Modeling management operations in agricultural production simulators

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Abstract. At the core of farm management lies the issue of work organization that concerns the configuration of activities in space and time, the material requirements for their execution (resources, sensors), and the anticipated means to adapt or react to contingencies. At a more micro level work organization has also to deal with operational aspects: the conditions and manner in which one or more people use purposefully information and tools in order to fulfill the specific objective attached to a primitive operation. This paper argues in favor of an investigation approach of farm management based on a simulation model of the decision maker's behavior, the course of implementing operations and the interaction of the above processes with the biophysical ones and external events linked, in particular, to climatic factors. Simulation of the management process can be of great help in conceiving new production systems or in improving their efficiency, robustness and acceptability. The paper outlines the specific modeling needs when the decision-making behavior and work process play a central role in the intended study. It proposes a conceptualization of the structure and behavior of the management related aspects of a an agricultural production system.

Keywords. farm management, management model, decision making, planning, simulation

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Introduction

Sustainability and profitability of farm enterprises depend heavily on good management practices and capabilities to adapt to technical, economic and social changes. 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 another.

For a producer farm management consists in making and implementing the decisions involved in organizing and controlling a farm enterprise toward an objective. For instance a crop producer has to plan ahead of time the use of his land, decide repeatedly what technical operations he should carry out, find out what is wrong in the production process and fix it with appropriate corrective actions. Central to the concept of farm management is the purposeful use of limited resources with less than complete information due to the role of various factors that are beyond its control such as weather in particular. Indeed the management of an agricultural production is a notably complex task because the behavior of the whole system depends on interactions between connected components, the occurrence of which being independent of the manager's will. Adaptation capabilities to circumstances are key features for successful management of an agricultural production process.

This paper argues in favor of an investigation approach of agricultural production management based on a computer simulation model of the decision maker's behavior and of the process of implementing the operations decided. Its originality lies in the consideration of the decision and work processes together with the complex dynamics of the biophysical process underlying the production process. Such an executable simulation model enables to study the anticipatory behavior in decision making, the implementation and effects of decision depending on context, the resource needs (labor, equipment, material input) along the production period, the work overload, the possible loss of control of the production process and so on. The reductionist simulation approach that focuses solely or essentially on crop growth processes assuming known weather conditions are not helping much to address the management question of the farmer who is faced with uncertain and fluctuating conditions. Bringing or maintaining a production system to a state consistent with purpose involves a kind of knowledge processing that needs to be modeled for several reasons. It is essential for the accountability and transferability of the management procedures adhered to, the checking or improvement of these procedures, the development of alternative designs, the analysis of impact of changes or the ease of controversies about particular commitments.

The rest of the paper is structured in four main sections. The first section discusses limits of the crop-science centered approaches to address realistic farm management problems. The second section outlines the specific modeling needs when the decision-making behavior and work process play a central role in the intended application. The third section proposes a conceptualization of the structure and behavior of this part of a production system. The last section concludes with expected benefits and current limits of the simulation approach that incorporates models of human activities in the production process.

On the need to go beyond crop modeling

Basically computer simulation is the imitation for some period of consideration of the dynamic behavior of a system that accepts inputs, produces outputs, and interacts with its environment. A model of a system in its environment is an abstraction of reality, and as such, certain details are excluded from it. The question is always what to include and what to exclude. If relevant aspects are excluded there is a chance that the model will provide inadequate representation to support the development of the understanding desired and to serve the intended use. On the other hand, if too much detail is included, the model may become so complicated that, again, it fails to promote the development of the deeper levels of understanding one seeks and obscure the phenomena of interest. A key discriminant feature, which is the main focus of this paper, concerns the representation of the decision making behavior and the various production constraints to take into account in decision making and implementation of decisions.

