A discrete events simulation of flock dynamics: a management application to three lambings in two years

Sylvie Cournut, B. Dedieu

Anim. Res. 53 (2004) 383–403

DOI: 10.1051/animres:2004025

Original article

A discrete events simulation of flock dynamics: a management application to three lambings in two years

Sylvie COURNUT[a*], Benoît DEDIEU[b]

[a] ENITA Clermont-Ferrand, UR Élevage et Production des Ruminants, 63370 Lempdes, France
[b] INRA, Unité Transformation des Systèmes d'Élevage, 63122 Saint-Genès-Champanelle, France

(Received 8 April 2003; accepted 3 June 2004)

Abstract – Sheep farmers are interested in models able to shed light on the consequences of new flock management decisions on the production level of ewes, and on the distribution of production within the annual calendar. In order to model the links between decisions and animal responses that lead to flock production, we conceived a simulator using the discrete events technique. The data came from the INRA Limousin flock, which used a three lambings in two years lambing management between 1974 and 1982. The process of the simulator design is presented. We formalised the flock as a system with two actors: the ewes and human decisions. The latter included strategic and operational steering, which are related to physical (i.e., animal and flock) and functional (i.e., groups, batch breeding cycles, ewe lambs stock) management entities. The ewe was defined by its productive trajectory and its biological responses (i.e., fertility, conception date, number of lambs born, and functional longevity) that were modelled statistically. The discrete events modelling technique is well suited to characterising the system since it includes various levels of abstraction and management of biological time and a decision calendar. The functional validation process was based on a plan of 50 computer experiments designed to test the correct functioning of the simulator. It shows a relative stability of the annual production level to moderate changes in the three lambings in two years management rules and in the fertility characteristics. We illustrate the regulation properties of the flock system by analysing the animal flows between the batch breeding cycles, entry/exit from the flock and the diversity of the productive trajectories of the ewes.

herd dynamics / model / discrete events simulation / flock / management / three lambings in two years

Résumé – Simulation à événements discrets du fonctionnement d'un troupeau ovin : application à la conduite du trois agnelages en deux ans. Les éleveurs ovin viande sont intéressés par des outils capables de simuler l'effet de changement de conduite sur le niveau et la répartition de la production de leur troupeau. Dans l'objectif de modéliser les liens unissant les décisions de conduite et les réponses biologiques animales lesquelles donnent lieu à la production et au renouvellement du troupeau, nous avons développé un simulateur à événements discrets dénommé « TUTOVIN ». Nous avons utilisé les informations collectées sur le troupeau Limousin de l'INRA, géré selon la conduite

* Corresponding author: cournut@gentiane.enitac.fr

« 3 agnelages en 2 ans » entre 1974 à 1982. Les étapes de la conception du simulateur sont présentées. Nous formalisons le système troupeau, avec les deux acteurs que sont les animaux et les décisions humaines. Celles-ci sont représentées selon deux niveaux (stratégique et opérationnel), et concernent des entités de gestion physiques (animal, troupeau) et fonctionnelles (lots, cycles de production de lots, stock d'agnelles). La brebis est un acteur élémentaire caractérisé par une histoire productive et des réponses biologiques (fertilité, date de fécondation, nombre d'agneaux nés, longévité fonctionnelle). Les techniques de modélisation à événements discrets sont adaptées aux caractéristiques du système, avec ses différents niveaux d'abstraction et les échelles de temps biologiques et calendaires. La validation fonctionnelle s'appuie sur un plan de 50 expérimentations informatiques. Elle souligne la relative stabilité du niveau de production annuelle du troupeau à des changements modérés dans le contenu des règles et dans les niveaux de fertilité. Nous illustrons les propriétés régulatrices du troupeau en analysant les flux d'animaux entre cycles de production de lots et en entrée/sortie du troupeau d'une part et la diversité des trajectoires productives du troupeau d'autre part.

système troupeau / simulation à événements discrets / conduite / performances / ovin

1. INTRODUCTION

Meat sheep farming in France is particularly sensitive to the combination of overall production and lambing and sales distribution challenges [19, 12]. Various reproduction management systems can be observed on farms from the simple organisation of one single period of lambing per year with a uniform individual pattern of one lambing per ewe per year to more complex reproduction organisations. These organisations multiply lambing periods and allow accelerated lambing patterns such as the STAR system, where ewes can have five lambings in three years [29], or the 'three lambings in two years' system [30]. These management systems are not stable over time since farmers often re-evaluate these in order to cope with a changing context involving income, work, market and environmental demand. Dynamic herd models are therefore useful in order to evaluate the consequences of new flock management decisions on production (level, distribution) over long time periods.

Dynamic herd models develop a particular point of view on the livestock farming system [17], since it focuses on the management and replacement of a flock (i.e., females used for reproduction). These dynamic models, based on Markovian, demographic or stochastic models [16, 27, 28, 35], require the formalisation of information, decisions and biotechnical aspects [23]. The degree of formalisation of each sub-system can be rather variable [18]. The decisional sub-model is often reduced to a set of rules without the decision process being formalised. This includes (i) the link between the expression of a production project by the farmer and a combination of rules, (ii) the existence of production management entities intermediary between the animal and the herd (e.g., the batch [21]), (iii) dates of decisions and actions and the schedule for implementing the decisions, (iv) procedures for adjusting the management system. The biotechnical sub-system is generally more detailed up to the biological mechanisms (for example [33]). Few models take animal lifetime production into account. Thus some studies suggest that the series of productive events is a significant factor on the production level or the survival responses in cattle [10] or in sheep [15, 26, 32]. More importantly, lifetime trait data is used by farmers, experts and genetic scientists as information for culling decisions [13, 34].

In this paper a flock dynamic simulator ('TUTOVIN') is presented. The practical aim of this simulator was to model how complex reproduction management systems such as the three lambings in two years system (3-in-2) acts on the production of a flock (e.g., size, distribution over the year, long term stability). The scientific aim was to produce knowledge on the herd system, its functioning and its regulation properties considering the complex interactions between herd management decisions and the animal responses [11].

2. MATERIALS AND METHODS

2.1. The 3-in-2 reproduction management system

The 3-in-2 system is characteristic of an intensive livestock project aimed at obtaining an individual pattern of three lambings in two years, with three lambing periods for the flock in the year [30]. Conceived in the 1970's, it is considered by economists as being very well suited for farms in the Centre of France considering the sheep breeds and market chain [6]. The flock is divided into two batches. Three reproduction sessions are organised yearly; each session concerns one of the two batches. In a given year, a batch is mated in January and October, the other in June and vice versa the following year. The ewes are synchronised at each period and the dose of PMSG is adjusted according to the season. At each mating, rams are introduced for 35 days in the whole flock. During this period, synchronised ewes in the batch can be mated, as well as the non-pregnant ewes of the other batch (repeated mating). Suckling lasts for a month and a half. At each production period, ewe lambs are kept for first mating at one year old. At the end of a lambing session, the non-lambing ewes change batch. Ewes with health problems (e.g., mastitis, no milk one or two teats) are systematically eliminated from the flock. Voluntary culling is based on age (the maximum age is 8 years) and succession of infertility periods (the maximum value is 3).

