of the epidemic. A risk profile provides probabilistic representation of the possible distribution of the consequences of an alternative. Based on the risk profile, the expected consequence can be calculated as the probability-weighted average of the consequences. The variability of the consequences can also be calculated.

Computerised simulations that account for chance events in the transmission and detection process make it possible to generate the risk profiles of control strategies in minutes. An important feature worthy of note is that the simulated risk profiles are dependent on the values of key parameters. If the values of the parameters are likely to change, the risk profiles will also change. A change in the risk profile, especially if favourable, encourages the deferral of decisions in the hope of gaining better information at a later date. Therefore, the influence of uncertainty on the decision-making process, in terms of the sequence of the decisions, should be carefully addressed as well (see the section on 'linked decisions' for a discussion of this issue).

Despite the recognition of uncertain dynamics in disease spread, a static and deterministic view is often adopted: strategic options are often ranked according to the expected consequences of the simulated risk profiles and these expectations do not change after the simulation. The deterministic treatment assumes the distribution of the expected consequences is constant and the uncertainty will remain the same. This rigid thinking rules out the possibility of collecting more information to reduce the uncertainties in expected consequences and, therefore, the consequences of the alternative set may not be correctly assessed. The optimality of the chosen alternative is therefore doubtable.

## Risk tolerance

If the consequences of the alternatives are uncertain, the choice of the alternative becomes risky because the actual outcome may not be the expected one. The decision-maker's risk tolerance, mainly determined by his attitude towards risk and size of the risk, can significantly influence his choice of alternatives, even among those having the same risk profile. A risk-averse decision-maker would be more concerned with the downside of the consequences while a risk-seeking decision-maker would be more tempted by the upside of the consequences. A risk-neutral decision-maker would base his or her decision instead on the expected value of the risk profile. The impact of risk attitude on the choice of alternative has been investigated by Dijkhuizen *et al.* (9). Many alternatives can be eliminated from the choice set by comparing their risk profile with the risk tolerance of the decision-maker. This highlights the importance of correctly identifying the risk profiles of alternatives.

## Linked decisions

In the process of decision-making, uncertainty necessitates the consideration of linked or interdependent decisions, or decisions that influence each other. The most common linkage between decisions is time. As described by Hammond *et al.* (16), linked decisions over time have the following characteristics:

*a)* a basic decision must be addressed now

*b)* the desirability of the alternatives in the basic decision is influenced by uncertainties

*c)* the relative desirability of the alternatives is also influenced by a future decision to be made after the uncertainty in the basic decision is (partially) resolved

*d)* an opportunity exists to obtain information

*e)* the typical decision-making pattern is a chain of decide, then learn; decide, then learn more; decide, then learn; and so on.

Hammond *et al.* refer to the decision of whether to wait and obtain more information as 'information decision', and to the choice of alternative as the 'basic decision'. The basic decision should be taken only when the information decision is considered unnecessary, i.e. when there is no gain in collecting more information. 'Future decision' refers to a decision to be made after the consequences of a basic decision become (partially) known. A future decision is linked to the 'basic decision' because the alternatives which will be available in the future depend on the choice made in the 'basic decision' now.

The key to analysing linked decisions lies (besides in understanding the uncertainties inherent in the basic decision) in the answer to the following questions:

*a)* Is it possible to obtain more information first and decide later?

*b)* What will be the future decision?

*c)* To what extent will the current decision influence the future decision?

In the series of decisions made in order to control an epidemic, the linkage between decisions can take at least two forms. First, the earlier choice of alternatives may open or exclude future alternatives, since some strategic options are exclusive of others while others are not. For example, the use of pre-emptive culling rules out the use of emergency vaccination on the same herds. Second, actions resulting from early decisions alter the potential course of the epidemic and therefore the situation for future decisions. A different choice might be made if the decision could be made in the future. An example is provided in Table I regarding the control of FMD.