The software systems that, to some extent, simulate farm or field production systems can be looked at from the standpoint of their use during simulation: users may interact with the simulator to provide decision inputs as the execution goes on or may be passive by just watching the results. Examples of use of the first type include on-line decision-making support (guidance based on real data) by exploiting the predictive power of biophysical models. Another application where on-line use of a simulator might be helpful is to study the on-line reaction of an operator in the course of realizing a particular task: the user can enter decisions as the simulation proceeds step by step (day or week for instance) and can learn to operate better by his mistake or poor performance results. In these cases, only a dynamical model, either mechanistic or empirical, of the biophysical system is required; no decision making model is needed.

Simulation software working in the passive mode are more common. Mainly in this case simulation is used as a device for helping capture and communicate intelligibly and convincingly how things work (interactions). By providing a well-founded, encompassing and shared body of knowledge about the behavior of a production system of interest this capability can serve as a virtual experimentation platform for extension agents and farmers. Simulation is then helpful in understanding why certain physiological phenomena occur (why did this growth problem happen on this crop ?) by exhibiting the chronology of interactions that are responsible of the observed results. Such simulators may also be able to provide a rough estimate of the economical performance or environmental impact of the management options across a range of climatic scenarios.

In these simulators, the underlying model as regards the decision making aspects may be more or less complex. Until recently, most of the above kind of simulators were essentially implementing crop models that, by nature, have very limited capabilities to represent management practices and to take into account production constraints during a season. They do not allow simulated decisions (e.g. crop species, sowing date, rate of nitrogen fertilization) to be planned and made in relation to the dynamic conditions on the farm both as regards biophysical state and operational constraints; decisions have to be made before each simulation regardless of what might happen and of feasibility considerations (see, for instance, Jones et al., 1998). Consequently they provide little help to evaluate realistic management strategies and operating procedures, identify production resource bottlenecks (e.g. peak of labor force demand), and design by iterative local improvement new management solutions adapted to changes in the technical, economical and social context.

Some simulation systems based on crop models include a simple representation of operational management aspects through the use of decision rules that can specify actions conditionally to the occurrence of some events or as functions of particular conditions (see, for instance, Meynard 1997; Keating et al., 2003; Jones et al., 2003). Nevertheless management issues can not be addressed adequately by focussing exclusively on crop processes. Other aspects that concern, for instance, temporal organization beyond sequential scheduling of activities, resource management or, more generally, human activities in the production system functioning require deeper representation capabilities and a change of scale from field to farm level. Addressing these aspects with simulation approaches is still a challenge. Some research works in this direction have been developed since the late eighties (see, for instance, Papy et al. 1988; Gibon et al. 1989; Deumier et al. 1996; Sherlock and Bright 1999; Cros et al. 2001). What is involved in these studies is the subject of the next section.

Human activities in a production system model

As argued in the preceding section if studying production management is the main purpose of a simulation project, one has to look at the production system as a human centered process that involves sequential sensing, decision making and execution of actions. At the core of such an investigation is the problem of gaining a better understanding of the interactions and interrelations that occur throughout the production period among the human actors (decision maker and operating agents), the biophysical entities (e.g. fields, crops) and the events in the external environment (e.g. climatic circumstances). A prerequisite for such a modeling enterprise is to have a comprehensive view of what these human activities are about and to identify and define some basic concepts enabling to describe and model this part of agricultural production systems.

Little attention has been paid to the managerial practices of farmers. See Aubry et al. (1998) and Papy (2000) for analyses reflecting essentially the thought of the French farming systems community. What kinds of activities does a manager perform and what are the distinguishing characteristics of this managerial work ? The managerial functions involved in dealing with the technical aspect of production (excluding financial and marketing aspects) include:

- organizing: configuring the production system resources both material (land, machine) and human (hiring, role assignment);

- planning: formulating an outline of activities to be done along the production season and methods for their execution with respect to production objective and constraints;
- determining actions and commanding:
  - identifying possible courses of action in face of current or anticipated situation (essentially in the biophysical domain) and constraints (availability and compatibility of resources, compatibility of activities);
  - selecting actions as functions of different criteria such as cost/benefit considerations, continuity and harmonization of activities, urgency (having some activities finished or state achieved before a deadline, having particular resources released by a date);
  - issuing instructions to cause activities to happen in a specific manner.
- information and knowledge handling: decision making is based on the ability to handle information and knowledge (what has to be acquired and stored, when to acquire it or recall it, how to use it in decision making: either directly or in a derivation process of a decision relevant synthetic indicator). The manager must therefore have monitoring and forecasting activities in which he seeks and acquires information to be aware of the present situation of the production system and envision its likely evolution.
- event handling: looking at environment for opportunities or disturbances and initiating/devising changes in planned activities.

