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MODELLING ANIMAL SYSTEMS PAPER

Simulation of sow herd dynamics with emphasis on performance and distribution of periodic task events

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SUMMARY

Currently, the diversity of sow herd management strategies has been described but there are no tools that explore how it promotes sow herd performance nor how it or performance are linked to work organization problems. The goal of the current study was to build a herd dynamic, stochastic object-oriented model capable of representing the herd dynamics and performance, and to predict the number of events workers will have to deal with. Each sow is individually represented in the model and the model works as a discrete event simulator with a predefined time step of 1 h. At each time step of simulation, the model searches for an event to be processed. An event may imply change of sow physiological state (e.g. oestrus, farrowing and insemination) and/or request an action from a worker (e.g. oestrous detection and farrowing supervision). This action may result in the planning of a new event (e.g. farrowing after mating) and/or modification of sow state (e.g. from oestrus to pregnant). The occurrences of some technical activities such as weaning are defined in time and frequency according to the management strategy of the farmer. The model is stochastic as sow biology is represented by several normal univariate distributions according to parity or by a threshold (fertility, abortion and mortality rates). When sows return into oestrus after mating they can be moved to another batch or culled depending on batch management strategy and culling policy. Outputs of this model focus on productivity of sows and distribution of tasks over the week. Definitions of the duration of simulation and number of replications to obtain the steady state and the variability of results are presented. The model is able to simulate several batch farrowing systems (BFS) and results of 1-, 3- and 4-week BFS are presented. Several simulations with modified management (no oestrous detection during the weekend and change of the weaning day) or with modified sow biology (increased variability of the weaning-to-oestrus interval and lower fertility rate) are performed. Results indicate that these modifications have specific consequences on performance and task distribution according to the BFS. The model provides useful information concerning the effects of herd management strategies on productivity and distribution of events over time and their sensitivity to biological criteria.

INTRODUCTION

The number of pig farms has dropped regularly during the last 30 years throughout the world whereas the sow population has increased. For instance, in France, the average number of sows per pig unit with more than 20 sows increased from 73·2 in 1990 to 156·3 in 2005. At the same time, the number of annual work units (AWU) (one AWU is defined as 1800 h of work per annum) increased from 2·23 to 2·63 per farm (E. Ilari, IFIP, France, personal communication). This resulted in an increase in labour productivity expressed as number of sows per AWU which emphasizes the work organization issue. Moreover, these transformations were accompanied by a reduction in the agricultural family workforce due to wage-earning and with the changes on work

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perception by farm owners. Farm workers are today looking for free weekends that they can spend with families as with other professions (Barthez 1986; Jean *et al*. 1988; Guillaumin *et al*. 2004). All these developments together have two main consequences on herd management. Firstly, pig producers organize their work in batches: the batch farrowing systems (BFS) that are characterized by the frequency of the periodic tasks which determines the number of batches in the herd. In the BFS, the main periodic tasks that farmers have to carry out on batches consist in detection of oestrus and insemination, supervision of farrowing and weaning. In the commonly called 1-week BFS, the same periodic task returns each week whereas in the 3-week BFS, the task is performed every 3 weeks. The BFS also modifies the possibility of managing infertile sows. Whereas in the 1- and 3-week BFS, sows that 'repeat' (i.e. that have an oestrous behaviour about 21 days after an insemination) fall into a service week and may be transferred to another batch, in the 4- and 5-week BFS, these sows are often culled because they cannot be moved to the following batch. Secondly, some adaptations aim at avoiding specific tasks during the weekend, such as oestrous detection or farrowing supervision. Thus, for analysing the herd operation, it is important to consider the distribution of periodic tasks over the weeks and separate the weekend from the five working days. Moreover, these modifications may impact on the overall performance of the herd and the capacity of each BFS to adapt their dynamics to various modifications of herd management rules or sow biology. The current study aims at analysing the dynamics, the productivity and the periodic task event distribution of different BFS as well as their adaptation to modifications of herd management and sow biological parameters. This is a complex question due to experimental difficulties in modifying the sow biological parameters and to the large time horizon required to evaluate the effect of the herd management. Thus, this requires using the systemic approach to take into account the relationships existing between the elements that comprise the herd and its management and the simulation approach to take into account the effect of time (Durand 2002).

Several sow herd dynamic models have been published since 1980 (for review see Martel *et al*. 2006 and Plà 2007). These models had various purposes but mainly focused on farm productivity such as feeding management (Tess *et al*. 1983; Pettigrew *et al*. 1986; Pomar *et al*. 1991), lactation length (Allen & Stewart 1983), culling and replacement rate (Teffène *et al*. 1986; Pomar *et al*. 1991) and farmer performance on oestrous detection (Jalvingh *et al*. 1992; Jorgensen & Kristensen 1995). However, the batch management of sow herds and the organization of farm work during the week have not been addressed in previous models. In most of them only continuous or weekly BFS were considered and consequently no decision rules for the transfer of sows between batches were needed. Only two models included farmer work (Allen & Stewart 1983; Jorgensen & Kristensen 1995). In one case work was considered as an output (duration of work in relation to the occurrence of events) and in the other as an input only (actions of the '*worker*' were planned). None of these models represented task distribution and density over the week according to the herd management strategy. Batch management is also rarely included in the study of herd dynamics in sheep (Cournut & Dedieu 2004) or in beef cattle (Romera *et al*. 2004), though batch management has been recognized as being very sensitive to workload intensity in herbivorous systems (Dedieu *et al*. 1997; Ingrand *et al*. 2003). Only Cournut & Dedieu (2004) developed a flock dynamic simulator on the basis of the three lambings per 2 years reproduction systems which could be compared to a 10-week BFS in pig production (two batches). The present paper presents a Management and Productivity of Sow Herd (MaProSH) model able to simulate dynamics, productivity and periodic task distribution of different BFS as well as their adaptation to modifications of herd management or changes in sow biological parameters.

MODEL DESCRIPTION

The studied BFS

BFS organize the work and make possible the use of an all-in/all-out management that improves the health status of the herd and thus increases its productivity (Carr 2006). The most common BFS space farrowing batches from 1 to 5 weeks. The week after weaning, sows are inseminated and farrowing occurs about 16 weeks after conception. The most usual lactation lengths in Europe are about 3 or 4 weeks. Thus, the full productive cycle lasts about 20–21 weeks. The number of batches in the herd can be calculated by dividing the cycle length by the time interval between subsequent batches. This number varies in the current study from 4 batches (5-week interval with a lactation of 3 weeks) to 20 or 21 (1-week interval with a lactation of 3 or 4 weeks, respectively). The distribution of the periodic tasks over time differs between BFS. All the periodic tasks occur each week in the 1-week BFS, one different task occurs each week in the 3-week BFS and some weeks are free of any periodic task in the 4- and 5-week BFS. Thus, for each BFS, the farmer can plan on a weekly basis the occurrence of these different tasks. However, it is more difficult to plan the exact day and time when these events will occur, because of the natural variability of animal biology. For the same number of sows in a herd, the number of sows per batch will differ between BFS resulting in different work load distribution within the week. The preferred BFS seems to vary between countries, often in connection with the size of herds. For instance, in North America the 1-week BFS is generally used whereas in France the 3-week BFS is the most common. Moreover, due to the possibility of having some weeks without periodic tasks, the interest for the 4- and 5-week BFS grows worldwide. This led to the choice of the BFS compared in the current paper: 1-, 3- and 4-week BFS.