2.2. Data

Three types of information were used to build the simulator:

- Ewe data from an ovine management database (i.e., Gestion Ovin) concerning the INRA experimental Limousin flock. For each female in reproduction, the information available is relative to its productive life: date of birth, date and cause of disappearance (culling and death), succession of production events (i.e., lambing or abortion, number of lambs born, perinatal mortality). Data concerned 5237 registrations relative to the mating of ewes (for 913 ewes).
- Reports and interviews of managers and agents in charge of the flock at the time of the 3-in-2 system (1974–1982). They made it possible to specify the way in which management of reproduction and replacement of the flock was organised.
- References on other management practices, implemented by private farmers, to ensure the generality of the approach.

The data of the INRA flock has the advantage of reliability of information over a long time period, although not all management practices have been specified. Following the flock managers opinion, we assume that feed and health were not limiting factors for the expression of animal production performances and that the experimental function of the flock did not unduly disturb the management. Ewes with a lifetime production and a longevity distorted for experimental reasons were identified in the ovine management database and eliminated from the file. The flock population was about 400 ewes between 1974 and 1976, and was reduced to 270 ewes in 1982. The "30 days productivity" (number of living lambs at 30 days of age per ewe and per year) varied between 1.8 and 2, with an average prolificacy of 165% and a lambing rate of 130%. Adult annual mortality was 6.5%.

2.3. Conception and development of the simulator

The conception of the simulator was based on the following set of specifications: (1) production should be expressed as the number of live-born lambs per calendar fortnight, (2) account for the diversity of reproduction and replacement management systems (including the complex 3-in-2 system), (3) account for the effect on production on different levels of reproductive performances of the flock, and on known variants of the 3-in-2 set of rules. These variants concern the information mobilised (e.g., lifetime or last lambing results), the criteria threshold (e.g., age at culling) or the application date (e.g., date and duration of mating).

We followed the classical procedures of conception and development of a simulator [4]: analysis, data collection, implementation and validation. The analysis phase corresponded to the characterisation of the flock system, which is the set of all the ewes used for reproduction, replaced and steered by the farmer according to his livestock project. The statistical modelling was made on the basis of the available data, in order to estimate the biological responses that are necessary for setting the model parameters: we focussed our analysis on reproductive and survival responses. The choice of the modelling technique took into account the characteristics of the modelled system. Finally, the validation showed that the model gave a good representation of the functioning of a real flock, and, via the modification of parameters, it also made it possible to understand and describe the regulation mechanisms at work in the flock system.

3. RESULTS

3.1. Formalisation of the information and decision sub-system

For decisions of reproduction and replacement management, procedures for analysing the management of production processes in an industrial environment were used. They were already applied to farm management [1, 20] and crop and forage systems management [2, 8]. These authors rely on notions of production projects, strategic steering and operational steering.

The farmer's *livestock project* can be defined by the production plan (i.e., number, types of animals, ewe productivity and distribution of production) and the composition plan that specifies the evolution of the flock size and the ability of the flock to fulfil the production plan. The farmer implements an action programme, which can be expressed as the definition, planning and adjustment of his/her interventions. With *operational steering*, everyday management of the flock will be carried out. The link between the livestock plan and operational steering is made via the *strategic steering* of production and replacement of the flock composition (Fig. 1).

In order to specify strategic steering and operational steering, management entities and their function as targets of steering activities and source of information for management need to be defined. The herd and the animal are well-known management entities. The *batch production cycle* (BPC) is the basic management entity for strategic steering. It is linked to two functional bases that are the animal collectives: batches and ewe lamb stocks. A *batch production cycle* is defined as the aggregation of ewe production cycles around a same reproduction period, organised by the farmer at the level of a batch with a view to obtaining a lambing session (Fig. 2). It corresponds to a combination of events linked to the management and biological processes that are characterised in relation to the production objective associated with it. It starts with the constitution of the mating batch and the introduction of the rams and ends when all the ewes are dry. The batch production cycle therefore represents a "production workshop" [8] in which the farmer intervenes. The production organisation configures and coordinates the batch production cycles (Fig. 3).

The configuration of a BPC concerns blocking on the calendar the mating session

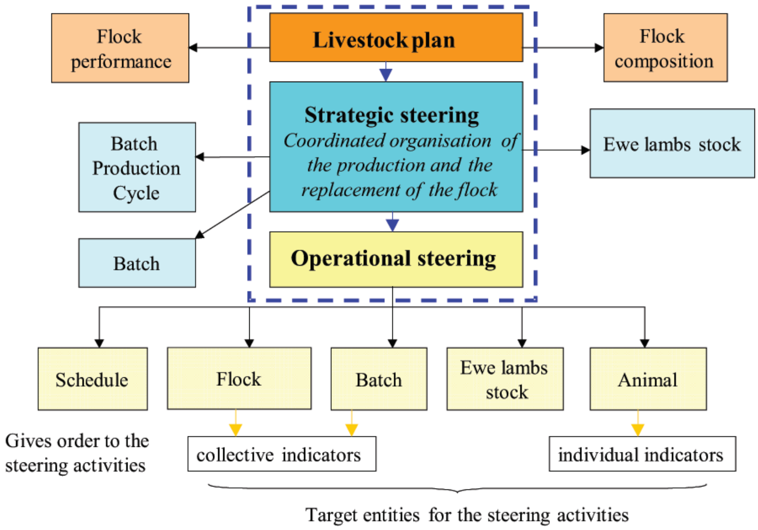


Figure 1. The decisional process.

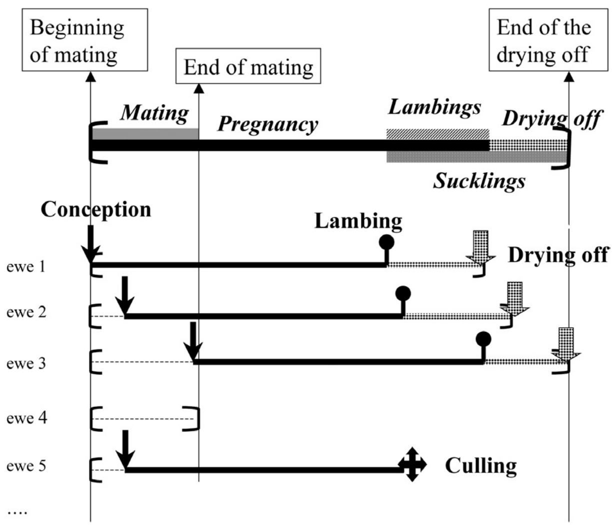


Figure 2. The Batch Production Cycle (BPC).

(dates and duration) and the end of drying off, and determination of the initial composition of the batch of reproductive females. The coordination between BPC refers to the following:

(i) the organisation of the linkage of successive BPC of a same batch (how to ensure that the ewes lamb approximately every 8 months). This will be translated by the allocation of a particular linkage of BPC to each batch and the definition of deadline dates for the end of drying off (in the 3-in-2, to keep a minimum rest time and apply the sponges to dry ewes).

