Decision support for natural resource management; models and evaluation methods

Chapter 1

Decision Support for Natural Resource Management Models and Evaluation Methods

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Abstract

When managing natural resources or agrobusinesses, one always has to deal with autonomous processes. These autonomous processes play a core role in designing model-based decision support systems. This chapter tries to give insight into the question of which types of models might be used in which cases. It does so by formulating a rough categorization of decision problems and providing many examples. Particular attention is given to the role of statistical learning theory, which may be used to replace mathematical modeling by training with examples.

Keywords: Decision support systems, natural resource management, mathematical programming, agromanagement, statistical learning theory.

1.1 Introduction

When speaking about decision support and decision analysis, it is important to restrict the subject, since decision support problems may have very different natures. For some decision problems it is most essential to structure the decision making process by indicating who should decide on which aspect and when. In other decision problems, it is most urgent to provide well-structured information about the current situation and possibly about the past. However, in natural resource management and in agromanagement, high priority is assigned to forecasting the consequences of possible decisions. Therefore, in this type of decision making, modeling is an essential feature, since models may be used to provide information about the consequences of possible decisions. This focus does not imply that structuring of the decision process and providing well-structured information are irrelevant. However, this chapter will concentrate on the modeling aspect.

When managing natural resources or agrobusinesses, the underlying processes are always relatively complex and, therefore, one needs models in order to obtain insight into the relationships between decisions and consequences. The only alternative might be to rely on methods from artificial intelligence or statistical learning theory. Such methods exploit experience in previous related cases or the knowledge of experts. In Section 1.9, I will return to this possibility, particularly to the use of statistical learning theory. In the other sections, I will primarily deal with modeling approaches.

Section 1.2 explains how the relevant decision problems may be categorized. The subsequent six sections each treat one category of decision problems. Each category is roughly outlined and mainly clarified by examples.

1.2 The Modeling of Decision Problems

Decision problems about natural resources or agrobusinesses are always related to underlying processes that are highly autonomous. Such processes can be of a physical, chemical, biological, demographic, economic, or technical nature. A typical example is the spreading and transformation of air pollutants by wind and sun. Another example is the growing of wheat under the influence of soil and weather. With respect to the air pollution example, decisions can only affect the emissions, but, once they are emitted, one must take the processes leading to deposition for granted. With respect to the wheat growing example, the farmer may affect the starting conditions by selecting the right seed and preparing the soil in the proper way, but afterwards his influence is restricted.

When making decisions, one has to take these largely autonomous processes into account, since the consequences of decisions are generated through these processes. Therefore, when discussing the modeling, these autonomous processes play a central role. It even seems natural to take the role and type of these processes as the basis for categorizing decision problems.

The reason for modeling is to obtain insight into the relations between possible decisions and consequences. Therefore, these relationships determine which processes should be modeled with which level of detail. Naturally, one also has to regard the possibilities of evaluating models. Hence, a compromise might be necessary.

If one considers air pollution, then one is interested in a chain of processes. The first link involves considering the processes that generate the emissions, like driving cars and producing electricity; the second link constitutes the technical, physical, and chemical processes of emission, transport, transformation, and deposition of pollutants; the final link involves the processes that represent the impact of pollutants on human health, quality of trees, etc. For making *decisions* on emissions, however, one may argue that a description of consequences in terms of depositions and air quality is sufficient. Such a conclusion obviates a lot of tedious modeling: one only needs a model that translates economic, technical, and demographic activities in emissions and a model that translates emissions in depositions and air quality characteristics. Thus we arrive at a kind of modeling in which the natural resources don't explicitly appear. And this is a quite common procedure if one considers large-scale environmental decision problems. This situation describes our first category of decision problems, as set forth with more examples in Section 1.3. In the subsequent sections, living creatures play an increasingly explicit role.

In Section 1.4, I consider problems where the behavior of living creatures is essential and in the sections that follow, the life cycles of animals or plants form the starting point for modeling. In Section 1.5, I analyze decision problems where life cycles generate tasks that have to be performed effectively and efficiently. In Section 1.6, I consider decision problems regarding the starting or stopping of life cycles. Section 1.7 involves decision problems that concern starting or side conditions that affect the proceeding of life cycles. Finally, Section 1.8 treats problems in which life cycles may be influenced dynamically.

1.3 Decision Problems Without a Direct Relationship to Living Creatures

Wierzbicki *et al*. (2000) give an extensive treatment of decision support for environmental problems. The cases treated there all belong to the category described in this section. As previously explained for the case of air pollution, there are good arguments for separating studies on the impact of air pollution from studies on depositions and air quality. For the latter type of studies, we are typically dealing with "physical" laws regarding emissions, transportation, transformation, and deposition of pollutants. Here, demographic and economic processes are described in the same way as truly physical processes.

