Integrated modeling of agricultural production systems: achievements and remaining issues

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ABSTRACT

Improving the sustainability of agriculture has become crucial to deal with tomorrow's challenges such as supplying food to a continuously growing world population while mitigating its environmental impacts (e.g. climate changes). Recycling organic wastes to substitute chemical fertilizers for various organic ones (e.g. sewage sludge, household refuses, plant residues, livestock manures, agro-food industrial wastes) is one of the ways towards this end. Addressing this calls for the coordinated use of heterogeneous knowledge on both the biophysical (i.e. organic products, soils, crops) and managerial (i.e. farmers' practices) components of the whole production systems. Computer models, encompassing various pieces of that knowledge, are built to represent these systems as linked production and consumption units spread over a territory. These models are used for simulating management scenarios and assessing their performances against agronomical and environmental criteria. This paper describes our main achievements: (i) a methodology for modeling and analyzing material flows on a territory scale; (ii) a conceptual modeling framework of farming systems; (iii) a way of representing human activity in farming systems based on the 'situated action' theory. It points also out two remaining issues: (iv) assessing simulated management scenarios; (v) using models with stakeholders to support their management practices.

Keywords: Simulation modeling; Hybrid dynamical system; Activity representation; Situated action; Operations management; Agricultural production systems; Environmental assessment.

1. INTRODUCTION

The research discussed in this paper is focused on simulation modeling of agricultural production systems considered at two organization levels: single farms (individual management) and organized sets of farms (collective management). The aim of this research can be rephrased as designing simulation models to help design management policies of farming systems (and conversely). These models are conceived with farming systems agronomists to help evaluate farming systems management. They allow the dynamics of the various material flows (namely, biomass) operating within the production systems in interaction with the farming practices to be simulated. Two modeling approaches have been favored until now: hybrid dynamical systems, encompassing both continuous and discrete variables, and multi-agent systems.

Two research issues of unequal importance, the second being tackled since only recently, are dealt with:

- Finding representational structures (i.e. conceptual and formal frameworks) to make operational the available knowledge: designing the model is here the focus;
- Finding tools (i.e. computer models and the way to use them) to support agricultural stakeholders: designing management policies is here the focus.

In terms of models, the main achievements are the following:

- Material flow dynamic simulation models, based on the analysis of agricultural practices [1], to reason about various cases of livestock waste management: single farms (MAGMA model [5]); groups of farms (BIOMAS multi-agent system [4]); collective waste treatment plant supplied by multiple farms (APPROZUT model [6]); collective manure application plan considering the interaction between the individual (single farms) and collective (groups of farms) levels of management (COMET model [21]).
- Simulation of flow networks using timed automata and model-checking [13].
- Joint representation of farming practices and biophysical flows within dairy farms (GAMEDE model [23])
- Modeling framework of human activity at operations level with generic aim [9].

This paper provides details about the principal methodological findings:

- A methodology for modeling and analyzing material flows on a territory scale (Section 2);
- A conceptual modeling framework of farming systems (Section 3) illustrated on three models among those enumerated above (Section 4) ;
- A way of representing human activity in farming systems based on the 'situated action' theory (Section 5).

It also discusses two important issues that still remain incompletely resolved:

- How to assess simulated management scenarios? (Section 6);
- How to use our models with stakeholders to support their management? (Section 7).

The perspectives open to the different sides of this work in the coming years are pointed out.

2. MODELING AND ANALYZING MATERIAL FLOWS ON A TERRITORY SCALE: THE 'MAFATE' APPROACH

Beyond the development of the simulation models enumerated in Section 1, one of the main achievements is the formalization of the approach which actually constituted the driving thread of the research done in partnership with systems agronomists. This approach, termed 'Mafate' [11], encompasses several steps yielding the following outcomes:

1. Farm surveys, covering the diversity of management situations found in the considered territory;
2. Farm typology, defining the main farming types and characterizing both their structure and management policies;
3. Conceptual models, synthesizing the knowledge gained on farming practices from surveys;
4. Computer models, designed to simulate the interaction between the material flows and the farming practices at both 'individual' (intra-farms) and 'collective' (inter-farms) levels of organization;
5. Simulation outputs of management alternatives checked by experts (e.g. agronomists, technical staff, skilled farmers) according to agricultural and environmental criteria;
6. Model validation as virtual experiment tools in relation with agricultural stakeholders.

