SIMULATING ROTATIONAL GRAZING MANAGEMENT

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Abstract Dairy systems predominantly based on rotational grazing are notoriously hard to manage. In order to ensure profitability, this type of production requires quite good organisation, planning and operating capability on the part 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 modelling of the management strategy that underlies a dairy farmer’s decision-making behaviour (real or hypothetical). The SEPATOU system is a discrete-event simulator that reproduces the day-to-day dynamics of the farmer’s decision process and the response of the controlled biophysical system for which models of grass growth, animal consumption and milk production are used. SEPATOU provides the means to evaluate and compare tentative strategies by simulating their application throughout the production season under different hypothetical weather conditions. The relative worth of a strategy can be assessed by analysing 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 fertilise and how much, the choice of fields to harvest and, most importantly, which field to graze next. Typically, SEPATOU is designed to be used by extension services and farming system scientists. It is implemented in C++ and is currently undergoing a validation process with the intended users.
INTRODUCTION

Unlike the rather stable context of the past decades, farmers must now strive for a dynamic competitive advantage that requires a thorough understanding of their production processes so as to control them under various constraints and towards specific objectives, both of which may change from one year to the other. Agricultural management tasks constitute a challenging field for modern decision support technologies. Traditional approaches focus on the simulation of dynamic models of the key biophysical processes to analyse production system performance under various weather conditions and operational management options (see for instance Boote et al., 1998). Most of the time, these systems provide little help for production management because they have rather crude and over simplistic models of the farmer's management practices during a season. Typically these systems use fixed dates for management events and address only some limited management aspects such as fertilizer applications and irrigation. They do not allow the simulated decisions to be planned and made in relation to the dynamic conditions on the farm both as regards timing and details of the corresponding operations. Attempts to correct these serious shortcomings are starting to emerge (Shaffer and Brodahl, 1998; Sherlock and Bright, 1999) through the development of simulators that integrate decision-making models with crop models.

This paper presents a simulation-based decision support system called SEPATOU that addresses the specific problem of rotational grazing management in a dairy farm. The approach underlying SEPATOU puts emphasis on the modelling of the interactive dynamics of the farmer’s decision behaviour and the biophysical system. Indeed responsiveness and context–dependent adaptation of the farmer’s management behaviour are a classical means to cope with the various sources of uncertainty that affect the production process. Moreover another key aspect of agricultural management practices is that successful farmers tend to anticipate situations by relying on flexible plans that span the full production period, taking into account contingencies and various constraints such as those on production resources (e.g. maize stock available for complementary feeding). At the core of the decision support approach lies an explicit and rigorous modelling of the management strategy that underlies a dairy farmer’s decision-making behaviour. SEPATOU simulates the day-to-day dynamics of the farmer’s decision process and the response of the controlled biophysical system for which models of grass growth, animal consumption and milk production are used. SEPATOU provides the means to evaluate and compare tentative strategies by simulating their application throughout the production season under different hypothetical weather conditions.
The paper introduces the rotational grazing management problem. The model that is simulated, in particular the management strategies underlying the farmer’s decision behaviour, is then presented. The main software aspects are then outlined.

**ROTATIONAL GRAZING**

*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 complemented by conserved feed (maize silage and hay) and concentrates, especially in winter when the herbage mass is insufficient. The late winter to early summer period is a particularly crucial phase in which the diet must switch progressively from purely maize-concentrate feeding to a predominantly or entirely herbage-based feeding. The general objective of the farmer is to keep milk production at a desired level throughout the production period by proper utilisation of the herbage resource despite the uncontrollable fluctuations of important factors such as weather. The factors which the dairy farmers can control include the stocking rate, the complementation, the nitrogen fertilisation of the pastures and, most importantly, the movement of the herd to a chosen pasture. The main difficulty in this management problem stems from the fact that the herbage production process interacts strongly with its concomitant use through grazing (Parsons, 1988). For rotational grazing to be successful, the herbage supply must constantly match the demand as closely as possible. The underlying control problem is a complex one because it involves a multivariable optimisation with both direct immediate effects (e.g. cow intake) and indirect delayed effects (availability and quality of the pasture for subsequent grazing). An appropriate quantity/quality trade-off of the available herbage should be maintained throughout the period under consideration in keeping with the intended profile and constraints of complementation. The herbage growth rate can be controlled to some extend by appropriate nitrogen fertilisation. 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, grazing should be intense and regular (Duru et al., 2000). For rotational grazing to be successful, the turnout time (Coléno and Duru, 1999) and the timing of rotations must be carefully chosen to match the state of the pasture (Kristensen, 1988). At some point, poor quality or an excess of herbage can be corrected by harvesting some pastures as hay or silage. Furthermore, the
rotational grazing management problem may change from one year to another because the stock of maize available may differ and the size and characteristics of the herd may also vary.