For an extensive treatment of the modeling of such problems, the reader is referred to Wierzbicki *et al*. (2000). Here I simply give some examples to clarify what type of problems fall into this category and what types of models are relevant. A common feature of these examples is that all regard policy making on a higher political level.

Examples:

a. *Transboundary air pollution*. In Europe, air pollution is an international problem, since some countries suffer more from emissions by other countries than from their own emissions. The RAINS-model of IIASA has been developed to support negotiations between European countries regarding abatement measures. The RAINS-model is one of the rare examples of a mathematical model being accepted as the basis for negotiations.

   The RAINS-model is a mathematical programming model with a large linear part, but also with a substantial nonlinear part caused by the generation process of tropospheric ozone. For algorithmic reasons, the model contains considerable simplifications like yearly averages and simplified sources.

   For a more extensive treatment and several references, see Amann and Makowski (2000), and Chapters 3 and 5 of this book.

b. *Energy planning*. There are many decision problems regarding generation and distribution of energy. For environmental reasons, medium-term and long-term decisions are particularly relevant. Several international bodies are involved in studies and negotiations between countries regarding energy supply and utilization. In such studies, linear programming models play an important role. These models provide a rather direct translation from reality. For an overview, see Messner *et al*. (2000).

c. *River basin water quality*. In river basins, the water is polluted by some players and used by others. It even occurs that several players pollute the water and are in extreme need of clean water at the same time.

   Several measures may be taken to improve the overall water quality. However, such measures are usually expensive and may have unpleasant side effects on the economy. Makowski and Somlyody (2000) show how such a decision problem may be supported by a mixed-integer linear programming model. This model uses a simplified version of the detailed model describing the transportation and transformation of pollutants in a river basin.

d. *Land use planning*. Different ways of using land compete for this scarce resource. Moreover, the way land is used has a considerable impact on the food supply, the water availability, and on several other important issues. Fischer and Makowski (2000) describe how linear programming models may support an integrated approach towards land use planning. In this volume, Fischer and Wiberg consider the possible impacts of climate change on water-stressed agriculture in Northeast China (see Chapter 16).

e. *Groundwater management*. Changes in groundwater level may have a considerable impact. Therefore, it is necessary to perform relatively detailed studies on groundwater in case of infrastructural operations which might affect the groundwater level in the neighboring area. Grauer *et al*. (Chapter 17 in this volume) provide a solution by coupling an optimizing algorithm to a simulation model based on finite elements. The computational complexity is beaten by using distributed computations.

A major problem in all these examples is their size, which, in some cases, is substantially diminished by simplifying process models considerably.

1.4 Behavioral Models

If living creatures are involved in the decision problem, then, usually, their life cycles provide the basic information for modeling. However, in rare cases, the primary source of modeling information is the behavior of animals. We give one example of such a case.

Example:

a. *Design of robotic dairy barns*. The most up-to-date dairy barn is equipped with one or more milking robots. The main advantage of milking robots over conventional milking machines is that cows may go for milking more than two times a day, which gives a considerable increase in milk yield. A dairy barn consists of different resources and the design problem is to find a good balance between numbers and sizes of the different resources. The needs are determined by the frequencies of visits and the time spent per visit.

   Halachmi *et al*. (2000) present a decision support system based on a queueing network model for the behavior of the cows.

1.5 Life-Cycle Generated Tasks

In several operational planning problems in agriculture, the life cycles are no longer influenced, but they do generate tasks which have to be performed effectively and efficiently. The nature of the products quite often dictates that tasks be executed quickly after they are generated.

Examples:

a. *Internal transport in pot plant nurseries*. Modern pot plant nurseries have specialized working areas for activities like potting, sorting, spacing, harvesting, and growing, since they apply dedicated equipment for each of these activities. Therefore, a lot of internal transport is necessary, which requires decisions regarding lay-out, transport equipment, allocation, and sequencing. Annevelink (1999) deals with the operational aspects of transportation in pot plant nurseries. He recommends a combination of simple rules for parking with the use of local search techniques like simulated annealing, tabu search, and genetic algorithms for the sequencing.

b. *Scheduling of inseminations*. Inseminators travel to the farms where cows are to be inseminated with the sperm of a bull selected by the farmer. The farmer calls for an insemination when s/he thinks that it is the right time for a particular cow. S/He also asks for sperm of a particular bull from the catalogue. For various reasons there is a tendency to use fresh rather than frozen sperm. Two times a day, farms should be assigned to inseminators and a route should be determined for each inseminator. Different techniques are in use for these purposes.