Steps 1 and 3 are deemed essential prior to constructing flow management models in order to account for actual farming practices, identify and explicitly describe actual management constraints and strategies. Step 2 is also very useful to take into account the diversity of situations found in the region considered. Performing simulations with the models (step 5), a long but interesting task, is mandatory to analyze dynamically (in contrast with widespread static methodologies as Life-cycle analysis) the functioning of the systems represented. Important work remain to be done, on the one hand, on multi-criteria assessment of simulated management strategies (step 5), on the other hand, on the use of models in management situations with agricultural stakeholders (step 6). These two issues, still incompletely resolved, are detailed below (Sections 5 and 6).

3. A CONCEPTUAL FRAMEWORK FOR MODELING AGRICULTURAL SYSTEMS

The ambition was to design a modeling framework with the following aims:

- Representing agricultural production systems on different temporal and spatial scales;
- Integrating the various pieces of knowledge available on these systems;
- Simulating the dynamics of interactions between management practices and material flows;
- Assessing the impact of these practices on the systems' viability and sustainability;
- Designing management strategies to improve the systems' performance against various criteria.

The material and work flow models that have been developed (cf. Section 1), the recent efforts of model generalization (extension of waste management to whole-farm operations in GAMEDE [23]; generic simulation of action [9]) and the design of a comprehensive approach ranging from the acquisition of knowledge to model building and simulation to support agricultural stakeholders (cf. Section 2) go in this direction.

These experiences allowed an understanding of the representation of agricultural production systems considered at different levels of organization on various temporal and spatial scales (farm, group of farms, agro-food supply chain) to emerge. According to this understanding, an 'Action-Flow-Stock' ontology has been devised [7].

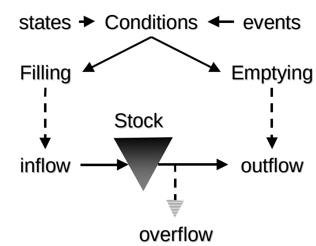

Figure 1. Action-Flow-Stock representation of a production unit (PU).

According to this ontology, agricultural production systems are represented as a set of stocks connected by flows of materials controlled by the farming activities (Fig. 1). Two types of flows are distinguished: "workable" flows, which take place only if there is human intervention, and "biophysical" flows, which take place even in the absence of human intervention. These flows interact through human activity, which aims to guide the biophysical flows, among which those leading to the "products" of the system, by the workable flows it generates. The management of the production system can then be seen as the control of a set of stocks by the activities of the operator (i.e. the farmer and farm workforce). These activities stem from the confrontation between encountered situations and strategies: implementing strategies helps create new situations; the experience gained by this implementation can, in turn, change strategies.

The relevance of this conceptual framework, derived by generalization of livestock effluents management models listed in Section 1 (i.e. MAGMA, BIOMAS, APPROZUT), has been verified, on the one hand, at the level of individual farm operation [23], on the other hand, at the level of collective management:

- Simulation of a hog slurry collective application plan in Brittany (Western France) using the COMET model [12][21];
- Draft modeling [8] and life-cycle analysis of the Reunion Island swine sector described as a supply chain.

The coupling of workflow management models with mechanistic models of biophysical processes may, however, be problematic when the data necessary to the setting of the latter are missing or when their generic feature is not guaranteed in the local situation investigated. To represent these processes, we thus moved towards the synthesis of expert knowledge in the form of simple empirical rules or formulae validated locally. An example of such an empirical coupling is provided by the GAMEDE model [23].

4. EXAMPLES OF MODELS BASED ON THE ACTION-FLOW-STOCK ONTOLOGY

MAGMA: Livestock effluent management at farm level

The MAGMA model [5] addresses the case of livestock effluent management within a farm. Two types of units are involved in such a “distribution” (i.e., one-to-many) configuration (Fig. 2): livestock enterprises producing animal wastes and consumption units, such as crop plots or waste treatment plants, where effluents are spread or supplied.

