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To cite this version:

B. Léger, O. Naud, L. Delière, P. Cartolaro, D. Gouache. Contribution of formal modelling and field experiment to leverage knowledge and expertise for designing crop protection guidelines. AgEng 2010, International Conference on Agricultural Engineering, Sep 2010, Clermont-Ferrand, France. 10 p. hal-00809588

HAL Id: hal-00809588
https://hal.archives-ouvertes.fr/hal-00809588

Contribution of formal modelling and field experiment to leverage knowledge and expertise for designing crop protection guidelines

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Abstract:

Pesticide use is still much too often systematic on many crops. However, there is scientific consensus that many farmers could change their crop protection practices without putting their revenue in jeopardy. There is need for crop protection management systems that yield significantly lower pesticide consumption. For many crops such management systems are not available, although knowledge about the pathosystems exists. We present here two crop protection formal guidelines (Decision Workflow Systems, DeWS,) which were elicited and formalised using the Statechart (GrapeMilDeWS) and the coloured Petri nets (POD BLé) modelling languages. Elicitation and formal modelling helped the pathologists to ameliorate their design and provided a convenient computer ready format. Moreover, the main purpose of DeWS models is to provide an exhaustive specification, which can then be transferred. This permits large experimental networks to be created. Such networks are necessary to collect data about the behaviour of the pathosystem under low input management and to assess the DeWS robustness and efficiency. Finally DeWS are learning tools for the growers, development workers and for its original designers as well.

Keywords: Formal Modelling, Decision Support Systems, Crop Protection

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1 Introduction

When it comes to sustainable agriculture, crop protection is a major issue, with concerns for environment, economics, social and health issues. In France, the problem is particularly acute as the country is the largest pesticide consumer in Europe. Yet there is a scientific consensus that lower consumption can be achieved without economic loss (Aubertot et al., 2005). There is need for crop protection management systems that yield significantly lower pesticide consumption. For many crops, such management systems are not available or empirically designed by a few farmers in their own farm. Yet, the knowledge to reduce pesticide use exists.

Since 2001, The Santé Végétale Laboratory at INRA (INRA-SV) is involved in the design of a low fungicide crop protection strategy in viticulture, using state of the art epidemiological results and know-how, yet keeping in mind the economic constraints of growers, including risk aversion. The result of this research, in collaboration with Cemagref-ITAP, is the GrapeMilDeWS Decision Workflow System (DeWS).

GrapeMilDeWS aims at managing the two most important cryptogramic pathogens in the French vineyard. *Erysiphe necator* which causes Powdery Mildew and *Plasmopara Viticola* which causes Downy Mildew. Alone, the control of these two diseases leads to 70% of yearly pesticide consumption in the French vineyard. This amounts to about 15% of the overall national fungicide consumption (ASK, 2000). It is very common among growers to mix in the same spraying operation phytosanitary specialties against both diseases. Yet, the regional information bulletins from the extension services separate information about these two diseases, as their bioclimatic characteristics differ. GrapeMilDeWS is original in that it manages at the plot scale both diseases in an integrated reasoning.

Since 2009, Arvalis–Institut du végétal has joined in and undertook to design a DeWS, named "BLé", for the management of winter wheat crop protection. With wheat, the difficulty is not in the lack of data or technical information to achieve low input (or near optimal) production. Printed guidelines that integrate reasoning about several cryptogamic diseases in an *a priori* spraying programme revised each year do exist. Yet, techniques and indicators had never been compiled in an integrated operational tool targeted at optimising the implementation of the spraying program throughout the season.

Although wheat production leads to less annual fungicide treatments per hectare than viticulture (3.49 vs 14.31 IFT[1] respectively), wheat represents one fourth of French arable land therefore reduction of fungicide quantities would have a significant impact on a national scale. The BLé DeWS manages seven diseases (*O. yallundae* - eyespot, *E. graminis* - wheat powdery mildew, *S. tritici* & *S. nodurum* septoria, *H. tritici-repentis* – tan spot, *P. striiformis* - yellow rust and *P. recondita* - brown rust, *F. graminearum* and *M. nivale.* and *M. majus* – Fusarium ear blight).