Herd representation in the MaProSH model

Several specifications for the MaProSH model were formulated: (1) it should reproduce the herd operation with different BFS; (2) it should give an account of the effect of modifications to the scheduling of periodic tasks execution on the herd operation and productivity: and 3) it should give an account of the effect of modifications to a sow biological parameter on the periodic task distribution and on the herd operation and productivity. According to these specifications the model represents several entities (Fig. 1). The principal entity is the *sow*. This entity has different processes (oestrous onset and farrowing) able to simulate the information needed for the reproduction of the animals. During the lactation period *sow* entities are related to several *piglet* entities. The *sows* are assigned to the following pools: *replacement gilts*, *batches* and *culled sows*. All *sows* start as members of the *replacement gilts* pool and move to one *batch* for their first productive cycle. Afterwards during their lifetime they may move to another *batch* depending on their biology, BFS and culling rules. They finish as part of the pool of *culled sows*. All the batches together and the replacement gilt pool compose the *herd* entity. The number of *batch* entities is variable to represent several types of management. The other entity needed to answer to the specifications is the *farmer*. The *farmer* is a manager and makes strategic and tactical decisions. The *farmer* is also able to plan the execution of periodic tasks. As a simplified representation of the farm labour force, the *farmer* carries out tasks on both *sows* and *batches*. A time representation close to a calendar was chosen in order to produce output on the distribution of periodic tasks. The time step for the simulation was chosen in order to be able to represent the biological phenomena and their interaction with the work. A time step of 1 day is sufficient to represent the distribution of events and tasks within the week, but the time step of one hour seems closer to the real management and was chosen. The specifications of the model directed the entities and time representation. The entities representation guided the choice of an object-oriented model whereas the time representation guided the choice of a discrete-event simulation controlled by a clock. The

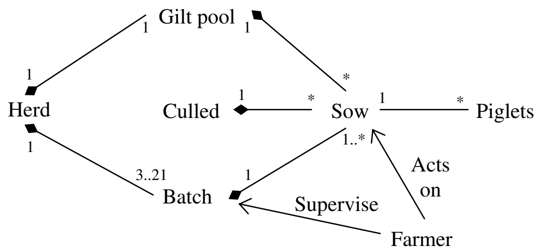

Fig. 1. Entities in the model and relationships between them. A ◆— B means that A is composed of B. The numbers indicate the number of A and B in relation. * stands for 0 to infinity, 1..* stands for 1 to infinity and 3..21 stands for from 3 to 21. A — B means that A and B are associated. A ⟶ B means that A operates on B.

programming language used for the implementation of MaProSH is Python2.4 (Python Software Foundation 2004).

Animal representation

The representation of the animals was directed by the elements comprising the global sow productivity which is mainly described as the number of weaned piglets (WP) per sow per year. This production parameter is a combination of two other parameters that are the number of litters per sow per year and the number of piglets weaned per litter. The number of litters per sow per year is dependent on the duration of the reproductive cycle (weaning-to-weaning interval) which depends on weaning-to-conception interval (WCI), gestation duration and lactation duration. The WCI depends on the weaning-to-oestrus interval (WOI), the oestrus-to-oestrus interval (OOI), the fertility rate and the farmer decision rules used to manage the infertile sows. The WOI used for this calculation is therefore dependent on the sow and the farmer. The sow part corresponds to the WOI observed if the oestrous detection was perfect whereas the farmer part corresponds to the oestrous detection rate. The number of WP per sow per litter depends on the number of live-born piglets (LBP) piglet survival and cross-fostering practices. The representation of sow biology also needs to take into account the random nature of the biological processes. This is why each sow is individually represented in the model with biological characteristics that are randomly estimated according to distribution curves. Thus to model the reproductive cycle duration, the sow part of WOI, the OOI and the gestation length were estimated from a normal univariate distribution according to the parity of the sows. The farmer part of the WOI is modelled as a detection rate according to the parity and the sow fertility was modelled by a threshold. When oestrus is detected, insemination

Table 1. *Default values of biological parameters included in the model according to the 2006 data from the Technical Sow Herd Management System (TSHMS) in France**

	Parity							
Parameters	0	1	2	3	4	5	6	7+
Fertility rate	90%							
Abortion rate	1·1%							
Gestation duration (days)								
Mean	114·24							
S.D.	1·07							
Live-born piglets (LBP)								
Mean	12·0	12·3	13·0	13·1	12·9	12·7	12·3	11·7
S.D.	3·30	3·46	3·21	3·25	3·93	4·59	3·01	1·15
Weaned piglets (WP)								
Mean	$12{\cdot}37 \times (1 - e^{-0{\cdot}93 \times LBP^{0{\cdot}31}})$							
S.D.	$4{\cdot}4 - 0{\cdot}4157 \times LBP + 0{\cdot}0153 \times LBP^2$							
WOI observed (days)†	7·3‡	7·3	5·3	5·0	4·5			
WOI supposed (days)								
Mean	4·5‡	4·5	4	4	4			
S.D.	0·9	0·9	0·9	0·9	0·9			
Detection rate (%)	86·7	86·7	93·8	95·2	97·6			
OOI (days)								
Mean	21							
S.D.	0·9							
Mortality rate per year	3·65%							

WOI, weaning-to-oestrus interval; OOI, oestrus-to-oestrus Interval.
* Data collected on about 3000 farms. Available at http://www.ifip.asso.fr/service/chai1.htm.
† WOI observed resulted from the combination of the WOI supposed and detection rate. WOI observed equals WOI supposed if the detection rate equals 100%. WOI observed is calculated in TSHMS.
‡ WOI for parity 0 correspond to the delay between the end of the synchronization treatment and oestrous behaviour.

occurs and a uniform random number is generated. If this number is below the fertility threshold, insemination is not successful and the sow will return to oestrus following the OOI distribution. In the other case another random number is generated in order to determine if the sow will abort or not. If the sow aborts, the duration between insemination and abortion is obtained from a uniform distribution generated between 21 and 110 days whereas if the sow does not abort, farrowing is scheduled according to the gestation length distribution. The number of LBP is estimated from a normal univariate distribution according to the parity of the sows. The number of piglets at weaning is estimated from a relationship between LBP and WP which integrates the piglet mortality rate and the cross-fostering practices.

The gilts are assumed to be sexually mature and hormonally synchronized. The interval between the end of the synchronization treatment and the onset of oestrus is represented by a normal univariate distribution similar to the distribution of WOI observed in primiparous sows. A constant mortality rate per day (annual rate divided by 365) is used. All parameter values and equations used in the simulation were obtained from the analysis of the Technical Sow Herd Management System (TSHMS) in France during the year 2006 (IFIP 2007) (Table 1).

Decision rules

The study aims to compare different herd management systems on the basis of productive performances, periodic task event distribution and the capacity to maintain a minimum number of sows at farrowing. These elements of comparison are defined as the herd objectives which are reached by applying strategic rules and tactical rules (Sauvant 2005).