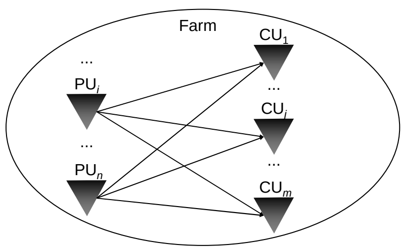

Figure 2. Distribution configuration in the MAGMA model to represent organic waste management within farms (PU: livestock enterprise; CU: consumption unit).

Simulating MAGMA allows management strategies of livestock effluents to be assessed with respect to several indicators: environmental (nitrogen losses due to stock overflowing, fallow land spreading, over-fertilization of crops); agronomical (nitrogen applied to crops); economical (working time, vehicle mileages…) and organizational (frequency and temporal distribution of spreading actions). MAGMA has been used to analyze waste management policies in livestock farms in Reunion Island, such as that described in [20].

APPROZUT: Supply of treatment plant by multiple farms

The APPROZUT model [6] deals with the case of simulating a two-stage production system where the first stage is a set of pig farms producing slurry scattered over a territory and the second is a unique collective treatment plant where slurry is brought in a many-to-one fashion (Fig. 3). Policy assessment is mainly done in terms of organization and logistics.

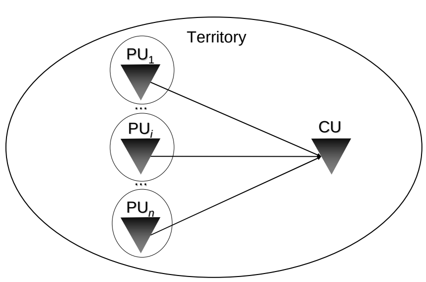

Figure 3. Supply configuration in the APPROZUT model (PU: livestock farm; CU: single waste treatment plant).

Approzut has been used to analyze a project of pig slurry treatment involving 51 pig farms located in a remote mountainous cirque in Reunion Island where available agricultural land was too scarce to spread raw slurry.

COMET: Mixed distribution and supply configuration

COMET [21] essentially results from coupling together the MAGMA and APPROZUT logistic models yielding the distribution/supply configuration displayed on Fig. 4. It also includes sub-models simulating biophysical processes used as environmental assessment criteria (e.g. the STAL model [19], which simulates ammonia emissions at spreading).

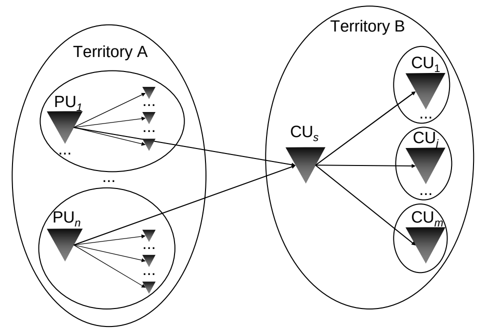

Figure 4. Mixed distribution/supply configuration in the COMET model (PU: livestock farm encompassing also crops; CUs: intermediate storage; CU: crop farm).

COMET has been used to jointly simulate individual manure spreading within single pig farms and the functioning of a collective spreading plan aimed at transferring manure surpluses from livestock farms to land loaned in remote crop farms in Brittany (Western France). The alternate use of dynamic simulation with COMET and static life-cycle analysis allowed the whole functioning of this case-study to be thoroughly assessed [12].

5. A CONCEPTUAL SHIFT: FROM PLANNED ACTION TO SITUATED ACTION

The confrontation of action representation in the flow management models based on the Action-Flow-Stock ontology [7] with the ontology of agricultural production systems devised by Martin-Clouaire and Rellier [17] led to question the paradigm of ‘planned action’ in favor of the theory of ‘situated action’ [22].

The management problems at the operational level are, indeed, typically formulated in terms of planning and decision. This is the very Western conception that actions necessarily result from deliberations made with representations (plans) to decide in response to previously established intentions. The study of many domains, however, shows that a very large part of human activity is non-deliberative or, even, reactive in nature; it takes place in interaction with the local situations in which each agent is involved [3][14]. Therefore, the theory of "situated action" alleges there is no need of representing explicitly the activity to be performed; plans, although they may be used to guide action, never determine it completely.