To show the relationship between linked decisions in the decision process of epidemic control, the authors follow the example of Hammond *et al.* (16) to describe the chain of the decide–learn sequences. A typical sequence of linked decisions that can occur at any decision stage (T) is shown in Figure 2.

**Table I**
**Examples of linked decisions in foot and mouth disease control**

| Basic decision [a] | Information decision [b] | Future decisions |
|---|---|---|
| National stand-still | Contact tracing | Pre-emptive culling |
| | Serological testing | Emergency vaccination |
| | | Stopping control programmes |
| Pre-emptive culling | Contact tracing | Culling over a larger area |
| | Serological testing | Stopping control programmes |
| | Logistic capacity | |
| Emergency vaccination | Contact tracing | Vaccinating over a larger area |
| | Serological testing | Keeping vaccinated animals |
| | Logistic capacity | Culling vaccinated animals |
| | | Stopping control programmes |

a) 'Basic decision': the choice of alternative
b) 'Information decision': deciding whether or not to wait and obtain more information before taking a decision

As time moves on, the 'future decision' at current stage (T) becomes the 'basic decision' at the next decision stage (T+1), when a new 'information decision' and 'future decision' should be addressed. This link repeats itself till the epidemic is considered to be over. The decide-then-learn pattern describes how the decision-maker responds to new information and knowledge gained during the decision-making process. As the epidemic develops, field data can be collected and analysed to correct or improve previous assessment or understanding of the actual epidemic. With the updated assessment of the epidemic, the decision-maker can then decide whether to continue with or adjust the original plan.

The elements described above, especially the existence of uncertainty and linked decisions, clearly show that decision-making in animal epidemic control is a dynamic and flexible process characterised by interaction between decisions and the impact of uncertainty. Therefore, research on epidemic control must direct itself towards these important features in order to strengthen decision support during epidemics.

# Towards flexible decision support in epidemic control

To acknowledge the flexibility of the decision-making process in animal epidemic control is only a start. The ensuing question is how to integrate it into existing research in various fields such as veterinary epidemiology