The strategic decisions considered in this model are the type of BFS (all systems are available), the duration of lactation (3 or 4 weeks), the scheduling of periodic tasks and the maintenance of a minimum number of sows at farrowing. The periodic tasks to schedule include the weaning of piglets, and the oestrous detection period. In order to have some outputs on the distribution of these tasks over working days (Monday to Friday) and weekends (Saturday and Sunday), the model has to manage the occurrences of these activities on a daily basis. The number of sows per batch at farrowing depends on the number of sows inseminated per batch and the conception, abortion and mortality rates. The number of sows inseminated is dependent on the number of sows tested for oestrous behaviour and on the oestrous detection rate. Sows tested for oestrous behaviour are those weaned the week before oestrous detection, the replacement gilts and sows from the batch inseminated 3 weeks before when it is possible. It is assumed in the model that the number of gilts included in a batch always fits the need to meet the target number of sows at farrowing. This assumption implies that the gilt pool is unlimited which differs from the reality of on-farm management. This choice was made for simplification and also because the decision rules concerning the management of replacement gilts are not well known.

Tactical decision rules included in the model concern the rules for the culling of sows at each step of the reproductive cycle (at weaning, at the end of the week of oestrous detection, at detection of return into oestrus and at ultrasonography). The culling decision rules may differ between BFS and will be detailed below.

Culling at weaning

The rules for culling of sows at this stage are the same for all BFS and they are based on parity number and sow productivity. By default the maximum number of allowed parities is 8. The productivity thresholds relate to the minimum number of LBP and number of WP. In the simulations, this minimum number of piglets is calculated as parity number +4. This threshold increases from parity 1 to 3 for the number of WP and from parity 1 to 4 for the number of LBP and remains constant thereafter.

Culling after the week of oestrous detection

The management of sows that are not detected in oestrus or that have not started their oestrous behaviour during the week of oestrous detection differs between BFS. The simulator includes three kinds of rules depending on BFS. In the 1-week BFS, undetected sows and sows with a delayed oestrus are noted for oestrous detection with the following batches for three more weeks. In the 3-weekly BFS, those sows are noted for oestrous detection 3 weeks later with the next batch. In the other BFS, they are culled because of a delayed oestrus.

Culling of inseminated sows after a return to oestrus

In the 1- and 3-week BFS detection of return to oestrus of inseminated sows occurs at the same time as post-weaning oestrous detection of the next batch and sows can be easily incorporated into this new farrowing batch. This is not possible for the other BFS and therefore these sows are culled because of infertility. In the model this is represented by a number of allowed returns which equals by default 1 for 1- and 3-week BFS and 0 for the others.

Culling after ultrasonography

Ultrasonography is performed 4 weeks after insemination and is considered as a perfect technique which means that after the ultrasonography the farmer knows precisely if sows are pregnant or not. At this time, farmers have to decide the management of sows detected by ultrasonography as not pregnant and which have not been seen in oestrus the week before. In the simulation, they are culled by default because of infertility. In addition, if the number of sows in the batch after conception confirmation is higher than the available space in farrowing facilities, the farmer has to cull some sows or find additional farrowing facilities. In the simulation, the space limitation is modelled as equal to the target number of sows per batch plus two. In case of overload the oldest sows from the batch are culled to fit this limit. These sows are recorded as culled because of overload.

Discrete event simulation controlled by a clock

A discrete event simulation corresponds to a representation of the system based on the discrete organization of time and the notion of a scheduled event being a modification of the state of a system at a predefined time. Two kinds of events are included in MaProSH which are linked to the animal (for instance oestrous behaviour, farrowing or death) or to the farmer (for instance oestrous detection, weaning or ultrasonography). Biological events may modify the sow physiological state, plan a new biological event or create some new entities called '*piglets*'. Task events may modify the sow physiological state, plan a new task or biological event or activate some decision rules. All the events that are supposed to occur are stacked in a calendar with the date and time of occurrence. Simulation date and time are controlled by a clock with a time step of 1 h. At each step, the simulator checks in the calendar for an event to proceed. If an event is found, it is processed otherwise simulation time is increased. This model conceptualization offers a flexible framework for herd operation close to the real operational management. It allies individual event occurrence (for biological responses) to the batch management of the farmer

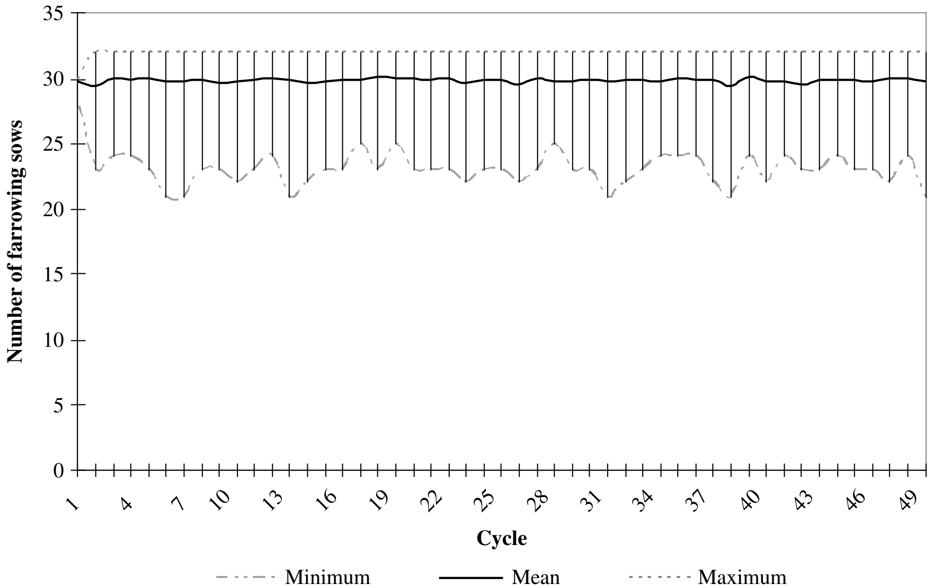

Fig. 2. Minimum, mean and maximum number of farrowing sows per batch for the different cycles.

and is so designed to simulate the interactions between management and animals.

Outputs

The model provides information on sow productivity and time of the events. Productivity data concern the performance of individual sows (number of piglets born and weaned, WOI, fertility and gestation duration) and farrowing batches (number of sows at service, farrowing and weaning; replacement rate; and fertility and number of piglets weaned). The global herd productivity will be expressed as the number of WP per productive sow per year i.e. *number of piglets weaned per sow × number of farrowing per sow per year*. The data relative to the dates of the events are analysed on a daily basis in order to produce outputs such as the percentage of sows farrowing during the weekend or the distribution of the oestrous onsets.

CALIBRATION OF THE NUMBER AND LENGTH OF SIMULATIONS

Initial structure of the herd

In order to reduce the calculation time required between the initial situation and the situation at equilibrium, the initial herd structure was created by affecting the parity of sows according to a beta distribution ($B_{(0{\cdot}98,\ 2{\cdot}6)}$) obtained from the parity distribution observed in the experimental herd of INRA (Saint-Gilles, France). The herd size was fixed at 210 sows which corresponded to 21 batches of 10 sows, 7 batches of 30 sows and 5 batches of 42 sows in the 1-, 3- and 4-week BFS, respectively.

