A DSS for Rotational Grazing Management: Simulating both the Biophysical and Decision Making Processes

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Abstract Dairy systems predominantly based on rotational grazing are noticeably hard to manage. In order to ensure profitability, such a type of production requires quite good organization, planning and operating capabilities on the side of the farmer. A simulation-based decision support system, called SEPATOU, has been developed for this purpose. At the core of the decision support approach lies an explicit and rigorous modeling of the management strategy that underlies a dairy farmer's decision making behavior (real or hypothetical). The aim of the SEPATOU system is then to compare tentative strategies (so as to select the best one), by simulating the application of any of them throughout the production season and under different hypothetical weather conditions. SEPATOU is a discrete event simulator that reproduces the day-to-day dynamics of the strategy dependent decision making of the farmer and the response of the controlled biophysical system for which models of grass growth, animal consumption and milk production are used. The relative worth of a strategy can be assessed by analyzing the effects on the biophysical system and their variability across the representative range of possible conditions that is considered. The activities to be managed concern the type and amount of conserved feed, where to fertilize and how much, the choice of fields to cut and, most importantly, what field to graze next. Typically, SEPATOU is designed to be used by extension services and farming system scientists. The implementation in C++ of the first prototype of SEPATOU is finished and the system is currently undergoing a validation process with the intended users.

1. INTRODUCTION

Unlike the rather stable context of the past decades, farmers must now strive for a dynamic competitive advantage that requires a well mastered understanding of their production processes so as to control them under various constraints and toward specific objectives that both may change from one year to the other. Agricultural management tasks constitute a challenging field for modern decision support technologies. This paper presents the SEPATOU system which is a simulation-based DSS developed for the specific problem of rotational grazing management in a dairy cow farm.

Most previous work on agricultural DSS have focussed on modeling key parts of the underlying biophysical system to be managed (soil, crop, animal), assuming that the management problem could be solved simply by assigning beforehand a set of decision variables or by addressing only some limited management aspects such as fertilization and irrigation. By contrast, the approach underlying the SEPATOU system puts emphasis on the need to model the interactive dynamics of the comprehensive farmer's decision behavior and the biophysical system. Indeed context–dependent adaptation of the farmer's decision behavior is a classical means to cope with the various sources of uncertainty that affects the production process. Moreover another key aspect of agricultural management practices is that successful farmers tend to anticipate situations by relying on flexible plans than span consistently the full production period taking into account contingencies and various constraints such as those on production resources (e.g. labor availability).

The paper introduces the rotational grazing management problem. The model that is simulated, in particular the management strategies underlying the farmer decision behavior, is then presented. The main software aspects are then outlined.

2. ROTATIONAL GRAZING

2.1 The management problem

Many dairy production systems rely strongly on a grassland feeding resource that is exploited through rotational grazing (moving animals from pasture to pasture) and completed by conserved feed (maize silage, concentrate and hay) especially in winter times when the herbage mass is still insufficient. The late winter to early summer period is a particularly crucial phase in which the diet must switch progressively from a fully maize-concentrate feeding to a predominantly or fully herbage-based feeding. The general objective of the farmer is to keep the milk production at its optimal level over the whole production period, despite the uncontrollable fluctuations of some important factors such as weather. The main difficulty in this management problem stems from the fact that the herbage production process interacts strongly with its concomitant use through grazing. For rotational grazing to be successful, the herbage supply must constantly match the demand as closely as possible. This requires anticipation (i.e. planning) as well as timely adjustments of the intended decision trajectory in order to cope with uncontrollable factors. The underlying control problem is a complex one because it involves a multivariable optimization. An appropriate quantity/quality tradeoff of the available herbage should be maintained along the considered period given that the maize distribution profile can only be non-increasing and the grass growth rate is partially controllable by the fertilization but also partially uncontrollable due to the climatic influence. Too much herbage can be as big a problem as too little. It has been shown that in order to have herbage of good quality it is necessary that the grazing intensity be high and regular on rotational periodicity. For rotational grazing to be successful, the turnout time and the timing of rotations must be carefully chosen in function of the pasture state. The rotational grazing management problem may change from one year to the other because the stock of maize available may be significantly different and the size and characteristics of the herd may vary too.