(ii) the way in which the movement of infertile ewes from one batch to another is

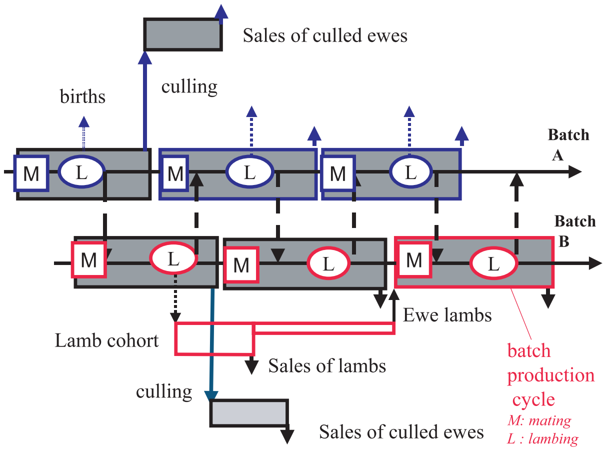


Figure 3. Production organization: configuration and coordination of Batch Production Cycles (BPC).

organised (how to manage the rapid recycling of infertile ewes). In the case of the 3-in-2 management system, limiting the length of the unproductive period of ewes that failed at mating, involves entering these in the following BPC, which concerns the other batch (via repeated mating and/or changes of batch when infertility is noted). Characterising the production organisation is therefore based on a dynamic and functional meaning of *a batch*: it is a replaced set of animals (by introduction of female lambs and disappearance of ewes) for which a particular batch production cycle linkage is organised.

3.2. Formalisation of the biotechnical sub–system: the animal

The ewe contributes as an elementary unit in the construction of the performance and evolution of the flock. It acts by its biological responses and its productive trajectory. The biological response is defined as the components of the ability of a ewe to react to stimuli induced by management, taking into account the random nature of the biological processes [14, 38, 39] and the other components of the farming environment (e.g., types of feed resources, movements, season). With our modelling specifications, four components of the biological responses are considered: (i) the ability to be fertilised during a mating session (fertility); (ii) the fecundation date and thus the lambing date; (iii) the number of lambs born alive at lambing; (iv) the ability not to be culled for involuntary reasons, health problems or death (functional longevity). The biological phenomena responsible for these components undergo the influence of factors linked to the environment and factors associated with the animals including the productive trajectory of the ewe. Fertility, date of fecundation and number of lambs born depend on well-known factors affecting the reproduction of ewes (i.e., mating season [40] and parity [26]). The modalities of chronological linking of production events are not neutral on these criteria, particularly in intensive reproduction systems [25, 29, 37]. Involuntary culling and longevity criteria are explored to a lesser extent for sheep than for dairy cows (see [13]).

The *productive trajectory* of a ewe is a formalisation of (i) the succession of production events of the ewe, (ii) the path followed by this ewe through successive batch production cycles. The productive trajectory, with its two components, conditions the biological responses of the ewe and also intervenes as information for management. In reproduction management such as the

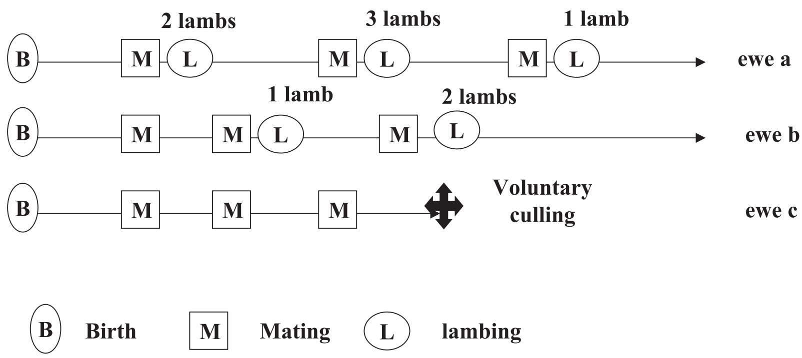


Figure 4. Building the diversity of the productive trajectories of the ewes.

Table I. Statistical modelling of the animal biological responses.

Model	Biological response	Random variable	Explanatory variables
Markov Chain	Success at exposure	Y 0: failure 1: success	Session Ewe lamb vs. adult Parity Last mating result
Multinomial model	Fortnight of conception Number of live-born lambs	Ft: 1, 2, 3 ou 4 N: 1, 2 ou 3	Session Ewe lamb vs. adult Last mating result
Stratified Cox model	Risk of involuntary culling	h: 0 to 1	Session Age Time passed by since the last lambing

3-in-2 system, the diversity of productive trajectories is very important as shown in Figure 4 for ewes belonging to the same birth cohort. The model identifies as many animal objects as there are ewes, and constructs a productive trajectory for each of them.

The general approach adopted for each of the components of the biological responses was:

– To identify the random variables brought into play.

– To study the factors affecting these variables whether they are associated with the animal or with the environment, combining these over time. With the available data, the individual effect of each of the factors could not be identified, but the effect of combinations of individual factors to each reproduction period can be shown. We defined the *reproduction session* as a particular combination of factors linked with sexual season, mating conditions and time interval between two BPC. For example, in the INRA flock, the January session covers an unfavourable sexual season, combined with the shortest interval between the late drying off of the batch and the start of the next mating. In addition, the ewe lambs are presented to the rams at 10 months of age (as against

12 months in the June session). All the biological components are influenced by the *reproduction session* factor combined with elements relative to the productive trajectory of the ewe (i.e., age and parity, chain of the latest productive events, result of the last mating, time since the last lambing).

– To model the distribution law for these variables.

The main statistical analyses are summarised in Table I and detailed in Appendix 1. The probability distribution laws are included in the parameter setting of the model, and used by the pseudo-random number generation mechanisms activated by events (Appendix 2). These events are those that determine the biological response of each ewe.

3.3. The discrete events simulation technique and simulator implementation

The discrete events simulation (DES) technique offers a representation framework of the flock system that is flexible enough to take into account the complexity of interactions between management and the animals. A DES corresponds to a conceptualisation of the system based on the discrete organisation of time and the notion of an event being a modification of the state of a system [7, 9]. It is translated by the description in algorithmic form of the occurrences of events as well as the precise nature of changes of variables of state associated with the events. Between the two events, the state of the system does not change and virtual time does not pass by during an action accompanying or characterising a change of state. The flexibility of the DES technique is appropriate for modelling of complex systems. It proved to be appropriate to our dynamic representation of the flock system, in which control activities are planned, modifying the state of various target entities and leading to animal biological responses, which are expressed by the occurrence of production events. Particularly, DES accounts for hazards in animal responses and respects the diversity of conditionings particular to each individual (i.e., influence of history, moment and relation to management decisions). It is thus very easy to take into account additional events, entities or conditioning.

We used the object analysis to describe the conceptual model. Figure 5 gives an overview of the major relations between the objects that were identified. We implemented the simulator using the Visual Basic (®) language. Although not really object oriented, it can easily be learned and offers useful procedures for rapid development. Figure 6 shows the scheduler management of the TUTOVIN simulator. It orders and activates events that modify object variables of the model, or add new events to the scheduler. In the virtual calendar, the time scale is the day. Involuntary culling events (ID) occur every fortnight by putting all animals under risk of culling. Every 1st of January marks the annual planning event (AP), which defines all the production cycle dates for the year, including coordination modalities of BPC, and an anniversary event (Ann) that accounts for the aging of the ewes. With this planning event, all steering activities can be scheduled (i.e., beginning of mating (BM), end of mating (EM), change of batch for infertile ewes (CB), culling and replacement event (CR)). Depending on the biological response of the animals, individual events may occur (e.g., conception (eF), lambing (eL) and drying off (DOe)). Appendix 3 details the series of management and biological events.