Number and length of sow herd simulations

Before being able to use the model to compare various management strategies, it is necessary to determine the minimal length of simulation for reaching the steady state and the number of replications needed to estimate the variability of the results. For this, the approach consisted in analysing the data obtained from 20 replications of simulation with the 3-week BFS over 20 years (49 reproductive cycles). The results were analysed according to four variables (i) the number of sows per batch at farrowing standing for the ability of the simulator to maintain a constant number of sows in the herd; (ii) the mean parity of sows at weaning which is an indicator of herd demography; (iii) the number and parity of culled sows per cycle as indicators of sow longevity; and (iv) the distribution of periodic tasks over several weeks.

Number of sows at farrowing

The average number and the minimum and maximum numbers of farrowing sows per batch and per cycle calculated over the 20 replications are illustrated in Fig. 2. The mean number of sows per batch ($30{\cdot}0 \pm 0{\cdot}14$) is very close to the objective of 30 sows

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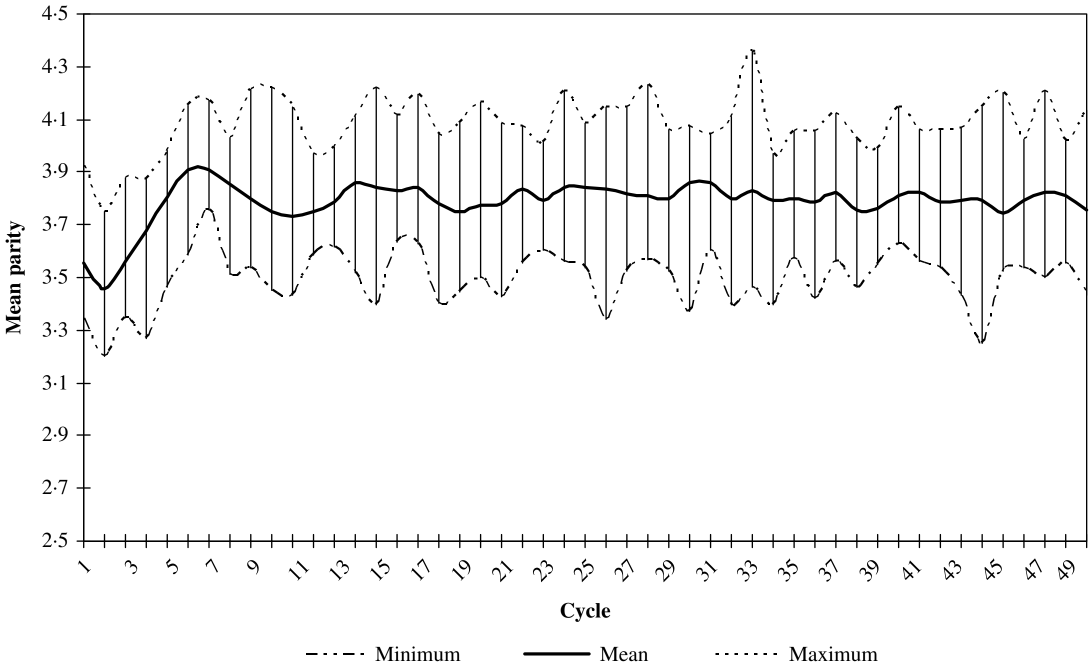

Fig. 3. Minimum, mean and maximum of the mean parity of sows at farrowing for the different cycles.

fixed for this BFS. The maximum number of sows never exceeded 32, which is in agreement with the culling rules after ultrasonography and the minimum number of sows never fell under 21. This validates the capacity of the simulator to maintain the number of sows per batch over a long period of time. Moreover it appears that the average, minimum and maximum number of sows per batch stabilize after about two cycles of simulation.

Mean parity at weaning

The mean parity per batch is calculated for each replication, cycle and batch. Mean, minimum and maximum batch average parity are thereafter determined for each cycle. The evolutions of these criteria over the 49 reproductive cycles are illustrated in Fig. 3. It takes about 15 cycles for the mean parity to stabilize, whereas the amplitude of variation of mean parity remains quite constant over the whole simulation period. This indicates that the first 15 cycles must not be considered when analysing the distribution of sow parity nor for all criteria affected by parity such as prolificacy or WOI (results not presented).

Culling

The minimum, maximum and mean numbers of culled sows per batch per cycle over 20 replications are shown in Fig. 4. The mean number of sows culled per batch at equilibrium is approximately six, which corresponds to a culling rate of about 20 % per cycle and about 48 % per year. A statistical comparison of means indicated that the mean and the amplitude of variation in the number of sows culled reached equilibrium after eight cycles. Since the culling rules do not oblige some sows to be culled at each cycle, the minimum number of sow culled could be zero, as shown in Fig. 4. In the same way there was no upper limit to the number of sows culled which explain that some batches might have a high culling rate during one cycle. A chi-square test indicated that the parity distribution of sows at culling reached stability after 15 cycles. Sows were culled at all parities. About 20 % of culling occurred at parity 8 which corresponded to the maximal number of parities allowed in the simulator.

Distribution of periodic task events

The number of occurrences of weaning, oestrous detection and farrowing events was recorded for each simulation. The average results obtained over the 49 cycles and 20 replications are presented in Fig. 5. The alternation of periodic tasks over three successive weeks which characterize the 3-week BFS appears clearly with a week with oestrous events (mainly on Monday and Tuesday), a week with farrowing events (mainly on Wednesday, Thursday and Friday) and a week with the weaning event. It appears that with a

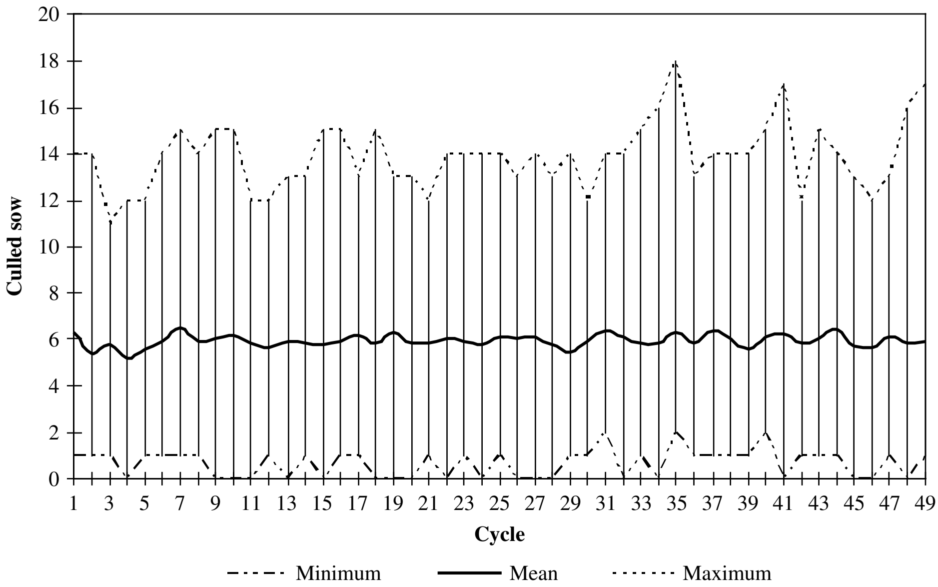

Fig. 4. Minimum, mean and maximum number of culled sows per batch for the different cycle.