We believe that successful rotational grazing depends on (i) careful planning of the tasks involved, (ii) timely response to certain events and performance indicators by the farmer and (iii) sound implementation of tasks with regard to current conditions. Short-sighted decisions may lead irreversibly to undesirable consequences such as insufficiency or poor quality of herbage. Information gathering is an important duty of the manager in anticipating trouble. Skilled management is required in knowing what to look for and when. Because weather varies from year to year, task plans must be flexible. Any notable event revealed by monitoring should lead to a prepared response. The management behaviour outlined in this paragraph proceeds from the application of what we call a management strategy.

A modelling and simulation approach

Achieving objectives and controlling risks in agricultural production cannot happen by chance. It is necessary to devise and apply a coherent management strategy defined as a set of planned tasks adaptable to random weather changes. A complete strategy will prescribe what actions to perform in any situation during production, and maintain the task plans for the rest of the production period. Formalising the details of management strategy is one of the objectives of this paper. Modelling the management behaviour of a farmer requires to verbalise the kind of procedural knowledge that is often partly unconscious in her/his mind. Modelling management strategies and how they are used in practice is a prerequisite for studying and hopefully improving them. There is little about this in the literature. A notable exception is the work of Sebillotte (1993) which is, to our knowledge, the first attempt to characterise the pattern of the farmer’s management strategy for the technical activities on a farm. The paper by Aubry et al. (1998) is a valuable source elaborating along the same line.

The modelling and simulation approach of SEPATOU is an attempt to help in constructing or improving management strategies. It enables any of these to be applied in a particular dairy farm context under various weather scenarios and reproduces the dynamics of two interactive processes: the cognitive one (the management behaviour of the farmer) and the biophysical one of the response of herbage and milk production to situation-dependent management practices. SEPATOU is a discrete-event simulator (Banks
et al., 1996) of the functioning of these interdependent processes that, taken together, constitute the production system. SEPATOU shares many features with the FSSF system (Farm System Simulation Framework) developed independently by Sherlock and Bright (1999) for the same application domain. The modelling framework underlying the concept of a production system used in this paper is outlined in the next section.

MODELING THE PRODUCTION SYSTEM

We view the production system as made up of three interacting subsystems represented by different shades of grey in Figure 1: the decision system 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 depend heavily on the operational management decision and on the external environment (weather) that is uncontrollable and only partly predictable.

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., 2000). 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. In the current model it is assumed that there is a single herd composed of cows that are considered identical with respect to milk production potential and calving period. The herbage production is distributed over a certain number of fields of different sizes, each assumed to be covered by the same grass species. The biophysical system responds to the climatic factors and farmer’s actions. The weather variables considered include the average daily temperature, average incident solar radiation and daily rainfall. The actions concern nitrogen fertilisation, grazing operations (moving the herd to a new pasture), harvesting operations and the provision of conserved feed or concentrate. The herbage production model of each pasture accounts for growth and senescence processes and calculates the effects of defoliation on pasture quantity and quality (digestibility). Intake and digestibility are used to estimate the metabolisable energy available to the cows and to compute animal performance in terms of milk yield. Feed intake depends on the physiological properties of the cows
(lactation pattern) and pasture-related constraints (herbage allowance and digestibility).