3.4. Validation and analysis of the results

3.4.1. Validation process

The validation of the model was carried out in two stages. The first corresponded to the confrontation with real data (the INRA flock) and will not be presented here. It showed the capacity of the simulator to reconstruct the functioning and the performances observed on the real flock. The

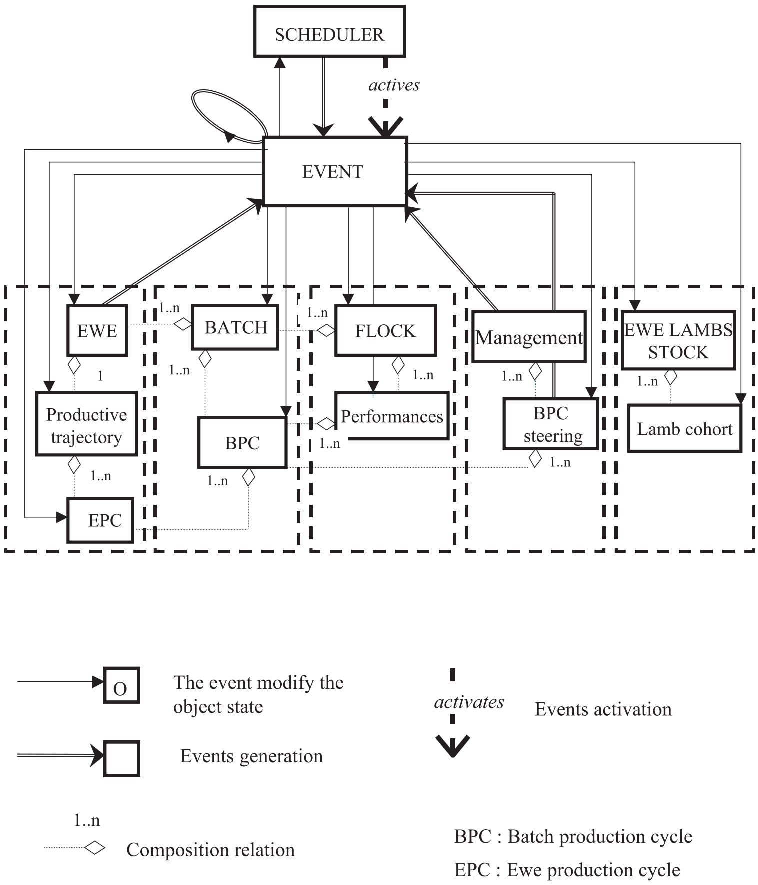


Figure 5. The conceptual model of the "flock system".

second stage concerned the so-called functional validation [3, 9], which is appropriate when other equivalent data are not easily available (which is presently the case) or when working on a random sample of the initial data is not possible. In that case, the system cannot be reduced to a collection of independent animals. Functional validation corresponds to the use of the simulator as a measurement instrument to check its correct functioning and to test the influence of parameter changes [4].

A plan of 50 computer experiments was designed that respected the principles of the 3-in-2 system. An experiment simulates the evolution of the flock system with the same initial state, but with differences on fertility parameters and/or management rules (e.g., culling, replacement, duration of mating period, identification of infertile animals) (Tab. II). The reference management is that of the INRA flock. In all cases, the initial state of the system is that of this at 1st January 1975 (399 ewes, 64 ewe lambs), the number of replications is 15 and the duration of simulation is 20 or 40 years depending on the duration of the stabilisation phase of the system. The results were analysed according to a precise grid including the study of the stabilisation phase of the system (not detailed here) and the stability

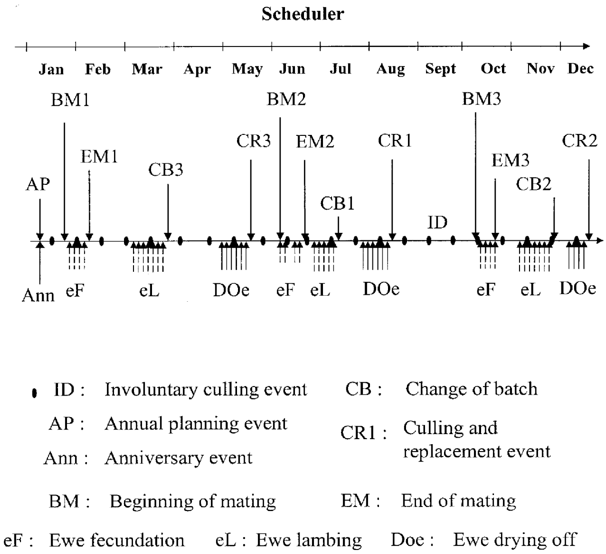


Figure 6. The management of the simulator scheduler and the sequence of flock management and biological events.

phase. The flock system functioning in a stable state is described on the basis of an average year, represented by the mean of the last ten years of simulation. The analysis grid combines a cross analysis interested in annual performance and flock replacement and a longitudinal analysis relative to the diversity of ewe lifetime production, and the description of animal flows between BPC (see below).

3.4.2. Analysing the results of simulations: the regulation mechanisms in the flock system

In most experiments, the flock system demonstrated an aptitude for rapidly installing a new balance that tended, in terms of annual production, to approach that of the reference system but with a wide range of lambing season contributions. Significant

Table II. Plan of experiments: type of change in rules and biological parameters.

Management rules	Biological parameters	Example	Number of experiments
Ewe lambs recruitment		One period recruitment	5
Culling for infertility		Culling at first mating failure	5
Culling for age		Age limit = 7 years	9
Coordination of BPC		Use of ultrasound scanning	3
Configuration of BPC		Length of mating period = 15 days	4
Two rule modifications		No repeat mating except for autumn session and replacement done for each batch separately	6
	Fertility	–17% drop in fertility	2
Culling rules	Fertility	–17% drop in fertility and culling at second failure	17

Table III. Main significant differences in productivity.

	INRA flock* Experiment No. 1	Bad fertility** Experiment No. 34	Without "repeat" mating Experiment No. 22	Culling at first mating failure Experiment No. 8	Use of ultrasound scanning Experiment No. 21
Number of lambings per ewe and per year	1.32 (0.011)	1.14 (0.011)	1.25 (0.011)	1.29 (0.009)	1.35 (0.009)
Number of live-born lambs per ewe and per year	2.16 (0.021)	1.87 (0.024)	2.03 (0.019)	2.06 (0.021)	2.21 (0.018)

Means and standard errors over 15 replications;
* Simulation with the rules and biological parameters from the INRA flock;
** Simulation with: 60%, 50% and 80% of fertility for January, June and October mating (which corresponds to an average –17% drop in fertility);
All these simulations present significant differences ($P < 0.05$) from the reference simulation INRA flock.

drops in the production level (Tab. III) were obtained when the individual fertility performances were considerably reduced, when the 3-in-2 management rules were much distorted, and when very severe rules of voluntary culling were imposed. On the contrary, the use of ultrasound scanning technique authorised better results than the reference.