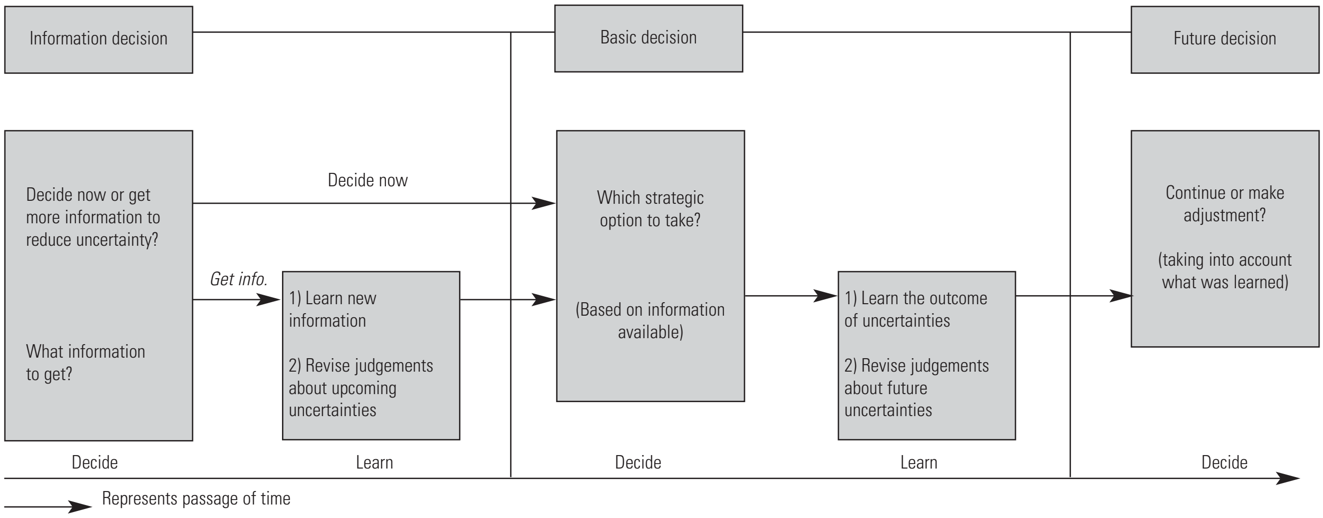


**Fig. 2**
**Relationships among linked decisions in epidemic control**

and economics. In this section the authors will explore ways to change the rigid evaluation of control strategies prevailing in current research so that there can be a move towards flexible decision support in animal epidemic control.

## Representing flexibility in decision analysis in order to select the best strategy

Decision analysis is considered the most suitable tool in support of decision-making in animal epidemic control (29). To address flexibility issues in decisions, the 'information decisions' in various forms can be added to the decision analysis as additional alternatives at any time.

Analysis of 'information decisions' can be done within many standard decision tools. For example, the option 'decide later' can be included in a decision-tree analysis as described in Tomassen *et al.* (35). The consequences of this alternative should be assessed in accordance with the objective of epidemic control. For example, if a decision to decide later is taken in place of immediate culling, it could have the following consequences:

– it postpones the costs of additional measures

– more farms might become infected

– more data on the epidemic would be available, which may change future assessment of the epidemic

– pre-emptive culling or vaccination can still be carried out later if the situation turns out to be worse than expected.

Adding flexibility in decision analysis necessarily complicates the decision analysis and might slow down the decision process. To provide a rapid response during epidemic control, conditions which favour 'information decisions' can be studied in 'peace time' to generate some 'rules of thumb'.

## Valuing flexibility with 'real options' thinking

Valuation of flexibility in the control of animal epidemics could be another line of research. The discovery of managerial flexibility and its implication for investment decisions has boosted the development of 'real options' theory and its wide recognition in investment decision-making (11, 36). Although real options theory deals primarily with investment decisions, 'options thinking' can be used in any strategic situation (24).

Since additional strategic options are options rather than obligations, they should be evaluated as an opportunity rather than an immediate commitment. Using the concept of irreversible investment, Mahul and Gohin illustrated the option value for a vaccination programme (25). Their analysis was, however, limited to a two-period situation and accounted for only one alternative strategic option.

The valuing of flexibility can be extended to more realistic, multi-period settings. Since the problem of animal epidemic control is dynamic and sequential in nature, more advanced techniques from sequential decision-making may be employed, for example, dynamic programming (4). Recently, a conceptual decision model has been developed to optimise the control strategy for FMD control and evaluate the value of flexibility (14).

### Designing flexible strategic options with real-time prediction

Although we have addressed only strategic decisions, the flexible decision-making process can be readily extended to operational decisions which concern the optimisation of strategic options. The strategic option itself should provide more flexible responses to unfolding uncertainties. In this case, flexibility may be applied in a more active way, i.e. to construct new strategic options which include waiting or stopping as a built-in action or incremental actions which can be easily upgraded or downscaled. The design of flexible strategic options requires more interactive use of epidemiological modelling. However, the limitations of models should be kept in mind and indiscriminate use of the model results discouraged.

Epidemiological predictions, having practical limitations, are often not able to closely represent reality, especially in the long term. Because of these limitations predictive models have even been compared to the 'emperor's new clothes', i.e. some commentators feel that the usefulness of such models has been overstated (22). This, however, by no means makes predictive models useless, but highlights the need for a new generation of epidemiological models to make short-term predictions which can be checked and updated during the epidemic. The new generation of models must recognise the impact of flexibility on control strategies when delivering scientific advice to the policy maker. Limitations in data and knowledge make models highly subjective. To compensate for the limitations, timely updates of knowledge are of extreme importance to steer the control strategy when necessary. The Bayesian paradigm is a ready choice to show the effect of learning through real-time data (37). The last few years have seen developments in this direction which can be further extended (28, 33).