**The decision system**

The management actions are generated by the decision system that essentially performs the decision making task which the farmer is confronted with each day. As already mentioned, the complexity of the management task requires that it be broken down into two simpler dependant modules: the temporal planner (planning system) and the generator of executable actions (acting system). The temporal planner produces a set of task plans and implementation constraints. The planner’s responsibility is to ensure a regular forward-looking commitment over the production horizon. The plans produced by the planner are not directly executable; they are made up of instructions that need to be expanded at execution time. This is the role of the executable action generator that decides what to do according to the general instructions of the planner in relation to the current situation.

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, which must be done in a way which is consistent with the fertilisation and feeding policy. On a given day within this cycle, the acting system is responsible for deciding which of the fields specified by the planner should be grazed. 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 in order to respond to weather fluctuations or other events.

**The information system**

The role of the information system is to provide 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 behaviour adopted. The information system has two functions:

- interpreting and storing some decision-relevant data about the biophysical system and external environment and communicating the results to the decision system;
- monitoring some expected events in the biophysical system or external environment and notifying their occurrence to the decision system that uses them as decision-making temporal landmarks.
These two functions are those of the observing and monitoring systems respectively. The interpretation functions of the observation system are used to reproduce the real situation of a decision-maker that (a) has only partial access to information (due to lack of time and sensing devices) and (b) relies on aggregated pieces of data for cognitive simplicity. For instance, the decision maker may plan on the basis of a rough appraisal of the size 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 calculation of the number of days of feeding possible with the maize stock available at that time. A typical example of an event that may be monitored (if so required by a strategy) is the latest ending date of the first rotation. For instance, in one of the strategies considered this event occurs on the first day after which the sum of the average daily temperature since the beginning of February is greater than a given threshold (e.g. 600 degree-days for a cocksfoot sward), which is important in connection with quality degradation.

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

**MANAGEMENT STRATEGIES**

*Components and formal representation*

The management strategy fully specifies the decision-making behaviour of the farmer who controls the biophysical system. It tells in a structured way how to respond to certain states and events. The strategies are structured around the concept of tasks, which consist of instructions and actions that have to be processed jointly. Currently four of them are considered, dealing with conserved feed, grazing, fertilisation and harvesting respectively. Each task is associated with a set of plan variables and a set of action variables. Plans correspond to the assignment of values to the plan variables of a task for successive intervals of time. The role of plans is to guide the day-to-day decision-making task, by providing some general directions to follow. A strategy is a formal representation of the way plans and actions are defined over the whole production period. We characterise it by the four following components:

- planning rules that define or modify plans for the different tasks involved in the production process;
- action rules that expand, for each active task, the current plan so as to generate situation-dependant actions;
- interpretation or translation functions that are defined in order to provide the condition information needed in the planning and action rules;
- temporal landmarks, involved in the planning and action rules and associated with monitored events that have to be defined.

The above items are the basic components used by the planning, action, observing and monitoring systems respectively presented in the previous section. Some examples of each of these components follow. They also illustrate how they are represented in the formal language (named LnU) created for this purpose in the SEPATOU project. The reasons for developing 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 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.

**Examples of strategy components in LnU**

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 triggered 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 grazing length that is equal to 0). Actually the set of grazing fields declared for that period is the same as the one for the next period (all pastures except field6). This piece of information is used 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.
In the above rule, the term $!\text{TurnOut}$, as with all those starting with the character $!$, is a temporal landmark that is associated with a specific event occurring at that landmark time. $!\text{TurnOut}$ designates a particular date, starting from the conditions that the biophysical system should satisfy at that day. Consequently $!\text{TurnOut}$ is given a numerical value only when the conditions are satisfied, the value being the current date on the Julian calendar. Before that, its value is unknown. Thus monitoring an event (e.g. the satisfaction of the conditions to turn out to grass) amounts to checking 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 needed to trigger the rule have occurred. For instance, a disjunctive (or conjunctive) trigger is satisfied as soon as one (or all in case of conjunctive trigger) of the corresponding events occur(s). Figure 3 shows how the $!\text{TurnOut}$ landmark is defined in the LnU language. Essentially the landmark is the date of the first day when the 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.