DeWS can be seen as crop protection guidelines specifications. Our case studies have been elicited and formalised using the Statechart (GrapeMilDeWS) and the coloured Petri nets (POD BLé) modelling languages, providing computer ready decision processes. The main purpose of DeWS models is to provide an *exhaustive specification* of the decision process, in order to transfer this operational knowledge to other researchers, development workers and eventually farmers. In both these case studies, the DeWS address tactical aspects of crop protection. Tactic, seen as the sum of treatment decisions (time and product dose at the intra annual scale), has a major impact on yield when lowering the input quantities.

The design methods and tools for these two DeWSs, which implement innovative fungicide protection strategies, are presented in the following pages. A brief description of the structure of the models is given, together with sample parts of the models. In the second part, the importance of the field experiments with respect to validating the decision workflows is explained. Finally, the choices of working at the tactical decision scale, and of the modelling paradigm, are discussed, particularly in the perspective of extending this work to the farm scale

2 Designing novel decision procedures

The French agronomic school has developed since the 1980s the model for action theory which gives a general framework to explain the managerial behaviour of farmers; articulating decision making at the crop level with the farm level (see Aubry & Chatelin, 1997). This conceptual framework has been developed in order to diagnose the farmer’s practices and help the farmer improve his management. It has inspired a wide range of tools developed in France for various applications in agriculture (Attonaty et al., 1994; Bergez et al., 2001; Chatelin et al., 2005; Cros et al., 2004; Debaeke et al., 2006). From the earliest to the latest, these systems have evolved to include biophysical simulation models taking advantage of the increase of computing power. Other international approaches to decision making for crop management should also be mentioned like (Audsley et al., 2005; Henriksen et al., 2000; Lemaire et al., 2003; Parsons & Beest, 2004; Zadoks, 1989).

Workflow modelling

The concepts of business process management, workflow modelling (W. van der Aalst & van Hee, 2002), has recently emerged in agriculture. Some authors emphasize on the need for modelling the farm business processes in order to cope with the complexity of agri-food supply chain networks (Wolfert et al., 2009) and novel e-government processes (Ntaliani et al., 2009). If the former have focused on the information system aspects of workflow modelling, Guan et al.(2008) have focused on the optimisation of the workflow in Japanese rice paddies.

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[1] IFT is the treatment frequency index (Champeaux, 2006) the data are from http://agriculture.gouv.fr/sections/thematiques/environnement/prevention-des-pollutions/produits-phytosanitaires6167

We have used the workflow concepts to develop decision systems based on expertise and synthesised knowledge instead of using the biophysical model approach to optimise the solution through simulation. Consequently, newly designed decision workflows need to be tested in field experiments. In order to avoid errors and inconsistencies and thus shorten the development and life cycle, the decision logics can be checked thanks to Formal modelling.

The Structure of Decision Workflow Systems

The idea underlying the design of DeWS is that optimal solutions for some pest management problems cannot be computed in practice (see ch. 2 in Léger, 2008). Therefore, the goal of the design is to reach satisfactory performance, both in terms of crop health and reduced fungicide quantities. The specification of the decision making procedure has to synthesise: an operational knowledge, including timing tactics, with the set of decision support tools that are available to the farmers, including field observation.

The work we present here builds on the workflow concept to model prescriptive decision procedures. The result should be a formal specification model of the process ready for integration into a simulator or a decision support system (Léger et al., 2010). We have experience that graphical workflow models can be understood by non-specialists and that elicitation and formal modelling can help the pathologists to ameliorate their design through a systematic approach of the decision logic (Léger & Naud, 2009).

In the case study conducted in viticulture, GrapeMilDeWS was elicited directly in Statechart. The ability for the expert to visualise at a glance the behaviour of the DeWS at design time has proved helpful, both for the knowledge engineer modelling it (the misunderstanding between him and the expert could be alleviated before any behaviour was displayed at run time) and for the experts who gained a better understanding of the system they had in mind, seeing it literally unfold before them.

The terminology "decision workflow" acknowledges the fact that timing and processes, that is, sequences of events and decisions all along the season, should structure system's design. Therefore, we have chosen discrete event system (DES) paradigm for modelling. This is a time abstraction for the dynamics of the patho-system (i.e. the crop, the disease and the control system) for which a detailed model would also include differential equations.