## The potential gain from flexibility: an illustration

The illustration below uses a simple example to demonstrate the potential gain from flexible decision-making in the control of a hypothetical contagious disease. The illustration is limited to the situation where the decision-maker has a single objective: to minimise direct control costs.

### Alternatives and the expanded decision tree

With the problem and the objectives known, the first step is to identify the alternatives. Suppose besides the basic programme (which has to be carried out according to regulations), there are two other strategic options available, namely, emergency vaccination and pre-emptive culling. The alternatives for the decision-maker at time T are: basic programme only (B), basic programme augmented by emergency vaccination (B1), and basic programme augmented by pre-emptive culling (B2). Further assume that the risk profiles of the three alternatives at time T can be compiled as shown in Table II. If the decision-maker is risk-neutral and the decision has to be decided at time T, alternative B1 should be chosen since the expected cost of 78 million outperforms alternatives B and B2.

A decision-tree can be drawn to represent the thinking underlying this 'now or never' decision-making approach,

**Table II**
**The risk profiles for all alternatives (costs in millions of euros)**

| Alternatives | | T (without future decision) | | | T+1 (with future decision) | | T |
|---|---|---|---|---|---|---|---|
| | | Risk profile | | Expected costs [(a)] | New decision | Expected costs | Expected cost |
| | Outcome | Probability | Costs | | | | |
| **B** | 1 | 30% | 50 | | B | 50 | |
| | 2 | 50% | 100 | 95 | B1 | 78 | 69.6 |
| | 3 | 20% | 150 | | B1 | 78 | |
| **B1** | 1 | 30% | 60 | | B1 | 78 | |
| | 2 | 50% | 80 | 78 | B1 | 78 | 78 |
| | 3 | 20% | 100 | | B1 | 78 | |
| **B2** | 1 | 30% | 70 | | B2 | 90 | |
| | 2 | 50% | 90 | 90 | B2 | 90 | 90 |
| | 3 | 20% | 120 | | B2 | 90 | |

T: time
B: basic programme
B1: basic programme + emergency vaccination
B2: basic programme + pre-emptive culling
a) a probability weighted average of the costs from all possible outcomes

as in Figure 3. This way of selecting a control strategy assumes that the decision-maker has to decide at time T whether or not to choose an alternative to the basic programme and which one of the two strategic options should be taken. It fails to recognise that at time T, both emergency vaccination and pre-emptive culling are just options rather than obligations and the decision can be made at a later stage too. Choosing either one of the two strategic options at time T eliminates the option of sticking to the basic programme, which permits the decision-maker to decide at a future time with better information.

## Considering linked decisions

To represent the optional nature of emergency vaccination and pre-emptive culling and the link between decisions at time T and decisions at a later stage (e.g. T+1), an expanded decision tree should be constructed for the underlying decision-making process, which is shown in Figure 4. This expanded decision tree explicitly recognises 'waiting' as an option when the basic programme is implemented and shows the possibility of deciding later.

To decide whether to postpone the decision to a later stage, the potential net gain of waiting must be assessed. Answers to three questions determine this potential:

*a)* How could the risk profile change given the additional observation of the epidemic during this period?

*b)* What could be the new decision based on this new risk profile?

*c)* How could the expected consequences for the alternatives change?

To answer the first question, the learning process must be understood: it is particularly important that decision-makers know what extra information would be available and how this may influence judgments about the consequences and their likelihoods. In animal epidemics, a period without new detections may indicate a more optimistic scenario than originally envisaged, i.e. that the risk is lower than expected and that the epidemic is likely to be smaller than predicted, while an explosive increase in new detections indicates a bigger risk than expected and therefore a more pessimistic scenario. Incoming test results might prove that the herds suspected of being infected are actually clean and therefore confirm the end of the epidemic.