The simulator makes intelligible the complex regulation mechanisms that are operating. These regulations result from interactions between biological processes and the farmer's decisions at different time scales (i.e., farming year, several farming years, ewe lifetime productive traits) and different organisation levels (i.e., animal, batch, flock). Figure 7 illustrates these regulations referring to the longitudinal and BPC flow analysis, with the comparison of two experiments: a bad fertility system with respectively, 60%, 50% and 80% of fertility for January, June and October matings (experiment 34) and the use of ultrasound scanning (experiment 21). Experiment 21 had better annual production results than experiment 34 (mean of 844 live-born lambs vs. 722). They also had a quite different spread of births within the three lambing sessions. For experiment 34, the proportion of lambing was respectively 48, 23 and 29% for the March, June and November lambing sessions. The fertility at January and June mating seasons was low. This led to a very big flow of infertile ewes (with one or two mating failures) to the October mating season, and so to a big number of ewes presented to the rams (mean: 276) during this favourable sexual season. The use of scanning to detect infertile ewes was associated with another distribution of lambings, respectively 38, 38 and 34% for March, June and November lambing sessions. The flows of ewes between BPC were here quite different from the previous case. With scanning, all the infertile ewes changed batch quite early and benefited from hormone treatments prior to mating. Thus, ewes that were systematically synchronised had better fertility performances at every out-of-season mating session, with reduced flows from one BPC to another. Scanning and synchronisation improved the productivity of the start of productive lifetimes, the most sensitive to infertility problems, and reduced the number of trajectories terminated rapidly by the culling of young ewes, whilst the reverse phenomenon was observed in the bad fertility experiment (Fig. 8). It implicated two different levels of replacement (16% experiment 21 vs. 19% experiment 34).

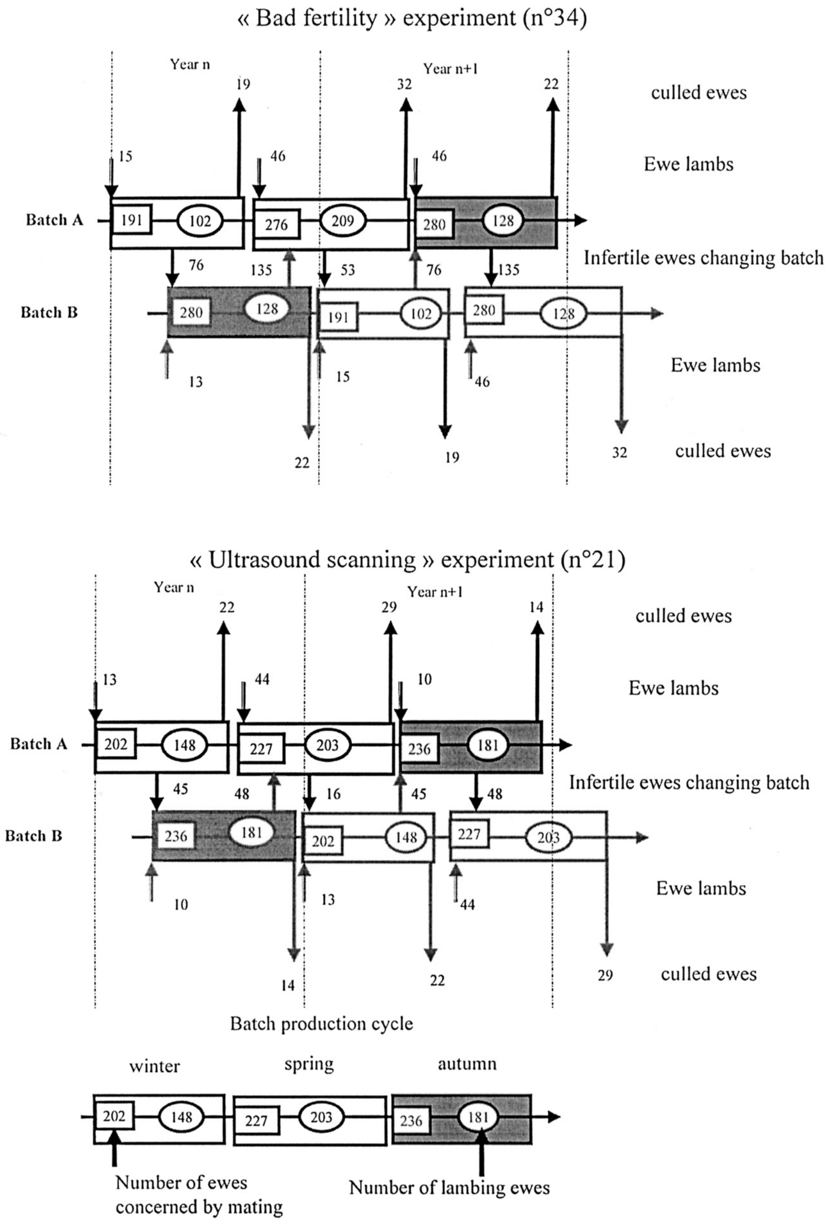


Figure 7. The animal flows between batch breeding cycles: comparison of two experiments.

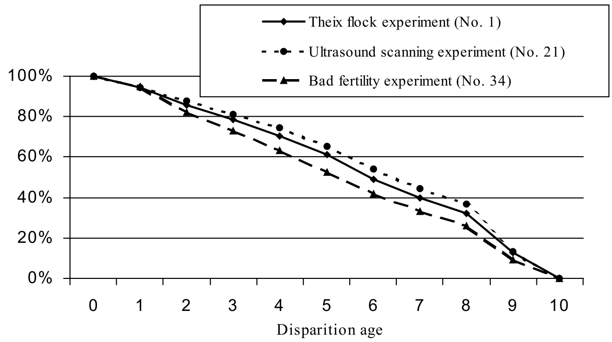


Figure 8. Survivor curves.

4. DISCUSSION – CONCLUSION

The formalisation of the flock system and its dynamic functioning was carried out by considering complex characteristics of the 3-in-2 system, which involves consideration of the batch production cycle (i.e., the management entity of the mating and lambing sessions) and the productive trajectory of the ewes. Modelling of sheep systems that have only one lambing period for the whole flock do not demand such notions since all animals are managed the same way in a single batch and all trajectories of the ewes are similar: the ewes lamb each year at the same period; if not, they are culled. These simple uniform management systems have been observed in large grassland flocks in the Centre of France [12] and are also well referenced in the Anglo-Saxon bibliography [26, 32]. Other management systems are developing at the instigation of the market chain, with several lambing periods in the year. These management systems involve less rigid and uniform management of infertility, which generates diversified productive trajectories and batch production cycle coordination. Taking account of these systems requires consideration of the following:

– temporal and calendar processes. It is notably the calendar that makes it possible to fix production distribution challenges and consistency in linking practices. It also plays a fundamental biological role considering the sensitivity of the ovine species to seasonal anoestrus.
– complex flows of information, coming either from instantaneous performance or medium term productive trajectories of the individual animals, or batches or flock.

Considering the herd as a dynamic and steered system, with interaction between management and animals has two consequences. Firstly, management and practices have no top – down effect on biological responses and herd production, which is mainly the general background of the herd dynamics models [24]. Secondly, it is possible to study the regulation properties of the system [36]. In our case, the study of the animal flows between BPC [5, 19] and the diversity of productive trajectories [31] constitutes two complementary trials for the analysis of different flock managements which are accessible with the simulator. They open up to new qualifications of farming systems, beyond the criteria of technical efficiency, and taking account of the flexibility properties of information systems and flock management decisions.