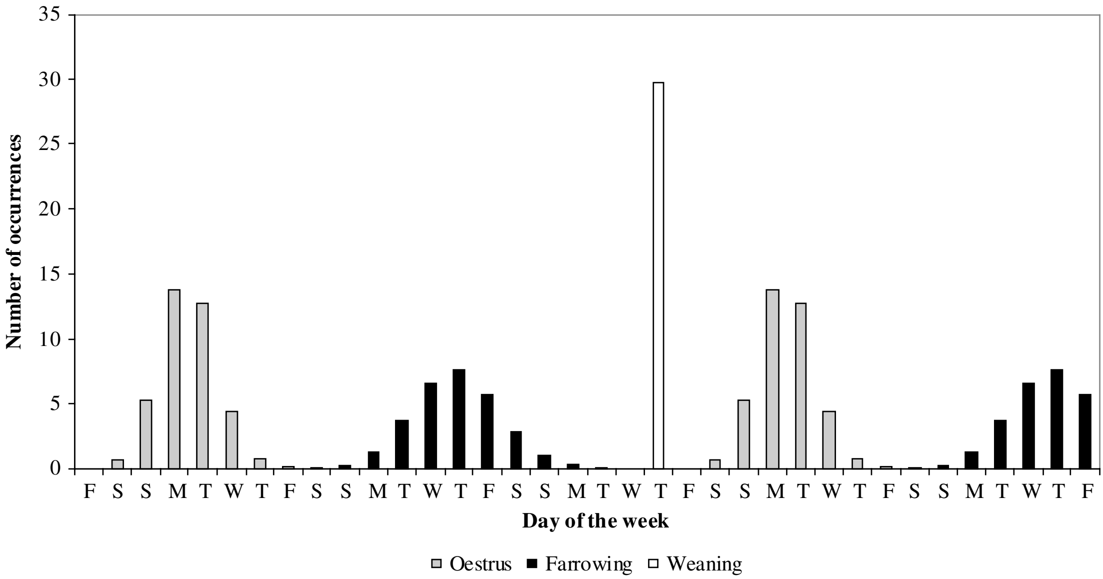

Fig. 5. Distribution of periodic tasks in the 3-week BFS.

weaning occurring on Thursday some sows (about 15%) are in oestrus during the weekend and about 10% farrow during the weekend.

The method used to determine the number of replications needed to estimate the variability of parameters of interest consisted in analysing the mean and standard deviation of the average value of these parameters at steady state according to the number of replications performed (Schwartz 1993). Two examples of this analysis are illustrated in Figs 6 and 7.

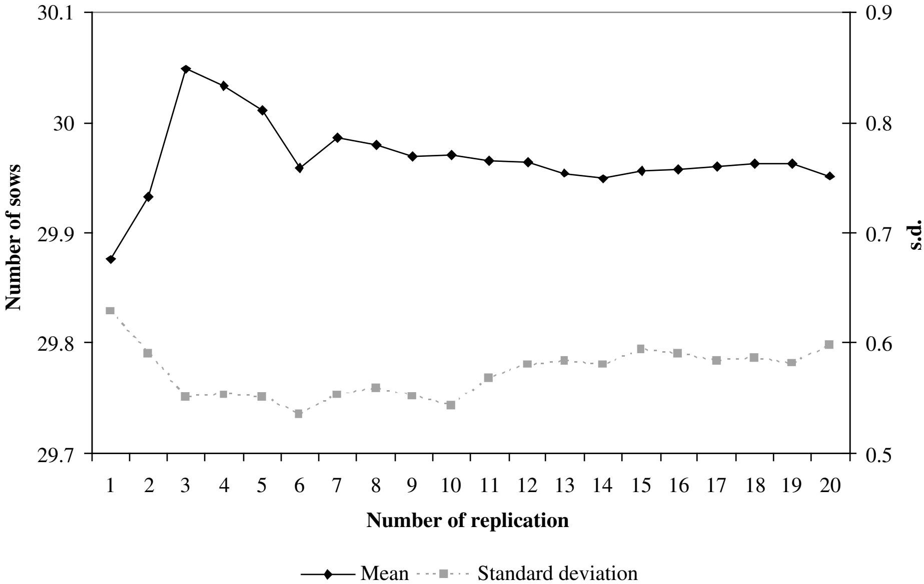

Fig. 6. Average and standard deviation of the number of farrowing sows between cycles 16 and 30 for 1–20 replications.

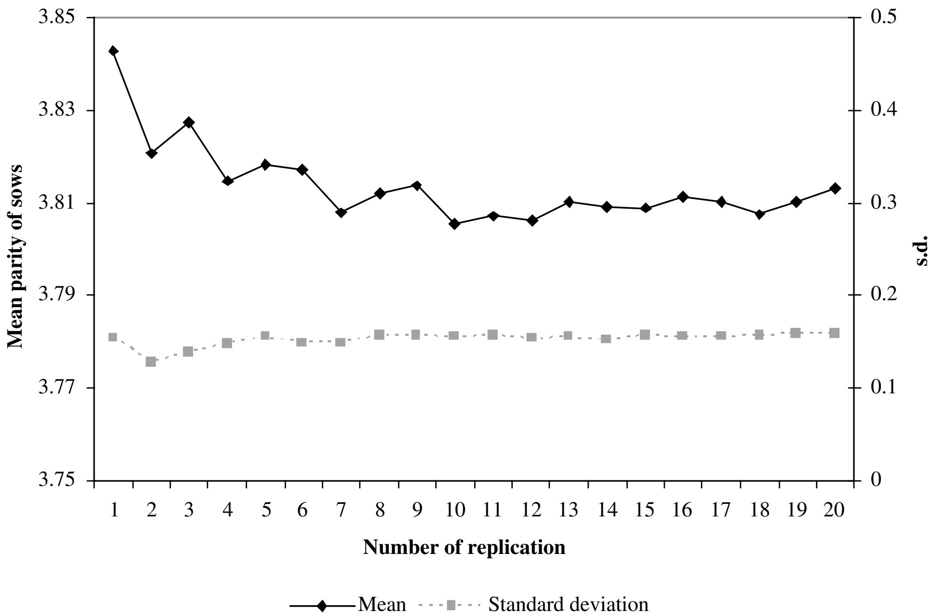

Fig. 7. Average and standard deviation of sow parity at weaning between cycles 16 and 30 for 1–20 replications.

Figure 6 illustrates the evolution of mean and standard deviation of the number of farrowing sows per batch and indicates that these values stabilize with 12 replications or more. Figure 7 shows the same for the average parity of sows at weaning and leads to the same conclusion.

Thus, in the following simulations the average value of sow and herd productivity at steady state will be estimated between the 16th and the 30th and 15 replications, corresponding to data from about 47 000 litters for a 210 sow herd. These data were collected in approximately 8 min.