Suppose at time T+1 the risk profile for the basic programme is reassessed and thereby it is known which outcome will probably unfold, while for the others, because they do not have any further linked decisions and their risk profiles remain unchanged, the expectations stay the same. If it is confirmed that the outcome with a consequence of 50 million euros is in place, the basic programme should be followed. If, on the other hand, the expected outcome has changed and there is a consequence of 100 million or 150 million euros, B1 would be chosen, since it still outperforms the basic programme alone or the B2 programme.

The possible linked decision in the next period having been foreseen, the risk profile of the basic programme changes because the expected costs are now different. For alternatives B1 and B2, as they do not have further linked decisions, the risk profiles can be considered to remain the same.

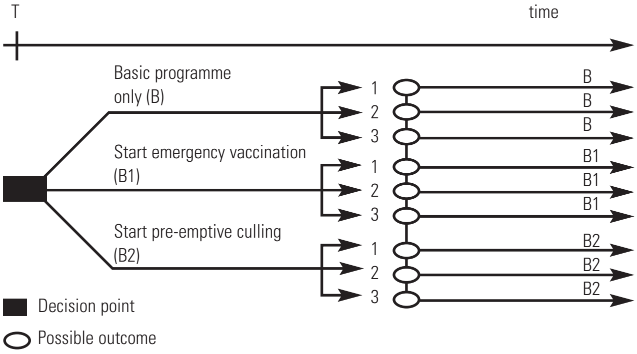


**Fig. 3**
**The decision tree underlying the now-or-never thinking**

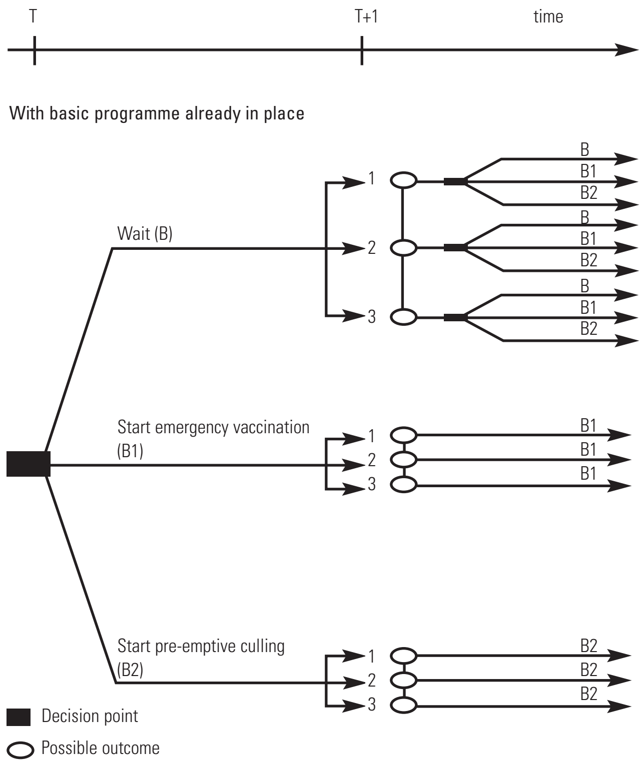


**Fig. 4**
**The decision tree underlying the flexible decision-making process**

### To wait or not to wait?

With possible future decisions (e.g. to add more stringent measures), the risk profile of the basic programme becomes different, because changing decisions in the future changes the possible consequences of the basic programme. The fact that alternative B1 can always be used at the worse scenarios of B makes the expected cost for the basic programme (alternative B) at time T 69.6 million euros instead of 78 million euros. The best decision at time T then becomes to wait to implement additional measures instead of implementing additional measures immediately. In this case, keeping the option to use additional measures open has the potential to reduce the costs by 8.4 million euros.