The TUTOVIN discrete events simulator is more an explanatory research model, than a decision support tool for farmers. Nevertheless, it refers to an explicit representation framework of the management process (livestock project; strategic and operational steering) that makes it possible to take finalised sets of rules into account, associated with simple and sophisticated managements, based on little or much information and bringing into play collectives of animals as well as individuals. It is probably this representation framework of decisions coming from management sciences, which most distinguishes our conceptualisation from herd models available in the literature. The entities of flock production management are neither the individual of stochastic models [33] nor the animal production categories of estimation of biological parameters of Markovian models, but batches to be replaced, productive trajectories to be questioned, production cycles to be coordinated. This representation framework is presently integrated into beef cattle herd dynamics modelling [22] and is being used to test the functioning of dairy herds.

ACKNOWLEDGMENTS

Thanks to M. Theriez, A. Brelurut, J.B. Teuma, C. Espinasse and M. Dacheux for their contribution to the work.

REFERENCES

[1] Allain S., Approche cognitive du pilotage stratégique de l'entreprise agricole, Eco. Rur. 250 (1999) 21–30.

[2] Aubry C., Une modélisation de la gestion de production dans l'exploitation agricole, R. Fr. Gestion 129 (2000) 32–45.

[3] Balci O., Verification, Validation and Testing, in: Banks J. (Ed.), Handbook of simulation, Principles, Methodology, Advances, Application and Practice, Engineering & Management Press, 1998, pp. 335–395.

[4] Banks J., Principles of simulation, in: Banks J. (Ed.), Handbook of simulation, Principles, Methodology, Advances, Application and Practice, Engineering & Management Press, 1998, pp. 3–30.

[5] Benoit M., Un outil de simulation du fonctionnement du troupeau ovin et de ses résultats économiques : une aide pour l'adaptation à des contextes nouveaux, INRA Prod. Anim. 11 (1998) 349–362

[6] Benoit M., Laignel G., Liénard G., Facteurs techniques, cohérence de fonctionnement et rentabilité en élevage ovin allaitant. Exemples du Massif Central Nord et du Montmorillonnais, Renc. Rech. Rum. 6 (1999) 19–22.

[7] Blasco F., Weill A., Advances in Environmental and Ecological Modelling, Elsevier, 1999, 230 p.

[8] Coleno F.C., Duru M., A model to find and test decision rules for turnout date and grazing area allocation for a dairy cow system in spring, Agric. Syst. 61 (1999) 151–164.

[9] Coquillard P., Hill D.R.C., Modélisation et simulation d'écosystèmes, Eds. Masson, 1997, 273 p.

[10] Coulon J.B., Pérochon L., Lescouret F., Évolution de la production laitière et du poids vif des vaches laitières au cours de leur carrière, Ann. Zootech. 44 (1995) 189–199.

[11] Cournut S., Le fonctionnement des systèmes biologiques pilotés : simulation à événements discrets d'un troupeau ovin conduit en trois agnelages en deux ans, Thèse, Université Claude Bernard – Lyon I, ENITAC, INRA SAD-URH, 2001, 418 p. + annexes.

[12] Dedieu B., Chabosseau J.M., Benoit M., Laignel G., L'élevage ovin extensif du Montmorillonnais entre recherche d'autonomie, exigences des filières et simplicité de conduite, INRA Prod. Anim. 10 (1997) 207–218.

[13] Ducrocq V., Statistical analysis of length of productive life for dairy cows of the Normande breed, J. Dairy Sci. 77 (1994) 855–866.

[14] Ducrot C., Legay J.M, Grohn Y.T, Enevoldsen C., Calavas D., Approach to complexity in veterinary epidemiology: example of cattle reproduction, Nat. Sci. Soc. 4 (1996) 23–33.

[15] Ercanbrack S.K., Knight A.D., Lifetime production of ¼ et ½ Finnsheep ewes from Rambouillet, Targhee and Columbia dams, affected by natural attrition, J. Anim. Sci. 67 (1989) 3258–3265.

[16] Frasier W.M., Pfeiffer G.H., Optimal replacement and management policies for beef cows, Am. J. Agric. Econ. 76 (1994) 847–858.

[17] Gibon A., Rubino R., Sibbald A.R., Sorensen J.T., Flamant J.C., Lhoste P., Revilla R., A review of current approaches to livestock farming systems in Europe: towards a common understanding, in: Dent J.B., McGregor F., Sibbald A. (Eds.), Livestock farming systems: research, development, socio-economics and the land manager, EAAP Publication No. 79, 1996, pp. 7–19.

[18] Girard N., Hubert B., Modelling expert knowledge with knowledge based systems to design decision aids. The example of a knowledge based model on grazing management, Agric. Syst. 59 (1999) 123–144.

[19] Girard N., Lasseur J., Stratégies d'élevage et maîtrise de la répartition temporelle de la production ovine, Cah. Agric. 6 (1997) 115–124.

[20] Hemidy L., Maxime F., Soler L.G., Instrumentation et pilotage stratégique dans l'entreprise agricole, Cah. Eco. Socio. Rur. 28 (1993) 91–118.

[21] Ingrand S., Dedieu B., An approach of grouping management practices as a contribution to the study of livestock farming systems, in: Dent J.B., Mc Gregor M.J., Sibbald A.R. (Eds.), Livestock farming systems: research, development socio-economics and the land manager, EAAP Publication No. 79, 1996, pp. 353–356.

[22] Ingrand S, Cournut S., Dedieu B., Antheaume F., La conduite de la reproduction du troupeau de vaches allaitantes : approche modélisatrice des prises de décision, INRA Prod. Anim. 16 (2003) 263–270.

[23] Keating B.A., McCown R.L., Advances in farming systems analysis and intervention, Agric. Syst. 70 (2001) 555–579.

[24] Kristensen A.R., Jørgensen E., Multi-level hierarchic Markov processes as a framework for herd management support, Ann. Oper. Res. 94 (2000) 69–89.

[25] Lasseur J., Landais E., Mieux valoriser l'information contenue dans les carnets d'agnelage pour évaluer des performances et des carrières de reproduction en élevage ovin-viande, INRA Prod. Anim. 5 (1992) 43–58.

[26] Lee G.J., Atkins K.D., Prediction of lifetime reproductive performance of Australian Merino ewes from reproductive performance in early life, Aust. J. Exp. Agric. 36 (1996) 123–128.

[27] Lehenbauer T.W., Oltjen J.W., Dairy cow culling strategies: making economical culling decisions, J. Dairy Sci. 81(1998) 264–271.

[28] Lesnoff M., Étude de la dynamique et de la productivité des populations domestiques tropicales par des modèles matriciels en temps discret : les populations d'ovins au Sénégal, Thèse, Université de Montpellier II, France, 2000, 294 p.

[29] Lewis R.M., Notter D.R., Hogue D.E., Magee B.H., Ewe fertility in the Star Accelerated Lambing System, J. Anim. Sci. 74 (1996) 1511–1522.

[30] Marzin J., Brelurut A., Performances comparées des brebis limousines et croisées Romanov en conduite relativement intensive, Bull. Tech. CRZV Theix 37 (1979) 15–23.