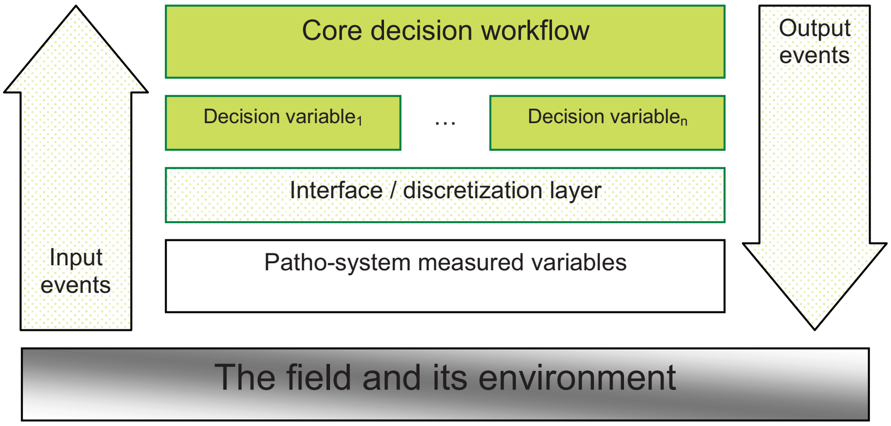


Figure 1 The Structure of a Decision Workflow System

DeWS architecture (see Figure 1) is composed of:

a core decision workflow which is modelled with a DES graphical modelling language like Statecharts (Harel & Kugler, 2004), for the GrapeMilDeWS case study or Coloured Petri Nets (CPN) (e.g. Jensen, 1996), for the BLé DeWS.

a set of decision variables which are either Boolean or Ordinal (e.g. {A-,A+,A++}). These decision variables are used to route the decision control flow from a reasoning state to another according to the latest known environment status. At design time, the semantic of these variables should be made as generic as possible. This means that they are linked for a given field implementation to concrete measurements from the environment but could be linked to alternative inputs for another. This provides some kind of loose coupling between the decision workflow and the observation protocol currently used.

an interface layer makes the link between the current observation protocol and the corresponding decision variable. Through this interface, the raw data from the observation is mapped onto the decision variable space. For field data, this may be achieved with simple discretization tables which are configuration parameters of the system.

a set of measured variables: These variables can be continuous or discrete. Values can be obtained via sensors or other information devices; measurement protocols in the field, or can be the output of a bioclimatic model.

input and output events: input events can be rain forecasts, changes of a variable value… the output events are decisions for actions like spraying or performing a field survey.

Design principles

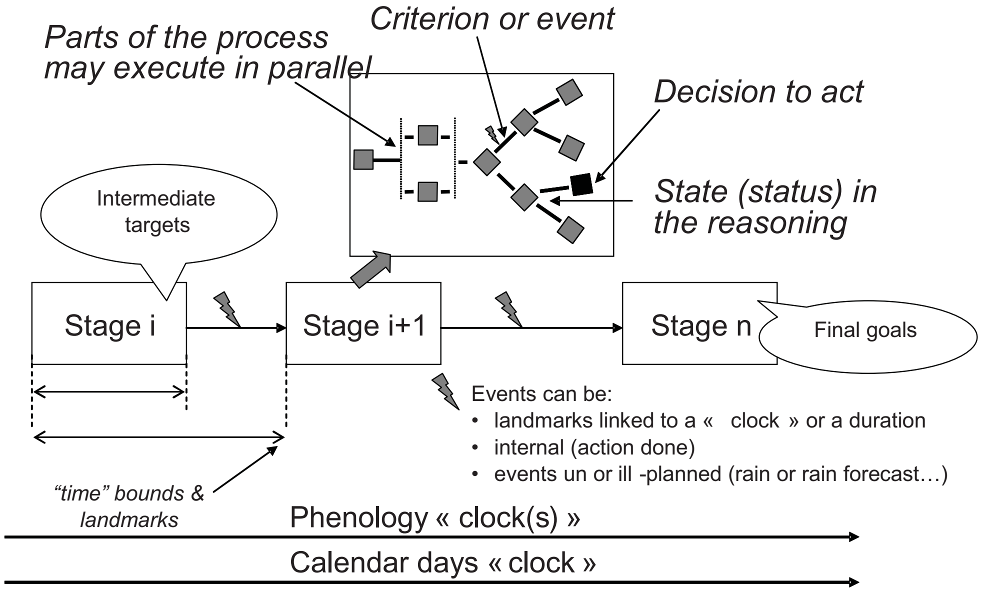


Figure 2 Conceptual structure for a Decision Workflow System in pest management.