The figure of 8.4 million euros indicates the value of flexibility, at time T, of keeping options open and planning actions with the future in mind. This potential gain from flexibility depends on future uncertainty and must take into account the additional cost of collecting the information. This could be done in many ways, including the well-known method of 'expected value of information' (6). With this simple example the authors show that the key to flexible decision-making is the dynamic assessment of uncertainty in the consequences and the adaptation of decisions accordingly.

## Conclusions

This analysis of the decision-making process of epidemic control revealed three major fields for improvement in existing research concerning decision-making in animal epidemic control:

*a)* the decision-making process can be better represented as a dynamic process rather than a single step

*b)* more attention should be paid to the impact of uncertainty on the decision-making process, especially the timing of control actions

*c)* a flexible decision-making framework is needed to deal with changing uncertainties during epidemic control.

The analysis of the decision problem shows that, for a dynamic system like an epidemic, a single decision to make the choice of the control strategy cannot reflect the changing risk profiles of those strategic options in the course of the epidemic. A strategy selected this way neglects the advantages that flexibility permits: not deciding in order to gain more information, adjustment of original decisions, or additional decisions.

This paper has described ways to model flexible decision-making for research on epidemic control, in which the information gained during the control process plays a crucial role. The recognition of the role of flexibility in choosing control strategies opens up a wide range of research opportunities, among which are real options evaluation of control strategies and dynamic optimisation models. Improved representation of the flexibility within the decision-making process will provide better decision support for policy-makers in selecting the optimal strategy.

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# Renforcer la flexibilité des décisions en matière de lutte contre les épizooties

L. Ge, M.C.M. Mourits & R.B.M. Huirne

**Résumé**

La prise de décision en matière de lutte contre les épizooties est un processus dynamique et flexible. Devant les incertitudes liées aux conséquences des stratégies de lutte adoptées, une prise de décision flexible permet d'éviter des coûts de prophylaxie injustifiés, grâce à un processus d'apprentissage et d'ajustement. Tout en reconnaissant l'importance et la complexité de la prise de décision, la recherche s'est peu intéressée à la flexibilité appliquée aux décisions d'utiliser ou non une méthode de lutte, et à quel moment. Le postulat implicite étant que la décision sur la stratégie de lutte à adopter doit être prise immédiatement ou jamais, celle-ci risque d'être biaisée par un fort parti pris. Les auteurs analysent méthodiquement les éléments intervenant dans le processus de prise de décision en matière de lutte contre les épizooties afin de démontrer l'importance de la flexibilité. Ils examinent également les différentes manières d'intégrer la flexibilité dans la recherche sur la prise de décision dans ce domaine.

**Mots-clés**

Analyse de décision – Flexibilité – Incertitude – Lutte contre les épizooties – Prise de décision dynamique.

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# Hacia un apoyo flexible a la adopción de decisiones para combatir las epidemias animales

L. Ge, M.C.M. Mourits & R.B.M. Huirne

**Resumen**

En la lucha contra las epidemias animales, la adopción de decisiones es un proceso dinámico y flexible. Frente a la incertidumbre sobre las consecuencias de una u otra línea de acción, un sistema flexible de adopción de decisiones puede evitar costos innecesarios gracias al aprendizaje y la adaptación. Aun siendo conscientes de la importancia y complejidad de la adopción de decisiones, los investigadores han prestado escasa atención a la flexibilidad a la hora de decidir cuándo y cómo aplicar determinados métodos de control. El supuesto implícito de que si no se opta de inmediato por cierta línea de acción ya no será posible hacerlo más adelante puede provocar importantes errores de apreciación a la hora de definir estrategias de lucha. Para ilustrar la importancia de la flexibilidad, los autores analizan sistemáticamente los elementos que intervienen en el proceso de adopción de decisiones para luchar contra epidemias animales. Asimismo, examinan varios procedimientos para integrar la flexibilidad en la investigación sobre la adopción de decisiones en este terreno.

**Palabras clave**

Adopción dinámica de decisiones – Análisis de decisiones – Flexibilidad – Incertidumbre – Lucha contra epidemias animales.

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