[31] Moulin C.H., Le concept de fonctionnement de troupeau. Diversité des pratiques et variabilité des performances animales dans un système agropastoral sahélien, INRA Et. Rech. Syst. Agr. Dév. 27 (1993) 73–94.

[32] Nugent R.A., Jenkins T.G., Effects of alternative lamb production systems, maternal line, and culling strategy on flock age structure, J. Anim. Sci. 70 (1992) 2285–2295.

[33] Oltenacu P.A., Milligan R.A., Rounsaville T.R., Foote R.H., Modelling reproduction in a herd of dairy cattle, Agric. Syst. 5 (1980) 193–205.

[34] Oltjen J.W., Selk G.E., Burditt L.G., Plant R.E., Integrated expert system for culling management of beef cows, Comput. Electron. Agric. 4 (1990) 333–341.

[35] Ostergaard S., Sorensen J.T., Kristensen A.R., A stochastic model simulating the feeding-health-production complex in a dairy herd, J. Dairy Sci. 83 (2000) 721–733.

[36] Santucci P.M., Le troupeau et ses propriétés régulatrices, bases de l'élevage caprin extensif, Thèse, Université de Montpellier, France, 1991, 85 p.

[37] Shoeman S.J., Albertyn J.R., Lifetime reproduction of Karakul ewes as influenced by season of birth, age at first lambing, and lambing interval, South Afr. J. Anim. Sci. 21 (1991) 169–172.

[38] Sorensen J.T., Kristensen E.S., Thysen I., A stochastic model simulating the dairy herd on a PC, Agric. Syst. 39 (1992) 177–200.

[39] Stott A.W., Stochastic dynamic programming as a framework for decision support in dairy farming, in: Dent J.B., McGregor F., Sibbald A. (Eds.) Livestock farming systems: research, development socio-economics and the land manager. EAAP Publication No. 79, 1996, pp. 315–332.

[40] Thimonier J, Pelletier J., Ortavant R., Photopériodisme et reproduction : bases physiologiques, IXe J.R.O.C, 1984, pp. 62–78.

Appendix 1. Bio-technical models for the biological events activation in the simulator.

A. Fertility

Markov transition matrix

initial state	final state				initial state	final state			
	if failure		if success			if failure		if success	
	description	P	description	P		description	P	description	P
p0s1	p0s12	0.19	p1s13	0.81	p3s13	p3s31	0.04	p4s32	0.96
p0s2	p0s23	0.17	p1s21	0.83	p3s32	p3s23	0.23	p4s21	0.77
p0s3	p0s31	0.07	p1s32	0.93	p3s21	p3s12	0.14	p4s13	0.86
p0s12	p0s23	0.65	p1s21	0.35	p4s12	p4s23	0.46	p5s21	0.54
p0s23	p0s31	0.21	p1s32	0.79	p4s23	p4s31	0.21	p5s32	0.79
p0s31	p0s12	0.67	p1s13	0.33	p4s31	p4s12	0.44	p5s13	0.56
p1s12	p1s23	0.46	p2s21	0.54	p4s13	p4s31	0.04	p5s32	0.96
p1s21	p1s12	0.14	p2s13	0.86	p4s32	p4s23	0.23	p5s21	0.77
p1s23	p1s31	0.21	p2s32	0.79	p4s21	p4s12	0.22	p5s13	0.78
p1s31	p1s12	0.44	p2s13	0.56	p5s12	p5s23	0.46	p6s21	0.54
p1s13	p1s31	0.04	p2s32	0.96	p5s23	p5s31	0.21	p6s32	0.79
p1s32	p1s23	0.13	p2s21	0.87	p5s31	p5s12	0.44	p6s13	0.56
p2s12	p2s23	0.46	p3s21	0.54	p5s13	p5s31	0.04	p6s32	0.96
p2s23	p2s31	0.21	p3s32	0.79	p5s32	p5s23	0.23	p6s21	0.77
p2s31	p2s12	0.44	p3s13	0.56	p5s21	p5s12	0.22	p6s13	0.78
p2s13	p2s31	0.04	p3s32	0.96	p6s12	p6s23	0.46	p6s21	0.54
p2s32	p2s23	0.13	p3s21	0.87	p6s23	p6s31	0.21	p6s32	0.79
p2s21	p2s12	0.14	p3s13	0.86	p6s31	p6s12	0.44	p6s13	0.56
p3s12	p3s23	0.46	p4s21	0.54	p6s13	p6s31	0.15	p6s32	0.85
p3s23	p3s31	0.21	p4s32	0.79	p6s32	p6s23	0.32	p6s21	0.68
p3s31	p3s12	0.44	p4s13	0.56	p6s21	p6s12	0.22	p6s13	0.78

The discrete state-space is defined with two variables: parity and series of last mating sessions. From each of the 42 states, only two transitions are possible: the first one corresponds to a mating failure and the second one to a success.

State description: pisjk.

pi: parity i in [0,6], 6 involves 6 and more parities,

sjk last mating sessions succession; j and k id. of mating session (winter: 1, spring: 2 and autumn: 3).

Example: the state p2 s12 corresponds to parity 2 ewes (p2) which failed at the winter mating session (id. = 1), and are mated again during the spring session (id. = 2).

p0s1 represents the case of ewe lambs born in the winter and mated for the first time during the winter session.

B. Fecundation date

This fecundation date determines the lambing date with a constant duration of pregnancy (145 days). Affecting a fecundation date to a ewe is based on 3 steps:

(1) determining in which fortnight after the beginning of mating the fecundation occurs (Ft);

(2) determining whether a late abortion occurs (Av);

(3) determining at which day within the fortnight the fecundation occurs (D).

Each step corresponds to a random variable (V), from which we modelled the probability distribution L(V).

(1) Determining which fortnight (Ft) after the date of the ram introduction. (Ft = 1 to 4). The model selected for L(Ft) is multinomial. Estimation on our data give the following values, depending on the mating session, the last mating result and the status of the animal (ewe lamb vs. adult):

Mating session	Ewe lamb vs. adult	Last mating result	Ft = 1	Ft = 2	Ft = 3	Ft = 4
Winter	Ewe lamb		0.84	0.12	0.04	0.00
Winter	Adult	success	0.39	0.42	0.13	0.06
Winter	Adult	failure	0.39	0.41	0.20	0.00
Spring	Ewe lamb		0.71	0.13	0.13	0.03
Spring	Adult	success	0.78	0.14	0.06	0.03
Spring	Adult	failure	0.11	0.19	0.58	0.11
Autumn	Ewe lamb		0.70	0.21	0.08	0.00
Autumn	Adult	success	0.72	0.24	0.03	0.00
Autumn	Adult	failure	0.32	0.56	0.12	0.00

(2) Late abortion (Av). This variable is assumed to be binomial with $P = 0.007$. If the result is yes, then the lambing date is assumed to be 10 days before the first day of the Ft fortnight of lambing.

(3) Which day within the fortnight (D: 1 to 14) when no late abortion (Av = 0). The cumulative frequency distribution of D knowing Ft, was approached by polynomial functions. When no structure appears (last case No. 5) in the distribution, the uniform law is assumed. $f_i(d)$ gives the probability estimation of $(D <= d)$.

