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Quantification by simulation of the effect of herd management practices and cow fertility on the reproductive and economic performance of Holstein dairy herds

M. E. A. Bekara[1,2]* **and N. Bareille**[1]
[1]BIOEPAR, INRA, Oniris, La Chantrerie, 44307 Nantes, France
[2]Laboratory of Molecular Biology, Genomics and Bioinformatics, Department of Biology, Faculty of Nature and Life Sciences, University Hassiba Benbouali of Chlef, 02000 Chlef, Algeria

ABSTRACT

The performance of dairy herds is affected mainly by factors related to cows' characteristics and herd management practices. However, these factors are interrelated, and as such, the estimation of their individual effect on the performance of dairy herds remains difficult. The aim of this study was to estimate the weight of these factors as well the interactions between them on the reproductive and economic performance of dairy farms. A stochastic dynamic model was used to simulate most physiological and management processes occurring on a dairy farm. A herd of 60 Holstein cows, with a milk yield of 8,000 L/cow-year, representative of French Holstein dairy herds, was simulated. A total of 216 scenarios were run by combining 2 levels of postpartum cyclicity resumption (average: 45 d, high: 75 d), 3 levels of 21-d conception rate of the herd (i.e., proportion of cows pregnant 21 d after insemination; low: 25%, average: 45%, high: 70%), 3 levels of probability of pregnancy loss until 120 d (low: 3%, average: 15%, high: 43%), 3 levels of sensitivity of estrus detection by the farmer (low: 20%, average: 50%, high: 90%), 2 alternative managerial goals (constant number of cows or constant volume of milk sold), and 2 types of management for the sale and purchase of animals (closed or open herd). The effect of each factor was estimated by sensitivity analysis. The parameter that had the greatest effect on reproductive performance was the sensitivity of estrus detection: a 10-percentage-point increase between the low and average levels and between the average and high levels reduced the calving interval by 16 and 5.7 d, respectively. However, the factor that had the greatest effect on economic performance was the 21-d conception rate: a 10-percentage-point increase between the low and average levels and between the average and high levels increased the gross margin by €62.2 and €22.3/cow-year, respectively. The pregnancy loss until 120 d had an effect on economic performance: an increase of 1 percentage point of this parameter decreased the gross margin by €2/cow-year. The other factors studied, and their interactions, did not have a major effect (low value of sensitivity indices). Closed herds or farms with a constant number of cows had economic losses of €58/cow-year compared with open herds or to farms with constant volume of milk sold. Altogether, our data suggest that, in a typical French dairy farm, farmers' efforts on estrus detection will be more profitable when associated with improvement of the conception rate of the cows.

Key words: dairy cattle, sensitivity of estrus detection, conception rate, gross margin, modeling

INTRODUCTION

The calving interval (**CIN**) of cows is the result of a succession of several events: resumption of the ovarian cycle, farmers' estrus detection, and decision-making regarding insemination, conception, and maintenance of pregnancy. Any failure during the transition between these events, caused by one or more of the following factors: prolonged postpartum anovulation (first ovulation occurring late), extended interovulation intervals, nondetection of estrus, conception failure, and abortion, will increase the CIN (Garnsworthy et al., 2008). Factors that influence these reproductive events depend on cow characteristics (e.g., genetic value, age, reproductive function, and health disorders) as well as herd management practices [e.g., production managerial goals (**MG**), feeding plans, estrus detection, and culling strategies; Lucy, 2001; Hudson et al., 2012].

The negative effect of poor reproductive performance on economic benefits of dairy cattle farms has been well demonstrated by several simulation models in Europe (Østergaard et al., 2005; Rutten et al., 2014) and in

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*Corresponding author: m.bekara@univ-chlef.dz

the United States (De Vries and Conlin, 2003; Cabrera, 2012; Giordano et al., 2012). However, these simulation models have been simplified to different extents, due to the complexity of the reproduction function. For example, factors which are well known to have effects on the reproductive performance, such as the different levels of estrus expression or their correlation with the number of ovulation after calving, and with the parity and the sensitivity of estrus detection (Orihuela, 2000), were not taken into account in these studies. Another limitation of the previous studies concerns the modeling of culling decisions in response to constraint-related MG (constant herd size or constant volume of milk sold). It is well known that in real life, farmers' culling decisions vary greatly within and across countries, and are influenced mainly by cows characteristics such as age, previous reproductive or health disorders, and milk production level (Gröhn et al., 2003); in spite of this, these reasons for culling were not always simulated in these models. As such, these models were not always appropriate in the context of the French dairy farming system.