2.2 A modeling and simulation approach

The management of rotational grazing requires planning of actions and information gathering because short sighted decision may lead lately to irreversible bad consequences (insufficient or poor quality grass resource). Pertinent sampling of information at key periods of time is necessary to anticipate the occurrence of undesirable situations. Moreover, it is necessary to establish expectation of significant future events and have ready-to-use decision responses whenever such events occur. In other words, it is necessary for the farmer to apply a coherent strategy, defined as a set of planned tasks that incorporates provision to adapt to stochastic fluctuations of the weather. A fully specified strategy enables to generate what actions to perform in any situation along the production period, these actions being chosen consistently with a management trajectory (i.e. the strategy) spanning the whole grazing season.

The modeling and simulation approach implemented as the SEPATOU system is an attempt to help in constructing such strategies by providing an evaluation tool of the application of any of them in a particular dairy farm instance. As far as modeling is concerned, the effort has been put on representing the dynamics of two interactive processes: the cognitive one corresponding to the management behavior of the farmer and the biophysical one stressing on the response of the herbage and milk production to situation-dependent management practices. Consequently, the SEPATOU system is a simulation model of the functioning of these interdependent processes that altogether constitute what we call the production system (see Section 3). The project has devoted particular attention to the characterization of the notion of strategy for rotational grazing management. Its modeling and formalization in a formal representation language are the most original part of the project and are discussed in Section 4. The implementation, functioning and user-interface aspects of SEPATOU are briefly presented in Section 5.

3. MODELING THE PRODUCTION SYSTEM

We view the production system as constituted by three interacting subsystems represented in different levels of gray in Figure 1: the decision system itself composed of the planning and acting systems, the information system composed of the monitoring and observing systems and, finally the biophysical system.

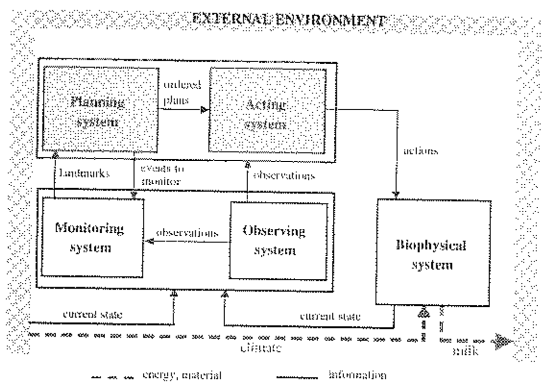

Figure 1. Systemic view of the production system

The production system dynamics heavily depends on the external environment (weather) that is uncontrollable and only partly predictable. The objective of the production system is to optimize the milk production by a proper use of the resources given the material constraints on the biophysical system.

3.1 The biophysical system

The biophysical system is the controlled system. A daily time-step model of this system has been developed for the SEPATOU simulator (see Cros et al. [1999]. It is based on a set of more or less empirical laws that express on a daily basis the dynamics of several interactive processes dealing with herbage production, cow intake and milk production. The herbage production is distributed over a certain number of fields having different sizes but each covered by the same grass species. The biophysical system responds to the climatic factors and farmer's actions. The climatic variables considered include the average daily temperature, average incident solar radiation and daily rain. The actions concern the nitrogen fertilization, the grazing operations (moving the herd to a new pasture), the cutting operations and the alimentation with conserved feed.

3.2 The decision system

The management actions are generated by the decision system that essentially performs the decision making task which the farmer is confronted to every day. As already mentioned, the complexity of the management task requires to decompose it into two simpler dependant modules: (i) the temporal planner of operations that produces a set of plans and operational constraints at an intermediate level (i.e. instructions that are not directly executable actions) so as to ensure a consistent temporal commitment over the production horizon and (ii) the generator of executable actions that tells what to do according to the current situation at execution time and given the general instructions of the planner. An example of instructions generated by the planning system is the specification of the set of fields to be used in the first cycle of rotational grazing, this set having to be elaborated consistently with the fertilization and feeding policy. On a given day within this cycle, the acting system is then responsible of the determination of the particular field to graze among the set fixed by the planner. The decision system must be responsive to the different situations that the production system is likely to encounter; from time to time the planning and acting systems must modify previously adopted commitments on the plans and actions generator in order to adapt to weather fluctuations or other events.