Designing DeWS requires first to select the target diseases. In order to build a decision system that significantly reduces the use of pesticides (under the hypothesis that its use is generalised) the system will focus on the most important sources of yield loss and fungicide consumption. Because the system addresses the tactical decision making, the diseases that are not dependent on the annual weather are excluded (e.g. wood diseases of the vine).

The second step is to have the domain expert identify sub-targets and issues that need to be addressed along the "pest management" season. With these sub target and issues, the designers break the season in a number of decision stages (see Figure 2). For each of these stages, some general principles should outline a solution to reach the stage targets. The stage time bounds, whether from calendar or phenology, should be defined too.

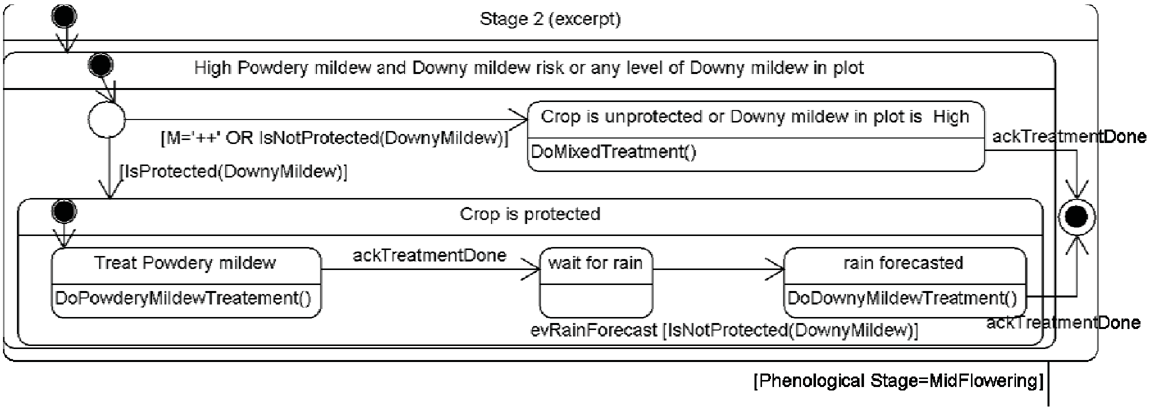
Then the detailed reasoning workflow is written as sub stages models. The decision variables define states in the reasoning process. Each state does not necessarily yield a decision (to treat or not to treat). At one moment in the reasoning, the state may be to wait for an evolution in the system that will trigger a treatment decision or alternatively the conclusion that no treatment is needed.

The formal specification of the process is iterative. The stage's sub workflow and the inter-stage transitions may therefore evolve during the design process.

In the two following sections, we give a short overview of the two case studies on which we implemented this design method.

The GrapeMilDeWS: Decision workflow system with Statechart

GrapeMilDeWS as hinted previously provides a structured reasoning specification, for the management of both Powdery and Downy of the vine at the plot scale. It is initialised at bud break and the final state is reached at harvest. The system is organised in 7 decision stages. Each stage corresponds to a decision about the opportunity to apply at most one fungicide treatment against each of the target disease. When both diseases should be treated against, the system is organised for spraying both treatments at the same time. To provide some robustness in the pest management, the minimum number of treatment is not zero. Indeed, there are two mandatory treatments against each disease. With mandatory treatments the question is limited to positioning the spraying properly inside the stage. When it comes to optional treatment, the positioning problem is doubled by the question of the treatment opportunity. This design was first formalised with Statecharts (Harel, 1987), which provide hierarchy and concurrency to mealy finite state machines. These mechanisms provide design ergonomic. Using so-called “flat” state-machines would yield a very high if not prohibitive number of states when modelling large systems. Statecharts are now part of the UML standard (Harel & Kugler, 2004)



M is the decision variable for in field Downy mildew
AckTreatmentdone = acknowledge Treatment done

● **Initial pseudostate**
○ **Conditional node**
◉ **Final state**

Figure 3 Excerpt from GrapeMilDeWS’ Stage 2.

Figure 3 displays several features of the Statechart model of GrapeMilDeWS. It can be noted that the reasoning is hierarchically decomposed from a high level evaluation of the patho-system’s epidemic risks to sub reasoning states guiding in detail the timing of the decision making process. The formalism is concise in that sub process will be aborted as transition conditions become true at a higher level. For instance, the ‘wait for rain’ state will not last after mid flowering because Stage2 will end at that time (see condition on the exit transition from Stage2). The model is limited to the management of a single plot.