In his management task the farmer has to deal with several interactive dynamics concerning the biophysical components, the environment of the system of interest (external events) and the unfolding of the technical actions resulting from the decision he has made. Most actions are durative; their execution may be disturbed, interrupted and even never finished. The farmer has to combine planned and reactive behaviors in order to organize the work in function of known and exploitable regularities and adapt to contingencies as they occur. Therefore the tight coupling between sensing and decision making in a timely manner is of primary importance. Managing an agricultural production process is a dynamic process in which plan revision and execution must be interleaved because the external environment changes dynamically beyond the control of the farmers and because relevant aspects are revealed incrementally.

The decision making behavior of farmers in their management task has been the subject of different kinds of investigation but the mental process that intervene between stimuli and response and by which that behavior is exhibited is still largely unknown. Nevertheless the concept of management strategy is often used as a means to express beforehand the farmer's management behavior. These management strategies do not pretend to reproduce what is happening in the manager's head. More modestly they attempt to enable the derivation of what the farmer does depending on the current state of affairs. Informally a management strategy can be seen as a manually elaborated construct that specifies a kind of flexible plan coming with its context-responsive adaptations and the necessary implementation details to constrain the stepwise determination and execution of the actions to perform. Due to evolving and unpredictable circumstances the plans are flexible with respect to the temporal organization of the constituting activities. The commitment to particular activities are delayed until run-time conditions are known. In particular, what can be executed is strongly constrained by the availability of resources and state-dependent requirements on the operations suggested by the plan.

Consider for instance the case of greenhouse tomato production. Greenhouse tomatoes have strong cultural requirements involving many technical procedures that must be followed to ensure a healthy and productive crop. Many weekly cultural practices (e.g. truss pruning, deshooting, deleafing, wrapping, harvesting) have to be performed. The experienced growers can reduce the time requirement by a proper organization of the activities. Some stages of the production process (for instance the long harvest period) are work intensive and adequate labor provisions should be made before costly help is actually required. Greenhouse tomatoes need regular attention. Unlike many field crops that can be planted, and operated on a fixed schedule, and then harvested after so many days have elapsed, tomatoes must be examined almost daily. Because the growth system is complex, many things can go wrong. In particular insect pest, fungi and disease problems are likely to occur. Proper management practices may reduce their likelihood but uncontrollable factors due in particular to weather are threatening the production process. With such a production system investigating management issues and potential improvements can hardly be done without having a comprehensive view of the production system functioning and the interplay of the mechanisms and knowledge sources upon which system performance depends, among which the decision-making process, the execution process and the information flow are of key importance.

Conceptualizing the management task: a proposal

A conceptualization of a domain is a modeler's commitment in isolating and organizing the relevant items of knowledge with respect to the problem that he/she wants to address. In this section we introduce a description of some core concepts enabling the modeling of human activities for simulating the production process. This conceptualization aims at a somewhat generic formalization of the domain so as to facilitate sharing across people and reuse across applications. It involves identifying the relevant notions, capturing clearly their meaning and the relations between them. This proposal evolves from research work conducted in our research team over the past decade (see for instance Gibon *et al*., 1989; Martin-Clouaire and Rellier, 2000a; Cros *et al*., 2001). Here only an informal description is given (see Martin-Clouaire and Rellier, 2000b for a more elaborated presentation). Italic characters are used to highlight the main concepts the first time they are mentioned.