Several studies quantified the influence of cow characteristics and herd management practices on reproductive and economic performances of dairy farms (De Vries and Conlin, 2003; Seegers et al., 2006; Rutten et al., 2014). For example, an increase of 10 percentage points in the conception rate (when its initial value is higher than 45%) and estrus detection (when its initial value is higher than 50%) reduced the CIN by 10 d (Seegers et al., 2006) and 5.3 d (Rutten et al., 2014), respectively, and increased the gross margin per cow/year by €8.3 (Seegers et al., 2006) and $7.8 (De Vries and Conlin, 2003), respectively. However, these studies did not estimate the relative weights of conception rate and of estrus detection on reproductive and economic performances of dairy farms. Knowing these relative weights could help farmers to implement appropriate corrective measures in their herds.

In this work, a stochastic simulation model was used to assess the weight of several factors related to (1) herd management practices (estrus detection, MG, and animal replacement); (2) intrinsic characteristics of Holstein cows (resumption of ovarian cyclicity, conception rate and pregnancy loss); and (3) the interactions between these 2 components on the reproductive and economic performance of dairy farms.

MATERIALS AND METHODS

Model Simulation Structure

We used a dynamic stochastic model ECOMAST, operating in discrete time, to simulate the cow's life, from herd entry (birth or purchase) to herd exit (culling or death). This is an individual-based model that was developed by UMR BIOEPAR (INRA, ONIRIS, Nantes, France; Dezetter et al., 2017), using a time step of one day. The model is coded using Visual Basic (1998, Microsoft Corp., Redmond, WA). The simulated individual in the model is a dairy cow. All discrete simulated events at the animal level are generated stochastically by random draws in the appropriate probability laws. The model simulates the events and biological processes (genetic characteristics, reproductive and lactation cycle, and health disorders), the herd management practices (feeding plan, management of reproduction, and animal replacement by sale, culling, and purchase), and the interaction between the biological processes and the herd management practices.

Because the objective of our study was to quantify the relative effect of several factors on the reproductive and economic performances of dairy cattle farms, only the simulated biological processes interfering with the reproductive cycle are presented in detail.

Modeling the Individual Genetic Value of the Cow

The genetic processes simulated in the ECOMAST model was used to compute the phenotypes of 5 major cow traits: (1) milk yield in kilograms over 305 DIM reached in the adult cow ($\mathbf{MY_{305}}$); (2) average milk fat content in grams per kilogram over 305 DIM; (3) average milk protein content in grams per kilogram over 305 DIM; (4) mastitis susceptibility; and (5) fertilization, which is defined as success after an AI (Dezetter et al., 2017). These phenotypic traits were calculated at each entry of a new female into the herd (birth or purchase) and remained unchanged throughout the life of the cow (Dezetter et al., 2017). According to the formulas provided by Dezetter et al. (2017), the value of each trait was calculated from (1) a basic value, which was defined from the average value of the herd, (2) the true breeding value of the given cow, which represents "the real value of the animal for breeding" (Oldenbroek and van der Waaij, 2015), (3) a heterosis effect for crossbred cows, (4) a permanent environmental effect, and (5) a random effect representing the inter-cow variability.

Modeling of Health Events, Feeding Plan, and Milk Production Processes

Health Disorders and Mortality. At each time step in the model, the cow was exposed to the occurrence of health disorders. Two health disorder groups were modeled: IMI and other health disorders (e.g., lameness and peripartum disorders). The daily risk of a health disorder was modeled taking into account cow factors (mastitis susceptibility only for IMI, daily milk yield, and parity) and the annual incidence rate of IMI and other health disorders (Dezetter et al., 2017).

These health disorders affected the cow reproductive performance and influenced the culling or the death of the cow with the probabilities $\mathbf{HD_{cull}}$ and $\mathbf{HD_{death}}$, respectively.