The BLé decision workflow: modelling with CPN

The BLé DeWS integrates the pest management of 7 diseases in a unified process. The season is divided in 6 decision stages. This breakdown is adapted to the protection of wheat in regions where 3 sprays are usually carried out and more generally to farms where wheat is the main crop. While GrapeMilDeWS manages solely the opportunity of spraying, BLé also manages doses. Septoria which is the main wheat disease in most of France is controlled through the dose of product applied. The selection of the products and the correct dose is part of a sub module which interacts with the core decision workflow (Hernandez et al., 2010).

The other major difference with GrapeMilDeWS lies in the use of Coloured Petri Nets (CPN) instead of Statecharts. CPN is a high level variant of Petri Nets (PN) (Petri & Reisig,

2008) which is semantically equivalent to standard Petri Net: a CPN can be unfolded into standard PN. Petri nets are common to represent industrial logistic problems; they are also at the foundation of most workflow modelling formalisms.

Our interest in Petri Nets lies in their ability to represent explicitly and compute the state of the whole farm level decision system. In addition this formalism is more explicit with respect to resource management than what could be achieved with Statecharts. Figure 4 illustrates how we implemented the BLé DeWS with hierarchical CPN using the “CPN Tools“ modelling and simulation tool (Jensen et al., 2007)

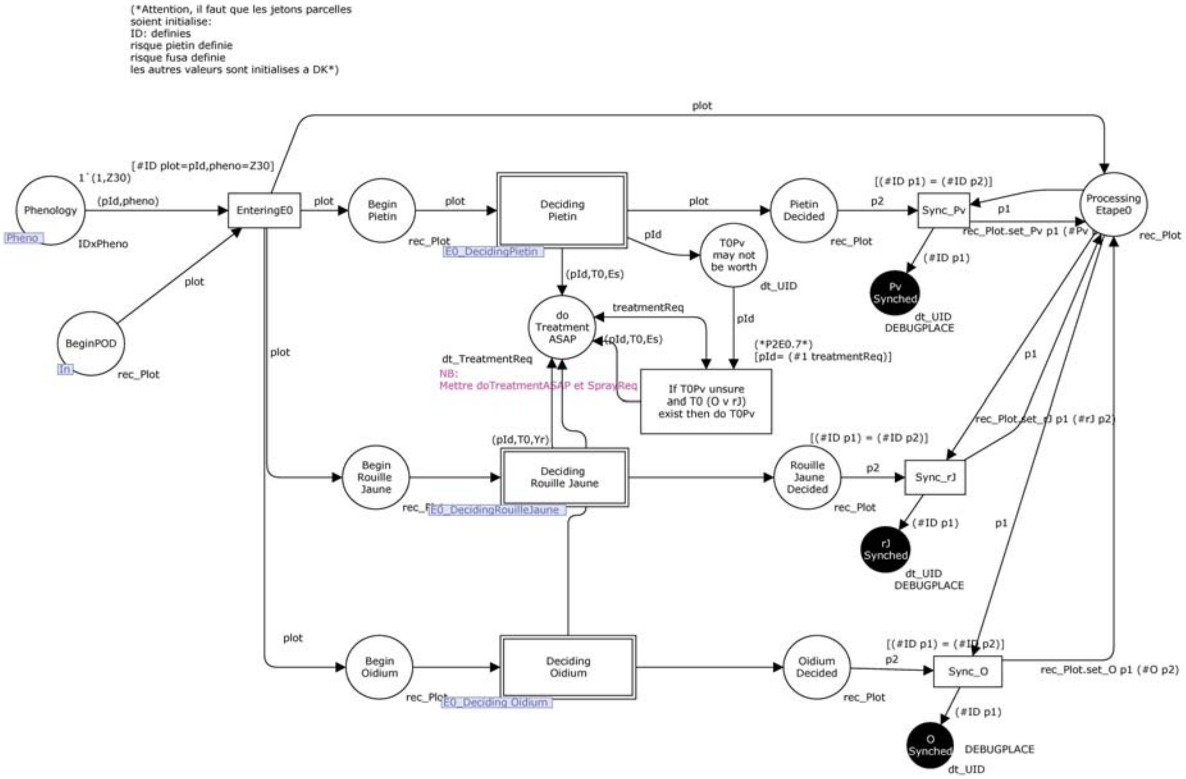


Figure 4 Stage 0 top level from the BLé DeWS.