Table 2. *Mean and standard deviation between replications of herd productivity indicators and event distribution in different batch farrowing systems (BFS)*

	4-Week BFS		3-Week BFS		1-Week BFS	
	Mean	S.D.*	Mean	S.D.*	Mean	S.D.*
Number of farrowing sows	40·8	0·22	30·0	0·14	9·8	0·06
Number of sows at service	51·2	0·07	37·8	0·16	11·4	0·07
Mean parity at farrowing	3·1	0·04	3·6	0·05	3·7	0·04
WOI (days)	4·6	0·02	5·9	0·08	6·0	0·09
WCI (days)	4·7	0·02	7·8	0·13	7·8	0·10
LBP per litter	12·5	0·06	12·6	0·08	12·6	0·07
WP per litter	10·7	0·04	10·7	0·04	10·7	0·03
WP per sow per year	28·0	0·09	26·1	0·10	26·1	0·07
Lactation duration (days)	21·2	0·02	28·1	0·02	28·1	0·03
Productive cycle duration (days)	139·9	0·02	149·7	0·13	149·7	0·13
Sows culled per batch per cycle	14·1	0·33	5·9	0·10	2·2	0·04
Parity of productive sows at culling	3·8	0·08	5·4	0·08	5·5	0·09
Parity of sows at culling†	2·9	0·07	5·09	0·1	5·19	0·1
Number of events over 4 weeks						
During weekends	11·5	–	14·3	–	12·2	–
During five working days	117·0	–	116·0	–	113·7	–
Days 'without' events over 4 weeks						
During weekends	4	–	2	–	0	–
During five working days	14	–	6	–	0	–

WCI, weaning-to-conception interval.
* Standard deviation in replications made between the 16th and the 30th reproduction cycles.
† Including the culled gilts.

EFFECTS OF ANIMAL BIOLOGICAL PARAMETERS AND MANAGEMENT ON HERD PRODUCTIVITY

Effect of changes on production strategies

Three production strategies combining a BFS (1-, 3- and 4-week) and the most usual lactation duration observed for each BFS (4 weeks for the 3-week BFS, 3 weeks for the 4-week BFS and both durations for the 1-week BFS, but only the results of the 4 weeks lactation duration will be presented) were compared. In addition to the number of farrowing batches in the herd and the lactation duration, these productive systems differed by their capacity to manage infertile sows and by their periodic task distribution. Whatever the production strategy simulated, herd productivity reached steady state with a variation coefficient between replications of only 0·5% (Table 2). This variation coefficient gives an estimate of the variability between herds with the same management rules and the same sow characteristics. This variability is lower than the variability observed in the French national database (IFIP 2007). This was expected because of heterogeneity of the database concerning farm management rules and animal characteristics.

With the MaProSH model, no effect of production strategy was observed on sow productivity per litter and the simulated average lactation duration corresponded to the strategy adopted for each BFS. In the same way, the average number of sows at farrowing was close to the objective. The WOI differed between BFS. It was shorter for the 4-week BFS because, in this system, sows which are not seen in oestrus within a week are culled and so not considered in the calculation of WOI. Also due to the differences between production strategies concerning the culling of infertile sows, the WCI of 4-week BFS is shorter than the observed in the other two systems. In relation to these results, the number of culled sows per batch per cycle is increased with this BFS and culling concerned mostly the young sows which are more difficult to detect in oestrus and less fertile resulting in a low mean parity at culling. Despite these drawbacks, the number of piglets weaned per productive sow per year is higher with the 4-week production strategy ($P<0·001$). No difference in herd productivity was found between 3-week and 1-week production strategies. Distribution of events (detection of oestrus, farrowing and weaning) is presented in Fig. 8 and summarized by four criteria in Table 2. In the 4-week BFS, the week following weaning is devoted to

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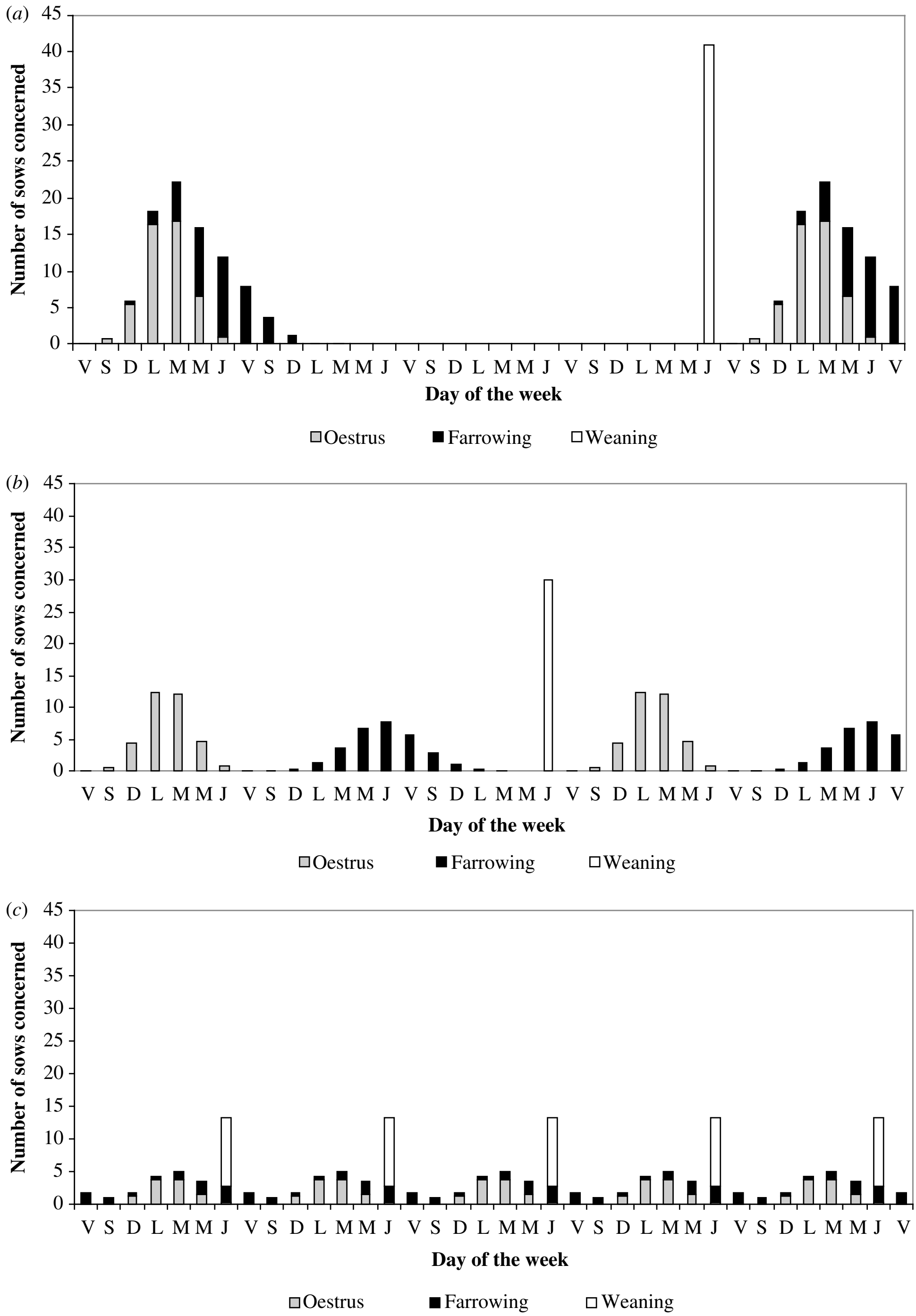

Fig. 8. Event distribution over week in 4-week BFS (*a*), 3-week BFS (*b*) and 1-week BFS (*c*).