3.3 The information system

The role of the information system consists in providing access to the relevant data concerning the biophysical system and the external environment. What is relevant is highly subjective and is actually part of the decision making behavior adopted. Two functions must be performed by the information system: (i) monitor some expected events in the biophysical system or external environment and notify their occurrence to the decision system that uses them as decision making temporal landmarks, and (ii) interpret and store some data about the biophysical system and external environment and communicate the results to the decision system. This is respectively what the monitoring and observing systems are doing. A typical example of event that may be monitored (if so required by a strategy) is the latest ending date of the first rotation. This event occurs the first day after which the sum of the average daily temperature since the beginning of February is greater than a given threshold (for example, 600 degree-days for cocksfoot sward) that has a meaning related to quality degradation. The interpretation functions of the observation system are used to reproduce the real situation of a decision maker that, first, has only partial access to information (due to lack of time and sensing devices) and, second, relies on aggregated pieces of data for cognitive simplicity. For instance, the decision maker may plan, on the basis of a qualitative appraisal of the maize stock at the beginning of February; an interpretation function computes a qualitative value (above average, average or below average) by a simple translation of the number of days of feeding that can be covered with the available maize stock.

The working of the decision and information systems highly depends on the management strategy that is applied. The next section describes what is in a strategy and illustrates how the strategy components are expressed in the representation language specifically developed for the SEPATOU system.

4. MANAGEMENT STRATEGIES

4.1 Components and formal representation

The management strategy fully specifies the decision making behavior of the farmer in charge of the control of the biophysical system. It tells in a structured way what to do conditionally to some states and events. Therefore, in order to define a strategy one has to state:

- planning rules that define trajectories for the different tasks involved in the production process;
- acting rule that expands, for each active task, the planned trajectory so as to generate situation-dependant actions;
- how the temporal landmarks involved in the planning and acting rules and associated to monitored events have to be defined;
- what interpretation or translation functions should be defined in order to inform the condition parts stated in the planning and acting rules.

The above items are the basic components used respectively by the planning, acting, monitoring and observing systems presented in the previous section. Some examples of each of these components follows. They also illustrates how they are represented in the formal language (named LnU) created for this purpose in the SEPATOU project. The reasons to develop such a language for expressing management strategies are threefold:

- studying strategies requires a rigorous framework to support scientific experimentation and analysis;
- the writing of strategies by users of the simulator (research scientists and extension services agents) has to be facilitated by providing an easily learned and understandable environment incorporating the essential conceptual structures needed in formulating a strategy;
- the strategies have to be stated in a format lending itself to machine interpretation since they are fed into a simulator.

4.2 Examples of strategy components in LnU

In addition to the components mentioned in the previous subsection, the strategies are structured around the concept of tasks which are constituted of instructions and actions that have to be treated jointly. Currently four of them are considered, dealing respectively with conserved feed, grazing, fertilization and cutting. To each task is associated a set of plan variables and a set of action variables that are assigned values by the planning and acting rules respectively. For each task, the planning rules are responsible of assigning values to the corresponding plan variables for a given period over which these values remain constant, except if an adaptation is required (which would be realized by firing another planning rule). An example (highly simplified) of a planning rule defining the *Grazing* task from the beginning of February until the end of summer is shown in Figure 2. This planning rule is fired at the beginning of the simulation (i.e. when the *!February1st* event occurs). It defines for two intervals of time (bounded by February 1st, the turn-out date and the end of summer) the set of fields that the farmer intends to use for pasture and the grazing length on any one of them. Note that in the period preceding the turn-out to grass the plan specifies grazing fields although there is no grazing in this period (as indicated by the gazing length that is equal to 0). Actually the set of grazing fields declared for that period is the same than the one for the next period (all pastures except field6). This piece of information is useful before the turn-out date for determining the effective turn-out date that depends on the total herbage mass availability on the fields planned for grazing.

```
PLANNING RULE : CreateGrazingPlan
TRIGGER : !February1st
{
FROM !February1st
TO !TurnOut
DO { ?GrazingFields = AllFields –Name("field6")
     ?GrazingLength = "0" }
FROM !TurnOut
TO !EndSummer
DO { ?GrazingFields = AllFields –Name("field6")
     ?GrazingLength = "day" }
}
```