3 Validation methodology includes field experiments

A DeWS relies on the modelling process of an expert based specification. Accordingly, we proposed in ch. 6 Léger (2008, pp. 162-178), an assessment based on evaluation and conformity-checking. The performance and robustness of the decision system are evaluated through field experiments, at the plot level, over several years and various pedo-climatic conditions. In the same time, the conformity of the experimental implementation to the specification is checked.

GrapeMilDeWS is currently experimented in several wine producing regions of France (Naud et al., 2009). This large scale experiment is necessary because of the lack of data about the behaviour of the powdery and downy mildews pathosystems under low input management and for various bioclimatic conditions. The data that is available concerns mostly untreated plots, or plots managed with periodic treatments according to specifications of products. These data are insufficient for the fine analysis of crop protection reasoning and tactics. GrapeMilDeWS has *de facto* become a learning tool for the growers and development workers involved in the experiment, and for its original designers as well (Naud et al., 2009).

With wheat, the focus is not on acquiring new biological knowledge on pathosystems but rather on integrating, into an explicit crop protection decision workflow, existing general and local knowledge, specialized models or disease-specific decision support tools. For instance, selecting the most effective DSS tool for eyespot between a very detailed agronomic decision table and the simpler cultivar resistance index to the disease.

Quantitative evaluation of the crop protection

Success criteria are defined in the first steps of a DeWS' design. In viticulture there are two major criteria. The plot must reach the grower's desired yield, for example the authorised production quota for a given wine type in a region. As for sanitary quality criterion, the percentage of infected berries should be comparable to results of a conventional practice. We consider that performance is not satisfactory when more than 5% of the berries are infected by powdery mildew. With wheat, our aim is to maximize the margin, therefore the DeWS must reach output that is equal or above the *a priori* optimal fungicide programs and respecting the sanitary constraints (e.g. mycotoxins).

The validity of low input systems lies in the ability to achieve satisfactory results in a number of different climatic and geographic contexts. The formal model provides an objective communication tool to extend the experiment beyond the original designer's own facilities.

Assessing the conformity of the field implementation to the specification

In order to identify potential weaknesses in the decision process specification and correct them, the DeWS design process is iterative; interleaving design phases, experimental evaluation phases, during which the decision process is closely monitored. The decision variables are recorded on a daily basis. Each decision is also recorded as well as the date of its implementation. This makes it possible to evaluate the conformity of the execution of a DeWS to its specification. As a result of this conformity evaluation, the data of a given plot for a given year may be partially or totally discarded in the performance evaluation. It can also happen, as it is the case for business workflows, that the model of the DeWS should be enhanced to account for a pertinent decision for a newly encountered situation.

The analysis method builds on the quantification of the conformity of an implementation's behaviour to its specification model behaviour (Cook & Wolf, 1999). The method is to compare the event sequence produced during the implementation of the process to the simulated event sequence produced by the specification model. There are two kinds of difficulties in assessing the conformity of processes and particularly crop protection decision processes. The first difficulty lies in the frequent impossibility to observe/record all relevant events. The second is the need to integrate quantitative time in the comparison. When seen as a simple sequence of event, conformity can be assess with a sequence edit distance measure (Levenshtein, 1966). However, taking into account the timing of the events makes the problem more difficult. In Léger (2008 in ch. 6), this second problem was partially addressed by taking advantage of the cycleless structure of GrapeMilDeWS' Statechart.

Many workflow modelling languages are Petri Net based and many Process mining tools are therefore adapted for Petri Nets. For instance the conformity problem is addressed by (Rozinat & van der Aalst, 2008) by counting the token missing or supernumerary ones in the net when replaying an observed event sequence. The ProM framework (W. van der Aalst et al., 2007) should be appropriate to analyse the conformity of the current BLé DeWS experiment implementation.

4 Discussion

Implication of choosing DES as modelling paradigm.

Our case studies were modelled as reactive systems. Simply said, this means that a decision should be applied in the field quickly after it has been taken, that response to new information should also be quick, and that anticipation under uncertain climatic events and revision are not taken into account. Although this hypothesis has proved unrealistic during the field implementation, it is a good heuristic at design time and makes the conformance checking (see above) simpler. Through field experiments in the first years, further knowledge of the time constraints and required flexibility that affect the decision system was acquired.