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oestrous detection as for the other BFS but is also the week of farrowing. After this week of heavy work load, there are 2 weeks without any specific periodic task events. In the 3-week BFS, no task superposition is observed and the number of periodic tasks per week is almost constant. However, this system has fewer week and weekend days free of periodic tasks. In the 1-week BFS, the number of periodic tasks per week remains constant, but all the tasks occurred each week and there is no day without periodic tasks. With this system, the beginning of the week (including Sunday) is mostly concerned with oestrus whereas the end of the week (including Saturday) is concerned by farrowing. The total number of periodic task events that have to be performed is not different between BFS, only the distribution over time changes.

Effect of period of oestrous detection

With the default management strategy, *farmers* plan oestrous detection days from the Saturday following weaning until the Monday 10 days afterwards. In order to limit work during the weekend it is convenient to evaluate the consequences of a shorter oestrous detection period, that is, from Monday following weaning until next Thursday. Results are shown in Table 3, columns A. The reduction of the oestrous detection period implies that fewer sows will be detected in oestrus which affects herd productivity due to less sows at farrowing, more young sows culled (decrease in the mean parity at culling and overall increase of in the number of culled sows per batch) and increased WCI, in particular in the 3- and 1- week BFS (more sows not seen in oestrus the first week are kept for another detection 3 weeks later). However, only a slight but significant ($P<0{\cdot}001$) decrease in the number of piglets weaned per productive sow per year was observed for these BFS. The week distribution of task events is modified with a strong reduction in the number of events occurring during the weekend but no consequences on the distribution of the farrowing events.

Effect of weaning day

This analysis concerns the consequences of planning weaning on Wednesday instead of Thursday. Results on productivity and event distribution are presented in Table 3, columns B. No consequences on productivity parameters were found but the occurrence of events during the weekend strongly increases. This mainly concerned oestrus which occurred more frequently during the weekend whereas this shift resulted in a decrease in the number of farrowings occurring during the weekend.

Effect of WOI and fertility

To evaluate if the model is able to respond to a modification of the biological parameters describing the animals, a simulation experiment was performed with an increase in variability of the WOI from 0·9 to 1·1 days. The results for each plan are presented in Table 3, columns C. Differences between the two experiments concerned only the distribution of events with an increase in the number of periodic task events occurring during the weekend when the variability increased.

In the same way, the effect of sow fertility was investigated with the aim of understanding how the different BFS will face a reduction in fertility from 90 to 70 %. The results of this experiment are presented in Table 3, columns D. The model was near to maintaining the number of sows at farrowing and variability between replications remained low despite a slight increase. However, this resulted in an increase in the number of sows at service by 20–30 %. In the 4-week BFS, many of these sows were replacement gilts resulting in a strong decrease in the mean parity at farrowing. In the other BFS most were non fertilized sows from the previous batch resulting in increase in the WCI. The number of culled sows per batch also increased in all BFS (multiplied by 2 in the 4-week and by around 1·3 in the other BFS) and concerned younger sows. From these different results it can be concluded that the 4-week BFS appears more sensitive to a decrease in fertility than the other two systems. Moreover, the increase in the number of sows at service also increased the number of events to be managed by the farmer but did not change their time distribution.

DISCUSSION

Operation of MaProSH

The simulation of the various BFS was successful and transcribed differences in herd dynamics. The 4-week BFS seems to diverge from the other two BFS tested, mostly due to the differences in management of infertile sows and associated culling policies. These differences involve modification of the WCI, number of sows culled and mean parity at farrowing and culling. The difference observed between the 4-week BFS and the other BFS for the number of piglets weaned per productive sow per year are mainly due to the shorter WCI and the shorter lactation period in the 4-week production system (21 days *v.* 28 days in the other systems). The 1-week BFS with a lactation of 3 weeks gives a mean productivity between the 4-week productive system and the other systems (27·4 weaned piglets per productive sow per year, data not shown). Indeed, in this production system the lactation duration equals the lactation duration of the 4-week production system and the WCI equals that

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Table 3. *Effect of changes* in practices (duration of oestrous detection (A) and day of weaning (B)) or in biological parameters (variability of the WOI (C) and fertility (D)) on sow productivity and distribution of events (farrowing, oestrus and weaning) in three BFS*

	4-Week BFS					3-Week BFS					1-Week BFS				
	Control	A	B	C	D	Control	A	B	C	D	Control	A	B	C	D
Number of farrowing sows	40·8	37·2	40·6	40·7	40·3	30·0	28·7	29·9	29·9	28·2	9·8	8·7	9·8	9·9	9·2
Number of sows at service	51·2	51·6	51·2	51·2	67·3	37·8	40·6	37·9	37·7	45·6	11·4	10·4	11·4	11·4	13·8
Mean parity at farrowing	3·14	2·71	3·15	3·17	2·24	3·63	3·42	3·62	3·62	3·26	3·74	3·55	3·74	3·75	3·29
WCI (days)	4·68	4·92	4·69	4·68	4·79	7·83	9·23	7·93	7·83	11·00	7·80	9·25	7·83	7·72	10·96
WP per sow per year	28·0	28·1	28·0	28·0	28·3	26·1	25·9	26·1	26·1	25·7	26·1	25·9	26·0	26·1	25·6
Culling per batch per cycle	14·1	16·9	14·3	14·2	28·7	5·9	6·8	6·0	6·0	7·9	2·2	2·3	2·2	2·2	2·7
Parity of sows at culling†	2·90	2·21	2·85	2·88	1·41	5·09	4·25	5·03	5·05	3·55	5·19	4·38	5·22	5·24	3·61
Number of events over 4 weeks															
During weekends	11·5	5·1	25·0	14·2	12·4	14·3	4·2	38·0	17·7	16·4	12·2	5·1	26·3	14·7	13·8
During five working days	117·0	111·6	103·0	114·0	128·4	116·0	120·1	91·1	112·3	125·0	113·7	103·9	96·3	109·2	114·8
Days 'without' events over 4 weeks															
During weekends	4	6	5	50	4	2	6	2	25	2	0	4	0	0	0
During five working days	14	14	13	70	14	6	6	7	30	6	0	0	0	0	0

* Control corresponds to a 10-days period of oestrous detection, weaning on Thursday, average variability of WOI and 90 % of fertility.
A corresponds to a 4 day period of oestrous detection, weaning on Thursday, average variability of WOI and 90 % of fertility.
B corresponds to a 10-days period of oestrous detection, weaning on Wednesday, average variability of WOI and 90 % of fertility.
C corresponds to a 10-days period of oestrous detection, weaning on Thursday, increased variability of WOI and 90 % of fertility.
D corresponds to a 10-days period of oestrous detection, weaning on Thursday, average variability of WOI and 70 % of fertility.
† Included the culled gilts.

observed in the 3- and 1-week BFS with 4 weeks of lactation. The annual culling rates in the 3- and 1-week BFS were 48 and 54% per year, respectively, at parity 5·4 on average. This is close to the observed values in France with a culling rate of 43% at parity 5·0 on average (Boulot 2004). The mean parity at culling is lower than expected for the 4-week BFS. This is mainly due to the representation of the decision of culling infertile sows. Indeed, it can be hypothesized that farmers using the 4-week BFS do not systematically cull the infertile sows, which are inseminated outside a farrowing batch instead. This results in sows which farrow 1 week before the planned batch and are weaned after a longer lactation. In the same way, it can be expected that farmers are more flexible with infertile young sows and gilts, decisions that the model does not yet consider. This limitation also explains why the number of sows culled per batch in the 4-week BFS seems to be overestimated. According to Plà (2007), only a small number of models aim at studying the culling rule effects on productivity, and the most usual culling rules included in sow herd model concern infertility and injuries only. There are three models in particular which deal with this issue. Two consider sow productivity as a criterion for the culling rules (Jalvingh *et al.* 1992; Pomar & Pomar 2005) and the one of Jalvingh *et al.* (1992) also included differential management between parities. The last one (Plà *et al.* 2003) operates in a different way. These authors represent the different physiological states of the sows and the possible transition between each state. These transitions are based on on-farm data sets and so included farmer management practices (culling rules and cross-fostering). This approach cannot easily simulate the effects of some modifications to the culling rules but is suitable for simulating future performances of the farm with the same rules.