Besides the planning rules that set up nominal plans, a strategy normally contains planning rules that simply perform adaptation of these through modifications of plan variables or parameters involved in plans. An example of such a rule is given in Figure 4. It specifies 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 of adding one pasture (field6) to the set of grazing fields considered at that time. The function $\text{HerbageMassAvailability()}$ is a pre-defined interpretation function (not shown here). The planning rules used for adaptation can be declared to be usable several times.
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 *Harvesting* task. The rule specifies that if the grass is sufficiently dry, then the fields to harvest as 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).

![Figure 5. An acting rule of the Harvesting task](image)

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 amount of 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 predictors of future states.

![Figure 6. The code of an interpretation function](image)

**THE SEPATOU SOFTWARE**

The implementation, functioning and user-interface aspects of SEPATOU are briefly presented in this section.

*Main components and functioning of the simulator*

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

![Figure 7. The structure of SEPATOU](image)

The discrete-event simulator at the core of SEPATOU is designed to work as follows. Every day it checks 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 action 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 figure for this day and an updating of the biophysical state that corresponds at this point to the situation at the beginning of the next day. The simulator then considers the next day and performs a 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 output that the user has requested (which must be written to files).

A sketch of a typical use of SEPATOU

The first step in using SEPATOU is to initialise 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 action 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 realise significant statistics on the results of simulations. Finally the user has to specify the desired outputs of the 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 visualise the outputs of simulations. A set of display capabilities is provided for helping analyse the results. The time series of any user-selected variable throughout a set of simulated years can be visualised 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 throughout one particular year, or the chronicle of the executed actions concerning rotations, silage cutting, hay cutting and fertilisation on each pasture (see Cros et al., 1999). To help between-year 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 behaviour 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.

CONCLUSION

The simulation approach adopted for the SEPATOU system requires that possible alternative management strategies must be fully specified, and enables their evaluation by virtual experimentation under various conditions. The project has devoted particular attention to the characterisation of the notion of strategy for rotational grazing management. The model simulated in the SEPATOU system distinguishes itself from the traditional simulation approaches used in agriculture by incorporating a model of the decision-making process that implements a management strategy established beforehand by the farmer or an adviser. The most original part of the project lies in the modelling and formalisation of management strategies in a formal representation language. Each strategy (hopefully) conveys a coherent anticipatory and adaptive decision trajectory that drives the enterprise production towards 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 over a representative range of climatic years helps in elaborating satisfactory strategies that fit the specific goals and constraints of the production system under consideration, whilst complying with acceptable production risks.

The SEPATOU simulation system is currently undergoing a validation process with the intended users. Validation means evaluating and improving the system until it is good enough for its intended purpose. At this stage, the preliminary results of one year of experiments are quite encouraging. SEPATOU proved to be appropriate for representing and evaluating significantly different farmers’ strategies. Use of the system
confirmed its catalytic ability to stir up technical discussion among users and raise new interesting questions about the whole rotational grazing management process.

In order to enhance the capabilities of SEPATOU to support the construction of management strategy we have undertaken some development of the software to incorporate optimisation procedures. These procedures enable parts of the defined decision space to be more efficiently explored through parameterised strategies. The basic structure of strategies is kept and only some parameters involved in the rules are stochastically optimised with respect to an objective function. Although within an optimisation framework the search for better management strategies still calls for interaction with users. This extension should help the adoption of the SEPATOU system. Most (if not all) decision support systems have to overcome some remaining barriers before they become accepted by the community of intended users and find their place in the scientist’s or adviser’s tool-box.
REFERENCES


Figure 1
**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" }  
}
LANDMARK : !TurnOut
CONDITION :
   HerbageMassAvailibility(?GrazingFields) > 3
PLANNING RULE : AdaptGrazingPlanEnd1st
TRIGGER : !EndFirstCycle
IF HerbageMassAvailability(?GrazingFields) < 8
THEN ?GrazingFields = ?GrazingFields +
   Name("field6")
**ACTING RULE** : FieldsToSilage

**IF** NotWetForSilage

**THEN** ?FieldsHarvestAsSilage =

EnoughDMforSilage(?FieldsPlannedForSilage) -

AlreadyPastured(?FieldsPlannedForSilage)

Figure 5.
FUNCTION : NotWetForSilage

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

Figure 6.
Figure 7.