Figure 2. A planning rule for the grazing task

In the above rule, the term *!TurnOut*, as all those starting by the character !, is a temporal landmark that is associated with a specific event occurring at that landmark time. *!TurnOut* designates a particular date through the conditions that the biophysical system should satisfy at that day. Consequently *!TurnOut* gets a numerical value only when the conditions become satisfied, the value being the current date on the Julian calendar. Before that, the value is unknown. Thus monitoring an event (e.g. the satisfaction of the conditions to turn out to grass) amounts to check whether the corresponding temporal landmark has got a value. A planning rule has a triggering part made of either a single landmark or a logical combination of landmarks using conjunction and disjunction operators. A planning rule is applicable as soon as the events that occur make the trigger satisfied. For instance, a disjunctive (resp. conjunctive) trigger is satisfied as soon as one (resp. all) of the corresponding events occur(s). Figure 3 shows how the *!TurnOut* landmark is defined in the LnU language. Essentially the landmark is the date of the first day such that total herbage mass over the set of grazing fields is equivalent to more than 3 days of what the herd needs if fed only with grass.

LANDMARK : !TurnOut
CONDITION :
HerbageMassAvailibility(?GrazingFields) > 3

Figure 3. The *!TurnOut* temporal landmark

Besides the planning rules that set up nominal plans, a strategy normally contains planning rules that simply perform adaptation on these through modifications of plan variables or parameters involved in plans. An example of such a rule is given in Figure 4. It tells that at the end of the first grazing rotation, the set of grazing fields should be enlarged if the total herbage mass on the grazing fields initially planned is below what would correspond to 8 days of herbage feed. The enlargement consists in adding one pasture (field6) to the set of grazing fields considered at that time. The function *HerbageMassAvailability()* is a pre-defined interpretation function (not shown here). The planning rules used for adaptation can be declared to be usable several times.

PLANNING RULE : AdaptGrazingPlanEnd1st
TRIGGER : !EndFirstCycle
IF HerbageMassAvailability(?GrazingFields) < 8
THEN ?GrazingFields = ?GrazingFields +
Name("field6")

Figure 4. A planning rule for plan adaptation

Another key component involved in the definition of a strategy is the set of acting rules that specifies completely for the current day what action to perform in the task under consideration. Figure 5 gives an example taken from the *Cutting* task. The rule specifies that if the grass is sufficiently dry, then the fields to cut for silage are those initially planned provided there is enough dry matter and provided they have not been grazed already (these should be taken out if not).

ACTING RULE : FieldsToSilage
IF NotWetForSilage
THEN ?FieldsCutForSilage =
EnoughDMforSilage(?FieldsPlannedForSilage) -
AlreadyPastured(?FieldsPlannedForSilage)

Figure 5. An acting rule of the *Cutting* task

The *NotWetForSilage* term in the above rule is defined by a user-specified interpretation function. Its definition is given in Figure 6 where D stands for the date of the current day. The function is here a Boolean one. It returns TRUE if it is not raining the current day and if the rain in the last three days is below a given threshold. It returns FALSE otherwise. Interpretation functions are essentially used to provide past and present synthetic information about the external environment and the biophysical system. They can also be used as a predictor of future states.

FUNCTION : NotWetForSilage
CODE :
IF Rain(D-1) + Rain(D-2) + Rain(D-3) < 10 AND
Rain(D) = 0
THEN TRUE
ELSE FALSE

Figure 6. The code of an interpretation function

5. THE SEPATOU SOFTWARE

5.1 Main components and functioning of the simulator

The SEPATOU software is composed of two main parts and structured as shown in Figure 7.