At the center of production management is the concept of *activity*. In its simplest form, an activity, which is then called a primitive activity, specifies something to be done on a particular biophysical object or location (e.g. a plant, a field or a set of these) by an actor (e.g. a worker or a robot or a set of these). Besides these three components a primitive activity is characterized by opening and closing constraints defined by state-related conditions and/or time windows. These constraints provide the necessary means to determine at any time the activities that are eligible for execution consideration from the point of view of the overall organization of the activities.

The something-to-be-done component of a primitive activity is an intended transformation called an operation (e.g. the harvesting operation). In order to be executable an operation must satisfy some enabling conditions that refer to the current state of the biophysical system (i.e. the field to be processed should not be too muddy). The execution of an operation is causing changes on the biophysical system also called its *effect* which are expressed under the form of values given to some variables of the biophysical systems. These changes are usually not instantaneous and are taking place progressively during the period of execution. The values taken by the changed variables depend on context dependant parameters that have to be determined at execution time by the farmer. For some operations some of these parameters have a reference value called a nominal setting. For example a fertilization operation has the effect of changing the nitrogen content of the soil. The extent of this effect depends on the rate of the nitrogen input that is determined by implementing specific practical know-how. This knowledge is constituted for each operation by a set of action determination rules that map a state-related situation to desired values of the operation parameters including those having nominal settings if necessary.

The possibility of executing an activity can be impeded by violation of its opening and closing constraints or by violation of the enabling conditions of its operation as already mentioned. In addition it can be obstructed by the violation of requirements concerning *resources*. A resource is a material thing required by an activity to be executable. Three types of resource exist in an activity: the performer of the operation, the object or location transformed by the operation and the specific resources used in the operation (e.g. the tools, the inputs). Any resource is possibly constrained with respect to the maximum number of operations simultaneously supported and the maximum number of resources of the other types that can be exploited simultaneously with it. A resource can be either consumable (usable only once) or reusable after it has been released. Its availability may depend on a qualitative state (e.g. ready or not ready) or a numerical capacity (amount of fuel in the tank). The availability of a resource is constrained by availability constraints. The availability constraint of a resource specify the conditions enabling its usage and consumption. The availability constraints might be temporal constraints (time window of availability), capacity-related constraints (the amount available) or state-related constraints.

The above considered activities are primitive activities. They can be further constrained by adding temporal relations between them (sequencing, synchronization, delay enforcement, concurrency) and by using programming constructs enabling specification of choice of one activity among several, iteration, grouping and optional execution. The opening and closing of such activities made by composition of other activities are induced by the opening and closing conditions of the underlying primitive activities and by the semantics of the composition operators. The macro activity that gathers all the primitive activities through composition operators is called a *nominal plan*. A nominal plan may also need to specify some incompatibilities between primitive activities that should not be executed concurrently. In order to cope with uncertainty the activities of the nominal plan have to leave room for flexibility, which is obtained thanks to loose opening and closing constraints and qualitative temporal operators of activity composition. This flexibility together with restrictions on the use of resources have the consequence that at any time several sets of activities may be considered for execution. Choosing the most appropriate one may be done on the basis of *preference rules* conveying criteria based for instance on suitable properties of continuity and harmonization of activities or on considerations of cost/benefit or urgency.

Besides the flexibility on the timing of the execution of activities it may be necessary to adapt the nominal plan if particular circumstances occur. Indeed a nominal plan conveys the rough course of intended steps to go through under normal circumstances. The specification of when and what changes should be made on a nominal plan is called a *conditional adjustment*. The triggering part of conditional adjustment is either a calendar condition that becomes true when a specific date is reached or a state-related condition that becomes true when the current circumstances match this condition. The adjustment can be any change on the nominal plan such as the suppression or insertion of activities, or on the resources used in some activities or on the action determination rules used an activity. Actually a conditional adjustment can also specify a change to be made on conditional adjustment themselves. By this means the management can be reactive and thus cope with unexpected (though still feasible) fluctuations of the external environment (weather in particular) and various contingencies.