   Also the inventory management of sperm provides interesting decision problems. The amount produced cannot be affected on short notice, but it should be decided for each bull which fraction should be frozen and how much fresh sperm should be dispatched to the regional subdepots.

c. *Dealing with manure*. Due to legal restrictions, manure may only be used in a restricted way in The Netherlands. These legal restrictions are based on conventions of the European Union. Because of the wide-spread bio-industrial activities in The Netherlands, particularly pig-breeding and poultry-keeping, these restrictions have much more impact than in most other EU-countries. Non-used manure should be processed or transported to other areas for controlled application. Processing and transportation are expensive for the farmers and direct application is only allowed to a restricted level. There are several decision problems related to dealing with manure.

   For strategic and tactical decisions on a regional scale, a decision support system has been developed (compare De Mol and Van Beek, 1991). This system primarily uses linear programming. For some extensions, mixed-integer linear programming is used.

d. *Logistics of biomass collection*. Biomass may be used as fuel in energy plants. One of the main cost factors for biomass energy production is the cost of transportation and handling. Biomass for energy production may stem from several sources, e.g., restproducts (like demolition wood and waste paper), agricultural by-products (like straw and tops) and crops which are specifically cultivated for energy production (like willow and poplar). De Mol *et al*. (1997) show that mathematical models can help in designing an efficient logistic structure for collecting biomass. The authors present some models of their own and review the literature on the topic. Their paper shows that several types of models may be useful for different types of decisions. These models range from simulation models through dynamic programming models to mixed-integer linear programming models.

e. *Design and management of distribution centers for perishables*. Perishables, like fruits and vegetables, generate special questions regarding the design and management of distribution centers with respect to stock allocation, inventory policies, lay-out etc.. Broekmeulen (1998) shows that local search methods may be used profitably for assignment of perishables to zones, for stock allocation, and for some other operational decision problems. For some other decision problems, stochastic dynamic programming and linear programming appear to be useful.

One conclusion we may draw from this set of examples is, namely, that explicit modeling of life cycles is nearly never needed in this type of decision problem. In the subsequent sections we will consider problems in which life cycles play an increasingly explicit role.

1.6 Decisions Regarding Starting and/or Stopping of Life Cycles

It is quite common that the proceeding of life cycles is only affected by the decision when they should start and when they should stop. Determining seeding and harvesting times are major decisions in agriculture. But determining which type of product should be seeded is also an important decision.

Examples:

a. *Crop selection*. There are different reasons why crop selection at the level of individual farms may be a complex problem. A first reason may be restrictions on the order of particular crops in order to avoid plant diseases and soil quality deterioration. A second reason may be the restricted availability of resources. A third reason may involve time restrictions with respect to the seasons. A fourth reason may be the risks with respect to prices, weather, and plant diseases.

   Models that are used for these types of problems are linear programming, mixed-integer linear programming, and stochastic programming models.

b. *Timing of insemination through estrus detection*. As explained in Example b of Section 1.5, the dairy farmer must determine when a cow is ready for insemination. For the milk yield it is important that the insemination has a high probability of success and that no opportunities are overlooked. The most important determinant of the success probability is the timing of the insemination. Usually, the farmers determine the right time by observing the cow. De Mol (2000) developed a method for automatic detection of the right time for insemination (estrus) of dairy cows. In a modern dairy barn (compare Example a of Section 1.4), the behavior of the cows can be observed continuously. For instance, the milk yield and milk temperature are measured, but also the intake of concentrated food and the tendency to roam. Using the time series of such measurements and a few others, De Mol applies a Kalman filter approach for forecasting the time of estrus.

c. *Determining harvesting strategies for fisheries*. In natural environments it is important to keep sufficient fish stock for procreation and for prey (e.g., for other types of fish or for birds). To determine good harvesting strategies (locations, timing, and quantities), a model of the life cycle is necessary. Such a model should at least include the interaction between growth, procreation, food availability, and other environmental aspects. Models exist for different types of fish and shellfish (see, e.g., Scholten and Smaal, 1999, for such a model for mussels). These models may be used for supporting scenario analyses.

   In fishing nurseries, it is particularly important to find a good balance between food, growth, and prices. Here linear programming is used, but also (stochastic) dynamic programming.

In these examples, we see an increasing need to use life cycle models. In the next section, a type of problem will be presented that requires more detailed models of (parts of) life cycles.

1.7 Decisions About Start and/or Side Conditions for Life Cycles

Problems become more complicated if one tries to influence start and/or side conditions for life cycles in order to affect their proceedings. One simple example involves decisions regarding the preparatory work before seeding. Two other examples follow.