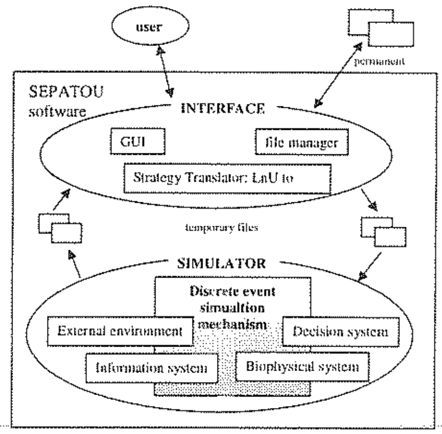

Figure 7. The structure of SEPATOU

The discrete event simulator at the core of SEPATOU is designed to work as follows. Every day it is checked whether a noticeable event has occurred and, if so the plans attached to the activities are eventually created or adapted, using planning rules. By using actions rules the general instructions specified in the plans are then transformed into executable actions that depend on the current situation of the biophysical system (more precisely on the decision maker perception of the current situation), the external environment and the current date. The changes that the actions cause on the biophysical system are then computed, resulting in a milk production realized during this day and an updating of the biophysical state that correspond at this point to the situation at the beginning of the next day. The simulator considers then the next day and performs similar processing. The iterations are pursued until the end of the simulated period. To give an idea of execution time, the compilation/linking of a strategy takes about 30 seconds and the simulation of one strategy application under 500 climatic years takes between one and five minutes on a 300 MHz Pentium II processor depending on the amount of outputs that the user has requested (and that must be written in files).

5.2 A sketch of a typical use of SEPATOU

The first step in using SEPATOU is to initialize the production system by describing the various components of the biophysical system (the fields, the herd and the stocks of maize silage and hay) and the strategy (planning and acting rules, indicators and interpretation functions). The user must also provide a set of climatic years taken from a database or constructed by using a weather generator that is incorporated in the simulator (Racsko *et al.* [1991]). Using a set of climatic years is necessary in order to be able to realize significant statistics on the results of simulations. At last, the user has to specify the desired outputs of simulations. Possible outputs include decision variable traces, chronicles of actions, time series of state variables, temporal occurrence of events, values of interpretation functions over time and statistics over the simulated years. A user friendly editor has been developed for easing the entering and modification of all these pieces of information. Any particular production configuration of the biophysical system or management strategy can be recorded and reloaded at will.

The second step encompasses a pre-processing phase and the running of the simulations. The pre-processing consists in parsing and then translating the strategy from the language specifically developed for strategy representation (LnU) into the C++ programming language in which the simulator is implemented. The translated strategy must then be compiled and linked with the code of the simulation mechanism. At this stage the simulations can be run as explained in the previous subsection.

In the third step, the user can visualize the outputs of simulations. A set of display capabilities, are provided for helping analyze the results. The time series of any user-selected variable along a set of simulated years can be visualized in tabular form or graphic form (in case of numerical data). Other types of display are also possible to show, for example the diet composition along one particular year or the chronicle of the executed actions concerning rotations, silage cutting, hay cutting and fertilization on each pasture (see Cros *et al.* [1999b]). To help between-years variation analysis some basic statistical tools are also available. By using these analysis tools the user can evaluate the strategy, pinpoint the causes of undesirable behaviors and from this build a new strategy by attempting to correct the previously tested one. The user can then start a simulation of this new strategy. A set of information recording possibilities is offered to store cases (farm configurations and strategies) and simulation results for bookkeeping purpose.

6. CONCLUSION

The simulation approach adopted for the SEPATOU system forces to fully specify candidate management strategies and enables their evaluation through virtual experimentation under various conditions. Each strategy (hopefully) conveys a coherent anticipatory and adaptive decision trajectory that drives the enterprise production toward an intended objective and reduces as much as possible the impact of the fluctuations of the uncontrollable factors. The SEPATOU software used in a trial and error process helps in elaborating satisfactory strategies fitting the specifics of the goals and constrains of the production system under consideration.

Presently SEPATOU is undergoing a thorough validation process with the intended users (see Cros *et al.* [1999b]). Whatever the conclusions might be the research project from which the system evolved has already generated fruitful questioning among the potential users by providing structure in the decision making process and by focussing modeling efforts on the most relevant aspects. One of the most rewarding aspects of the project is the chance for scientists and extension service to interact.

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