The action modeling framework already drafted [9] has the ambition to contribute to this situated action theory. The first reason is the construction of models. If the goal is to represent detail of agricultural, large and complex production systems, basing any action on a comprehensive and coherent plan appears elusive, due to the complexity of planning itself. This challenge is also justified from a theoretical point of view, except to enter an infinite recursion loop: if any action is planned, then so is planning, and planning for planning also, and so on... The other reason is linked with the usefulness of the models. If the objective is to evaluate production systems, it is by representing as better as possible what is actually done, and not what should be done (i.e. tasks specified by the plan), that can allow the impacts of activity to be measured and, in turn, the mutual influence of the context, thus modified, on the activity itself to be appreciated. Taking an a priori defined plan of action as essential determining factor would be similar to taking a static referent in an inherently dynamic environment to generate a process which is, also, dynamic. In contrast, taking action as a focal point, the present approach is designed to meet Checkland’s wishes: "...modelling purposeful human activity systems as sets of linked activities which together could exhibit the emergent property of purposefulness" [2].

It is, hence, the operational level that must the models represent in being primarily focused on action rather than on decision and planning. However, it is at the strategic level that these models must be used to assist researchers in experimenting the systems and, possibly, stakeholders in their decision processes, in keeping with Mc Cown’s view [16]. In other words, if the model must represent the action of virtual agents at the operational level, its use must contribute to the decision-making of real actors at the strategic level. These are currently the main research objectives:

- Develop an ontology for representing systems of activities at the operational level by a minimum and consistent set of concepts;
- Formalize this framework to build simulation models of agricultural production systems;
- Analyze with these models these systems operation viewed as the interaction between biophysical processes and human activities;
- Infer practical lessons to help manage these systems.

In this perspective, the concepts relevant to describing the coordination between actors, the spatial location of activities, the physical structure of the work setting and the relationship between the concepts of agent and action shall be specified. This is part of an ongoing PhD thesis project supervised by the author.

6. THE ISSUE OF ASSESSING FARMING SYSTEM MANAGEMENT

Any management requires the assessment of the system’s performance it relates to. The comparison of management policies, so far, was based only on a few indicators calculated by the flow models: agronomic (e.g. nitrogen applied relatively to crop needs), environmental (e.g. nitrogen excess, ammonia and methane emissions), economic (e.g. working time, distance traveled by vehicles) or organizational (e.g. temporal distribution of activity, robustness to disturbances). These indicators take into account only two dimensions: technical, measured in terms of efficiency, and environmental, measured in terms of risk, taking nitrogen as main criterion. The technical dimension assesses the system at the level where it is represented. If it qualifies its viability in the short term, it does only little in appreciation of its contribution to sustainable development in the long term. The environmental dimension concerns the system outputs on a scale that encompasses it immediately (i.e. the impact on its immediate environment). Environmental risk is addressed only as "hazard" (occurrence of a risk factor) and ignores the sensitivity and the particular nature of the receiving environment. In both cases, the assessment is performed with a normative view.

To address these problems, we must distinguish between two questions:

- How to evaluate the technical performance of production systems?
- How to evaluate their actual or potential environmental impacts?

In the first case, modeling biophysical flow is needed to simulate their interactions with the workable flows. This does not imply to represent all mechanisms in detail but, at least, to have a robust approximation of their evolution. To do this, the knowledge on the biophysical processes is synthesized by expressions for linking, as simply as possible, the causes and effects without going into the details of the underlying mechanisms (cf. Section 3). In the second case, comparing different management strategies is needed. The issue of sustainable development, which has become the essential assessment criterion, leads now to think the impacts of these systems in terms of risk (proven or alleged) on other time and space scales (often larger) than the ones on which they were previously considered. Hence, the interest in overall assessment approaches (“from cradle to grave”), such as life cycle analysis (LCA), which allows this comparison (although statically) through standardized indicators representative of different categories of impacts. An example of alternatively combining LCA with simulation modeling in a comprehensive approach to assess and help improve the design of a collective manure management plan by a group of farmers has been realized recently [12] [15].

These preliminary results are far, however, from exhausting the subject of environmental assessment which deserves to be rethought in the light of the objectives: what has to be assessed, for which purposes, with which actors? The goal of assessing the sustainability of farming systems striving to adapt to multiple change factors requires also defining the relevant space and time scales to be accounted for. The choice of the ‘scale of representation’ of a production system becomes, thus, a central issue for modeling, along with the methods of up- or downscaling the current models as soon as an extension or reduction of scope necessary to embrace larger or finer scales is sought. This questioning is a research perspective.