The state-related situations referred to in the opening and closing conditions of activities, in the action determination rules and in the conditional adjustments are pieces of information about the biophysical system that are either directly accessible by the manager or synthesized by him so as to construct a decision-relevant *indicator*. An indicator can also take into account past facts for instance about some activities already executed or about an aspect of the biophysical state at a particular time.

The activities together with their temporal constraints, programming constructs, incompatibility constraints, their action determination rule, the resource-related constraints, the set of conditional adjustment and the preference rules constitute a *management strategy*. A management strategy is also characterized by the rhythms at which the manager should monitor the occurrence of new events and scrutinize the indicators or salient aspects of the current state of the biophysical system in order to update the status (open or closed) of the activities or revise the management strategy using the conditional adjustments.

A strategy spells out how the behavior of performers (humans or machines) is to be driven by events around them in order to achieve (hopefully) the strategic purpose of the farmer. A strategy (its nominal plan more specifically) is not simply a sequence of operations fully specified beforehand as is often assumed in many agricultural production models. Indeed at strategy-construction time the strategy specification must stay rather abstract in terms of which operations to perform and when. The scheduling of operations must only be stated in a procedural context-dependant form. Later, at execution time, the part of the strategy corresponding to the current time has to be expanded so that finding what operations to execute and how can be done on the basis of the current situation. The executions of operations have extents in space, time and require resources to be available and various constraints to be satisfied (about state of the world and interference with other operations). These restrictive properties prevents the planner to specify fully when the operation will be executed, how long their execution will take and how they will overlap with other concurrent operations.

Within this framework the simulation of the management task is viewed as the problem of repeating two processes: i) modifying (if needed) the components of the strategy as specified by the conditional adjustments, ii) scheduling a set of executable primitive activities and then concurrently executing them until an interruption happens. The first process takes place at every occurrence of specific triggering circumstances. The activation of the second process is connected to events related to particular discontinuities (e.g. beginning of a new day or week, change in the resource availability, change in the labor capacity). At each scheduling time, the nominal plan is visited to update the status of the activities to reflect changes that might affect their opening and closing conditions. The next step aims at finding the sets of primitive activities that are eligible for execution. These sets are initially the possible sets of open primitive activities made to take into account the disjunction of the plan. They are pruned or split according to incompatibility and resources-related constraints. This involves a resource allocation process. Finally the best set of instructions is chosen according to the preference rules. The operations involved in the selected primitive activities can then be performed using the action determination rules. The execution carries on until an interrupting event occurs (e.g. completion of an operation, end of working hours). A nominal plan fails if any activity cannot be closed or cancelled (i.e. if the activity is not optional). The reason of the failure could be that it has never been possible, consistently with the induced constraints, to either open the activity or close it once open.

Conclusion

This paper has argued that if studying management of a particular production process is the main purpose of a simulation software, then human activities decision making and work processes can usefully be included in an encompassing model of the production system.

Simulation in the spirit advocated in this paper enables one to evaluate management practices and understand why and in what cases they may perform acceptably well or fail. Simulation can stimulate the farmer's thoughts about the management problems and potentially augment their innate knowledge handling abilities. A simulator can make revealing and reliable projections in a range of external environment scenarios, which nobody would even attempt due to the complexity of the system. Simulation enables for instance uncertainty analysis (robustness of management strategy), timing analysis (when is any particular phenomena occurring in the absolute or relatively to another phenomenon ?) or resource use analysis (what are the critical needs and when ?). Simulator can provide more compelling evidence to demonstrate beforehand that the production processes are in compliance with norms of social acceptability. From the point of view of the model developers the activity of modeling may reveal new ways of thinking about decision domain and help partially formalize aspects of decision making.

Decision making is a problem of knowledge management and as such is concerned with representing and processing knowledge. The conventional modeling and simulation technology (Banks *et al*., 1997) must be combined with knowledge representation and reasoning capabilities rooted in artificial intelligence (see for instance McCluskey *et al*., 2000) and with software engineering practices to build simulation software. The investigation of the deep rationale behind the farmer's management practices may greatly benefit from disciplines such as ergonomics or cognitive psychology.

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