Examples:

a. *The choice of the right bull-cow combination*. Farmers consult the performance indicators of the available bulls in the catalog at the insemination station when choosing sperm for their cows. In practice, very few bulls appear to be favorite sperm providers for Frisian-Holstein cattle worldwide. In fact, all Frisian-Holstein bulls and cows belong to one genetic line. For instance, the popular bull Sunny Boy has about a million offspring. This situation poses a considerable risk of increase in inbreeding. Bijma *et al*. (2000) provide a general procedure for predicting rates of inbreeding. This procedure can be used to decide to avoid the sperm of certain bulls for a particular cow.

b. *Improvement of a population*. Apart from possible harvesting and predation losses, a population of fish, shellfish, mammals, or birds is affected by climatic circumstances (e.g., water temperature), physical environment (e.g., water flows) and food availability. These circumstances may be affected to some extent – deliberately as well as by happenstance. The consequences of changes may be evaluated by using a life cycle model which includes the relation between growth, food availability, and the reproduction success rates as a function of the circumstances. For an example of such a model, see Scholten and Smaal (1999).

As would be expected, these examples require rather detailed models of (aspects of) life cycles.

1.8 Problems in Which Life Cycles May Be Affected Dynamically

Environmental or agricultural management often reacts to the state of life cycles. However, decision support for problems of that operational management type is rare.

Examples:

a. *Operating a cut flower nursery under dynamic demand and price.* In cut flower nurseries, the growth can be speeded up or retarded to some extent. For instance, some flowers need a cold period before they are willing to blossom. By putting them in a freezer for some time and in a hothouse afterwards, the time of blossoming may be influenced. Good timing may have a considerable influence on the price, but it also affects costs.

   For a decision support system for this purpose, one needs a model of the relationship between growth and temperature profile and also a dynamic forecasting procedure for market prices, since prices of flowers are affected by the weather and by some other dynamic features.

b. *Operational management of commercial woods*. The growth of trees is largely determined by dynamic features like weather, diseases, and tree density. Operations like thinning and harvesting can be based on the actual situation as measured by remote sensing or aerial photographs. Also availability of resources is a relevant constraint. Different types of models are used, ranging from linear programming to (stochastic) dynamic programming.

Here we conclude the overview of models based on the way life cycles play a role in the modeling.

1.9 Statistical Learning

In the preceding sections, the emphasis was on explicit modeling of relationships that were supposed to be important for making decisions. However, explicit modeling is not always possible, particularly where relationships are complex and not well-understood. In such cases *statistical learning techniques* may replace explicit modeling. Statistical learning techniques make a systematic use of experience in related cases. In practice it has appeared that statistical learning techniques may be useful for recognizing patterns. This facility may be applied to performing classification tasks and also to estimating response functions. Clearly, this approach only works if enough experience in related cases is available.

Examples of statistical learning techniques include:

i. *Neural nets*. Among several variants of neural nets, we mention:

   - multi-layered perceptrons,
   - Hopfield networks, and
   - self-organizing maps.

ii. *Support vector machines*. For further information on this topic, the reader is referred to Vapnik (2000).

When managing natural resources or agricultural systems, three possible roles exist for statistical learning techniques. Below, we explain each of these roles and provide an example of each:

1. *Interpretation of observations or measurements*. Many situations present a lot of data that require interpretation. If many data points exist, which are already associated with an interpretation, then it may be attractive to train a neural net or other statistical learning technique as an interpreter.

   Example:
   Translation of remote sensing data of woods in operational characteristics may be used in Example b of Section 1.8. For an example of classifying remote sensing data with different types of neural nets, see Suurmond and Bergkvist (1996).

2. *Forecasting of time series*. There exist several decision problems for which forecasting of time series is an essential part. Particularly in cases where modeling seems to be difficult, statistical learning techniques provide an alternative.

   Example:
   For detection of estrus or mastitis of dairy cattle, forecasting of time series is essential (compare Example b of Section 1.6).

   By using Kalman filters a relatively rigid model is chosen [see De Mol (2000)]. Statistical learning might provide a more flexible class of relationships.

3. *Suggesting decisions*. If it afterwards becomes clear which decision should have been taken, it is possible to collect a set of learning pairs, consisting of a possible situation and the corresponding desirable decision. Particularly if it is difficult to provide a model which generates the decisions, it is attractive to use the learning pairs for the training of some statistical learning technique.

   Example:
   When determining market strategies in a market with a high price variability (like nursery products, fish, potatoes), it may be attractive to avoid explicit modeling and train some statistical learning technique instead.

The future will show what kind of position statistical learning techniques will obtain in management of natural resources and agricultural businesses.

1.10 Final Remarks

It would have been possible to introduce another approach to partitioning decision problems for managing natural resources and agricultural systems. However, every partitioning has its weak sides. With the presented partitioning and the large number of examples, I hope to have shown how rich the set of relevant decision problems is and how effective model-based decision support can be for taking well-founded management decisions in this area.

Quite a few of the references noted here are related to research with which the author has some familiarity, executed either at IIASA in Laxenburg, Austria, or in the Netherlands. Most of the publications cited contain ample references to related work elsewhere.

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