Specificity of MaProSH

The simulated number of WP per litter takes cross-fostering practices into account since sows can wean more piglets than the number they farrow. To the authors' knowledge this is the first model that takes cross-fostering practices into account to predict the number of WP. Several authors model the mortality rate of piglets according to litter size (Pettigrew *et al.* 1986; Sing 1986) and some others consider the effect of piglet birth weight (Pettigrew *et al.* 1986; Pomar *et al.* 1991) or age (Allen & Stewart 1983; Pomar *et al.* 1991) on this criterion. Cross-fostering practices allow the number of piglets to be adapted to the number of teats of the sow resulting in a decrease in piglet mortality. In the present version of MaProSH, there is no physical representation of cross-fostering practices which are only considered on an empirical statistical basis. A more mechanistic representation of cross-fostering would require considering the number of teats available and the milking ability of each sow. However, this would require on-farm enquiries to better understand cross-fostering practices in the different BFS.

Focusing on the distribution of periodic tasks, specificities of each BFS appear clearly. In the 4-week BFS most of the tasks occur within 10 days but make some free days available. A weekly specialization of tasks is observed in the 3-week BFS whereas in the 1-week BFS all tasks occur each week but on a more limited number of sows. This indicates that the MaProSH model is able to simulate several BFS with their own characteristics in terms of work pace. Only a few models incorporated work in their representation. The model of Allen & Stewart (1983) predicts the labour time required both for unskilled labour (cleaning, moving of animals and feeding) and for skilled labour (farrowing supervision and insemination). The MaProSH model distinguishes the day and the weeks more than the labour time and categorizes tasks on their frequency (periodic or daily) (Madelrieux *et al.* 2006) instead of classification on the skill needed. Both approaches are useful since the skill determines the labour distribution among workers, whereas distribution of task events over weeks can produce heavy workload periods which are difficult for farmers to manage. Jorgensen & Kristensen (1995) represent work in a similar way as MaProSH. Working sessions are planned on specific days and hours and a worker intervenes to do it. However they only consider the 1-week BFS and do not provide any outputs on the number of technical acts according to day of the week. For the future, it would also be convenient to consider the effect of work, in terms of both quantity and quality, on animal performance. This is already the case in the present MaProSH model for the efficiency of oestrous detection which is affected by the duration of the oestrous detection period. In the same way the survival of piglets at birth could be affected by farrowing supervision (White *et al.* 1996).

Intelligence of the herd operation

In addition to its capacity to simulate several BFS, the MaProSH model makes it possible to study the effect of modifications to herd management or sow biological parameters on animal performance and occurrence of task events. The simulation experiments presented in the current paper focused on oestrous detection rules which are known to affect the WCI. The model was able to simulate this relation as indicated by the response of WCI to changes in the biology or the management of oestrus. The results also indicated that the number of WP per productive sow per year was not affected by these changes in the 4-week BFS and was only slightly affected in the other

BFS. In fact the model compensated for the change in efficiency of oestrous detection or of sow fertility by adapting the number of replacement gilts and culled sows. The number of WP per present sow per year (including replacement gilts and sows between the last weaning and the removal) would be a better indicator to evaluate these effects. However, the calculation of this indicator requires more information than available on the replacement rules (quarantine duration) and on the delay between culling decision and removal of the culled sow. Data are available in the literature concerning the effect of feeding and boar exposure on puberty, and optimal age for insertion in a batch (Young *et al*. 1990; Rozeboom *et al*. 1996; Willenburg *et al*. 2003). What is missing for considering this aspect in the model relates mainly to farmer practices concerning the periodicity and the number of gilt inserted into the gilt pool and how culling and replacement interact. Other sow herd models also produce outputs on the number of piglets weaned per sow per year but without any clear indication as to the way it is calculated. Only a few models have a representation of the puberty attainment and of the quarantine period which suggests that these sows are also not considered as present sows in the majority of the models.

Modifying the global fertility rate of sows induces an important adaptation of the systems, with two different kinds of adaptation. In the 4-week BFS, the adaptation involves a large culling rate (and replacement rate) resulting in a decreased mean parity at farrowing. In the 3- and 1-week BFS, the adaptation involves the insemination of sows that return to oestrus after 3 weeks with, as a consequence, increase of the WCI and only a limited increase in the number culled. It would be interesting to know if this occurs in practice but until now no studies have been carried out on this subject. Jalvingh *et al*. (1992) also simulated a decrease in the fertility rate in a 1-week BFS and observed an increase in the culling rate, but they did not give any information about the other traits of the herd (number of sows and non productive sow-days per culled sow). With a similar approach, Singh (1986) observed that a low conception rate lowers the number of piglets weaned and increases the variability of results. It was explained that the decrease in number of WP is due to the replacement of productive old sows by less productive gilts. However this effect may be overestimated in his model because cross-fostering was not considered and prolificacy was lower. Indeed, with the MaProSH model, the mean number of LBP is decreased (about 1% lower, data not shown) as the fertility rate decreases, but no effect is reported on the number of WP per litter.

The distribution of events between 5-day week and weekend was affected by the management of oestrous detection (farmer part of WOI). The absence of oestrous detection during the weekend decreases the number of events occurring during the weekend and slightly increases the number of events occurring during the 5-day week and the number of sows that farrow during the weekend. Another effect of this practice consists in the diminution of the number of sows at farrowing, because fewer sows are observed in oestrus. To advance the day of weaning leads to a large increase in the number of oestrous event occurring during the weekend but it limits the number of sows that farrow during the weekend. These experiments emphasize the relation between periods of oestrus and periods of farrowing. The distribution of events was also sensitive to the modification of the sow part of WOI which accounts for a more mechanistic model of the WOI as in Jorgensen & Kristensen (1995) and Steverink (1999). These authors model the physiological processes of the oestrous cycle (LH, FSH and ovulation) whereas in general WOI is modelled with a normal univariate (Plà 2007).

In conclusion, the MaProSH model is able to simulate various BFS and predict their event distribution, productivity and dynamics. By allowing the analysis of the effects of different periodic task schedules, the model starts to investigate the issues concerning on-farm work. These issues require on-farm enquiries to evaluate the work pace expectations of farmers and their interactions with on-farm practices. The MaProSH model can also be used to analyse the differential adaptation of the BFS to modification in management rules and sow biology. However, the relationships between replacement and culling have to be clarified which confirms the need to carry out on-farm data collection to complete a further model.

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