No.	Fortnight Ft	Mating session	Ewe lamb vs. adult	Last mating result	Model
1	1		Ewe lamb		$f_1(d) = 0.314713 + 0.077224\,d - 0.002037\,d^2$
2	1	Winter	Adults	success	$f_2(d) = 0.020002 + 0.208289\,d - 0.014602\,d^2 + 0.000333\,d^3$
3	1	Spring and autumn	Adults	success	$f_3(d) = -0.034995 + 0.12864\,d - 0.003827\,d^2$
4	2		Adults	success	$f_4(d) = 0.005359 - 0.002072\,d + 0.01545\,d^2 - 0.000735\,d^3$
5	Other cases				$f_5(d) = 0.071428571\,d$

C. Number of lambs born alive

The number of lambs born alive is assumed to be a discrete random variable N with 3 possible values: 1, 2 or 3. Bigger values, quite rare, were gathered with value 3. The model selected for *L*(N) is multinomial. Estimation on our data gives the following values, depending on the mating session and the parity of the ewe.

Mating session	Parity	N = 1	N = 2	N = 3
Winter	1	0.66	0.29	0.05
Winter	2	0.73	0.22	0.05
Winter	3 to 5	0.60	0.36	0.04
Winter	More than 5	0.53	0.42	0.05
Spring	1	0.60	0.34	0.06
Spring	2	0.48	0.45	0.08
Spring	3 to 5	0.42	0.47	0.11
Spring	More than 5	0.47	0.43	0.09
Autumn	1	0.52	0.42	0.06
Autumn	2	0.36	0.55	0.09
Autumn	3 to 5	0.27	0.64	0.09
Autumn	More than 5	0.26	0.60	0.14

D. Functional longevity

The functional longevity represents the ability not to be culled for involuntary reasons.

For adults, the risk of being culled for involuntary reasons is modelled with a stratified Cox model in which the length of life variable is the duration of life after lambing expressed in fortnights. The only explanatory variable selected is the age at lambing. The strata correspond to the 3 lambing sessions:

$$h(t; a, s) = h_{0,s}(t) \exp(a\beta)$$

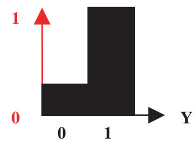
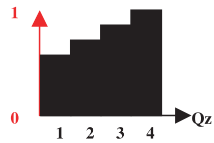
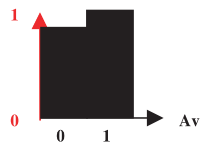
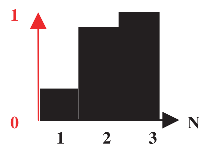
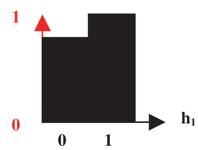
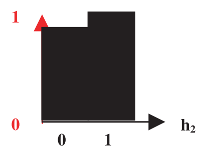
a is the age of the ewe (5 classes), h_0 the baseline hazard function for each lambing session, β is a multiplicative coefficient. The baseline hazard function is given in the following tables, as well as the value of exp (a β) for each age class.

Age at lambing	exp (**a** β)
1 year	0.5014
2 years	0.4096
3 years	0.4648
4 years	0.4395
5 years and more	1

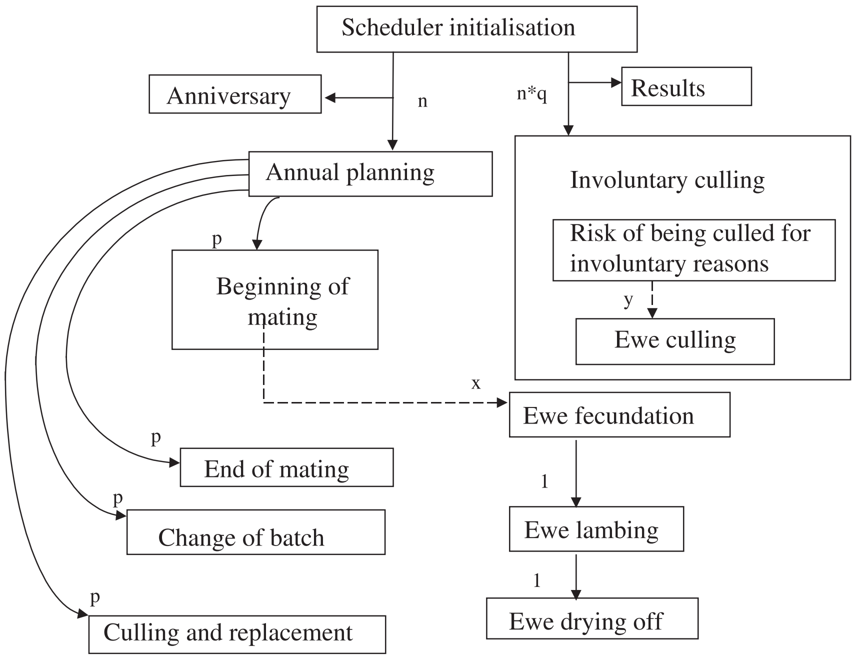
Number of fortnights since last lambing	Baseline hazard function		
	Winter lambings	Spring lambings	Autumn lambings
1	0.0181	0.0115	0.0308
2	0.0051	0.0073	0.0095
3	0.0082	0.0029	0.0166
4	0.0062	0.0059	0.007
5	0.017	0.0118	0.0028
6	0.0316	0.0091	0.0029
7	0.0101	0.0106	0.003
8	0.008	0.0062	0.0044
9	0.00175	0.0015	0.0074
10	0.00175	0.0063	0.0074
11	0.0012	0.0047	0.003
12	0.0035	0.004	0.0044
13	0.0024	0.004	0.0015
14	0.0011	0.0081	0.009
15	0.0048	0.0065	0.0107
16	0.0071	0.005	0.005
17	0.0049	0.0017	0.0098
18	0.0028	0.0077	0.0072
19	0.0042	0.00425	0.0033
20	0.007	0.00425	0.0033

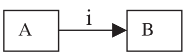
For ewe lambs, we considered that the risk of being culled for involuntary reasons during the next 14 days is constant and equal to 0.0005; except during the last month of pregnancy where it becomes 0.002.

Appendix 2. The use of the variable distributions in the simulator.

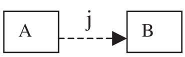
Random variable	Name	Activating event and preliminary conditions	Distribution used for the random draw
Y 0: no 1: yes	Fertility	Beginning of the mating	
Qz 1 à 4	Fortnight of lambing	Beginning of the mating If **Y** = 1	
Av 0: no 1: yes	Abortion	Beginning of the mating If **Y** = 1	
D 1 à 14	Day in the fortnight	Beginning of the mating If **Y** = 1 and **Av** = 0	
N 1 à 3	Number of lambs born alive	Ewe lambing if **Av** = 0	
h_1 0: survival 1: culling in the next 14 days	Involuntary culling in the next 14 days for adults	Involuntary culling	
h_2 0: survival 1: culling in the next 14 days	Involuntary culling in the next 14 days for ewe lambs	Involuntary culling	

Appendix 3. The series of the events in the simulator.





The « A event » generates **i** « B events ».



The **j** number of « B events » generated by « A event » depends on biological responses (see Appendix 1).

n: number of simulated years;

p: number of lambing sessions;

q: number of fortnights in a year.