When implementing a DSS from the DeWS, these constraints and planning strategy could be added to the formal model. Indeed we have shown (see ch.6 in Léger et al., 2008) that the experts when implementing the decision process tend to anticipate a number of decision as soon as they can “compute” it in order to simplify their planning. Developing a DSS would require providing the farmer with the ability to project into the possible futures, plan future operations and yet keep the possibility to “roll back” or revise the planning. Plan technologies (e.g. Martin-Clouaire & Rellier, 2009) would allow such behaviour, but the tradeoffs for that would be to loose the ergonomic graph representation. An alternative would be to interleave planning and revision processes with the core reactive decision process. We have undertaken to test this latter alternative with YAWL, which is a computer language dedicated to workflows (W. M. P. van der Aalst et al., 2004). Integrating reactive and planning behaviour is definitely one of the tasks ahead of this research.

Why work at the tactical scale?

Within the agronomical research community, it is common to admit that the most promising way to reduce pollution of a given cropping system, which should be run at its optimum, while preserving the revenue is to modify the cropping system itself. In other words the largest reduction in pesticide use would only be made at the strategic pluri-annual level through drastic changes. It seems that this assumption has lead to a low level of interest among crop protection researchers about the ways and methods that will allow a producer to manage a given cropping system close to a steady optimal.

Furthermore, the DeWS approach, which is process based, could be adapted to non conventional farming paradigms like integrated production or organic farming.

Yet, our experiments show that even under the traditional agronomic production paradigm, most farmers have a technically suboptimal use of fungicides (i.e. GrapeMilDeWS achieved commercial standard production with 40% to 60% less treatments, in 80% of the tests.). Our understanding of these result, is that the farmers put more emphasis on organisational risk management, and projected consequences on the yield, than on the economic loss caused by spending on unnecessary sprayings. Our efforts aim at developing decision devices which, from the earliest steps of design, take into account the farmers most stringent organisational constraints while outlining for them the safe paths to make the most productive use of their inputs. In this context, the field experiments that we undertook show that low input crop protection is economically efficient (yield and cost efficiency) and that it is technically feasible under normal production conditions.

Going upscale: the farm level

Our work has so far been limited to the plot scale, ensuring the design is safe, and efficient at that scale. The farm scale is the research step ahead for DeWS. We believe that having a formal model of the system will help us study through model checking or simulation the behaviour of the whole farm system.

One way to think about the farm scale level is a distributed decision system, either holonic or multi-agent, where spraying needs for each plot, with its own instance of the DeWS, would be managed by a planning module with optimisation algorithms.

Alternatively, if the DeWS is implemented with CPN, the farm level could also be implemented with this same formalism. This second solution would require altering the original design in order to include the resource management constraints. This CPN model could however be adapted to a commercial workflow management system easily.

5 Conclusion

With the Decision Workflow System methodology, we address the need for novel pest management methods at the tactical decision scale. This design methodology aims at more rational use of pesticides.

This methodology blends field experiment and formal modelling to assess the quality of candidate solution, allowing incremental improvement of the designed solution. Formal methods are used to ensure the quality of experiments.

The traceability in the decision making process gives a renewed perspective in the study of decision support systems. For instance while developing a new bio-climatic model, epidemiologists and pathologist will be able to use the DeWS as a realistic and yet instrumented complete pest management strategy, which allows comparison of various candidates. In the same process, a DeWS will help identify when more information is needed to provide better decision making.

Our experience with the field experiment networks is that it is an efficient tool for scientists, development worker and farmer to learn about new crop protection principles that would at first hand go against their intuition. This is achieved by providing a safe environment: the experimental set up, but more important the structured reasoning framework.

This structured reasoning framework does not only facilitate communication within the experiment network. It also allows to gather data about performance and feasibility, including pragmatic details about use of weather forecasts or interpretation of bioclimatic models, and to relate this data to decision paths. The accumulation of cases permits to consolidate scientifically sound knowledge without implementing the usual blocs and repetitions.

In the same time, extension workers participating to the experiment have gained experience about low input strategies, and participating farmers have gained confidence in reducing fungicide intensity.

Besides continuation of experimentation of existing DeWS, further research will investigate decision at the farm scale, planning and revision of decisions, and optimisation of sampling within a plot and between the different plots of the farm.

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