Modeling Feeding Plan and Energy Balance. The daily feeding plan was variable for each cow, and depended on DIM, actual milk yield, and to a lesser extent, on the reproductive status (pregnant or not) of the cow (Dezetter et al., 2017). However, we fixed the maximum amount of concentrate and roughage distributed for each cow, based on the expected average of daily milk yield of the simulated herd over 2 periods: the first one being between calving and the day of the peak in milk production, and the second one being between the day of the peak in milk production and 60 d before next calving (dry period). Thus, at day t of lactation stage, if a cow has a daily milk yield higher than the expected average of the herd, it will be coded as a cow with a negative energy balance for this day. The effect of the negative energy balance on cow milk production and reproductive performance was also simulated in our model.

Lactation. The daily milk yield in kilograms ($\mathbf{MY_t}$), the daily milk fat content in grams per kilogram, and the daily milk protein content in grams per kilogram were simulated in the model using Wood's equation (Wood, 1967). In this equation, among many others parameters, we used the values of the MY_{305}, the average milk fat, and the average milk protein content (in grams per kilogram over 305 DIM; Dezetter et al., 2017), which were computed in the section "Modeling the Individual Genetic Value of the Cow" (see above). Therefore, the Wood curve allowed the estimation of the lactation curve and its components (fat and protein), whatever its length (shorter or longer than 305 DIM), taking into account the milk production potential of the cow on 305 d of lactation. These daily performances could be modified by several factors: season (Coulon et al., 1995), pregnancy (Coulon et al., 1995), negative energy balance (Jarrige, 1989), IMI (Hortet and Seegers 1998; Hortet et al., 1999), and other health disorders (Fourichon et al., 1999, 2000). For details, see Dezetter et al. (2017).

Modeling of the Reproductive Cycle

Figure 1 represents the different steps of the reproductive cycle of a cow: (1) resumption of ovarian cycle after calving and its duration, (2) estrus expression, (3) conception, and (4) pregnancy and calving.

Step 1. The Resumption of Ovarian Cycle and its Duration (Figure 1). In the model, the calving to first ovulation interval (**CFOI**), the time for the resumption of ovarian cyclicity after abortion (event 1.2, Figure 1), and the ovarian cycle length were determined by random draw in truncated normal distributions (Table 1). The probability of occurrence of one of the following cyclical postpartum disorders (**CPD**): (1) prolonged postpartum anovulation (CFOI longer than 50 d), (2) delayed resumption of ovarian cyclicity after the first or the second postpartum ovarian cycle (interval longer than 26 d), was randomly drawn at calving using a multinomial law:

$$\text{CPD} \sim M\,(1;\ [\text{p0, p1, p2, p3}]), \qquad [1]$$

with p1, p2, and p3 being the probability of a prolonged postpartum anovulation, a delay after the first or the second postpartum ovarian cycles, respectively; and p0 the probability of having no cyclical disorder ($p0 = 1 - p1 - p2 - p3$). The probabilities p1, p2, and p3 were determined according to the MY_{305} (Table 1). The occurrence of a CPD had an effect on the CFOI and the ovarian cycle length, which we have considered in our model (Table 1).

Step 2. Estrus Expression (Figure 1). In this step, 3 major events were simulated: estrus expression with ovulation (event 2.1, Figure 1), estrus expression without ovulation (event 2.3, Figure 1), and ovulation without estrus expression (event 2.2, Figure 1).

For each simulated ovulation (events 2.1 and 2.2, Figure 1), 4 levels of estrus expression were simulated in the model (without expression, discreet, normal, and high). The distribution of these 4 levels was different according to parity (primiparous or multiparous) and the number of ovulation after calving (1, 2, and >2).

The probability of ovulation without estrus expression ($\mathbf{P_{EW}}$; event 2.2, Figure 1) was modeled by the interaction of several factors (Dezetter et al., 2017):

$$P_{EW} = P_{EWref} + P_{MYt}, \qquad [2]$$

where P_{EWref} was the baseline probability of ovulation without estrus expression, depending on the number of ovulation after calving and the number of estrus post-AI (Table 2); P_{MYt} was the additional risk of ovulation without estrus expression related to the daily milk yield. The P_{MYt} was calculated using the following formula (Cutullic et al., 2011; Ledoux et al., 2011; Dezetter et al., 2017):