7. THE ISSUE OF USING MODELS FOR MANAGEMENT SUPPORT

The main question is: How to use simulation models to help stakeholders evaluate and design management strategies of production systems? This issue calls to other more specific questions related to:

- The ways of using the models: Which users? What situations? What modes of interaction?
- The engineering of simulation likely to facilitate users' learning: Which cases to simulate? What scenarios? Which protocol? How to capitalize the knowledge gained through simulations?

Dealing with these questions was first attempted in the period 2004-2007, unfortunately with too little achievements. If a first experience of participatory simulation had been made to assist in the choice of the treatment process for pig manure in the locality of Grand Ilet in Reunion [18], it was using a GIS and a spreadsheet model developed by fellow agronomists. The dynamic simulation models listed in Section 1, although quite used by these colleagues, have not yet been tested truly to design management strategies with "real" agricultural actors. When it could have been the case, actually, the projects aborted prematurely for unexpected reasons: in Grand Ilet (with APPROZUT), the action-research dynamics that had been initially launched by researchers was interrupted once the folder had been assigned to one of the institutional partners; in Brittany (with COMET), the collective manure application project was stopped due to the opposition of residents, not accounted for in the model...! The phase shift between the researchers' and the actors' time explains, in part, this state of affairs. However, deeper causes must also be sought in our inability to correctly grasp the social games of players in these organizational or political processes. In these contexts, beyond a purely technical rationality, one might ask if actual decision still requires the support of a model. It seems not.

Nevertheless, the work with the MAGMA [20], APPROZUT [10] and COMET [12] models allowed the way for a simulation approach to design management policies of production systems to be paved. The protocol was designed with an experimental logic: (i) construction of a base scenario corresponding to the current situation, (ii) assessment and analysis of the scenario through simulation, (iii) introduction of gradual changes for designing iteratively new scenarios. This dimming of the changes introduced in the simulation scenarios corresponds, from the point of view of operations management, to challenging firstly very short-term operational choices, then medium-term tactical decisions, and, finally, longer-term strategic decisions. The objective of this approach is not only to understand why farmers do what they do, but, above all, to understand their rooms for maneuver.

The production of documents allowing the user's approach to be represented and the knowledge gained by simulation to be capitalized is, for now, manually performed in a paper form. Using more sophisticated tools (e.g. mind maps, concept maps) to better organize this multimedia information (texts, graphics, data, etc.) should be considered in relation with the model users. If the simulation of actual cases of farms is interesting in view of advising individual farmers, reasoning on farm types can be useful for the purpose of supporting agricultural advisors or professional and public policy-makers to develop general scope alternatives at a micro-regional level. However, a too short experience in trying to elucidate the place of models in a decision process and finding the way to capitalize the knowledge gained from simulations has led, eventually, to consider cooperating with "real" researchers in management science, ergonomics or knowledge engineering to tackle these issues that are far from trivial.

8. SUMMARY

A way to improve the sustainability of agriculture is to design new management policies of agricultural production systems based on the integration of heterogeneous knowledge on their biophysical and human components. Simulation models, representing those systems as productive units spread over a territory, have been designed to assess these systems performance against agronomical and environmental criteria and, so doing, help design new management policies. Beyond the various simulation models realized to date, the main achievements were pointed out: a comprehensive approach and a conceptual framework for modeling and analyzing material flows on a territory scale; the challenge of the 'situated action' theory to represent human action in farming systems. Two incompletely resolved issues were also pinpointed: assessing the impacts of management policies at various scales and setting the practical ways to use simulation modeling with agricultural stakeholders. The research avenues that are thought of were also underlined: complete a generic modeling framework of human activity in agricultural systems, namely, by introducing the spatial dimension of action in addition to its temporal one; decide on the relevant temporal and spatial scales for assessing the sustainability of these systems and the related representational scale of the models used to simulate them; find the practical ways to use the models with agricultural stakeholders in decision making and capitalize the knowledge gained from practicing simulation.

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