$$P_{MYt} = 0.005 \times (MY_t - 20), \qquad [3]$$

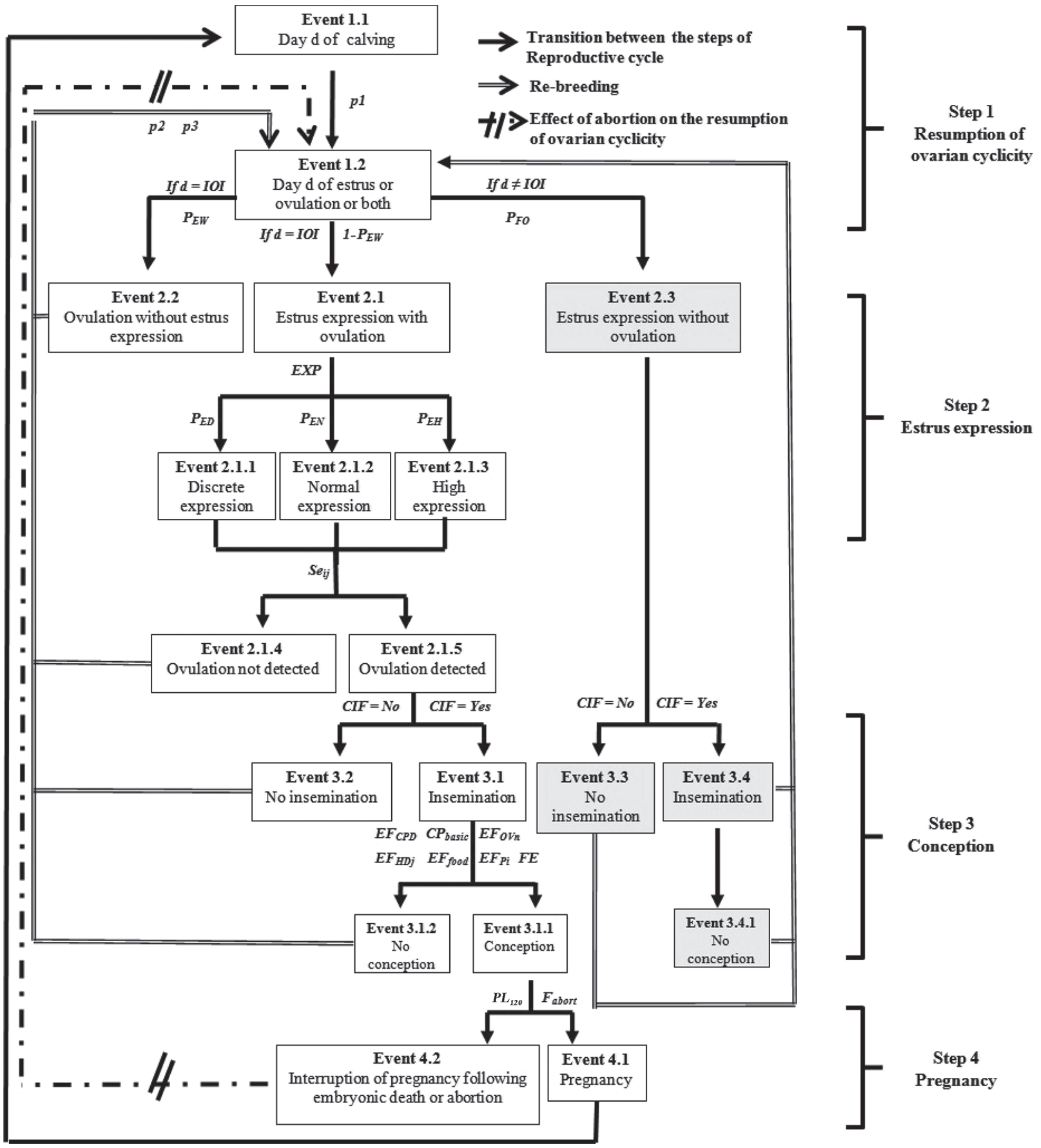

Figure 1. Diagram of the cow's reproductive cycle simulated in the ECOMAST stochastic simulation model of reproductive and economic performance in dairy herds. p1 = probability of a prolonged postpartum anovulation (first ovulation occurs late); p2 = probability of delay after the 1st ovarian cycle; p3 = probability of delay after the 2nd ovarian cycle; IOI = inter-ovulation interval; P_{EW} = probability of ovulation without estrus; 1-P_{EW} = probability of estrus with ovulation; P_{FO} = probability of estrus without ovulation; EXP = estrus expression level; P_{ED} = probability of discrete level of estrus expression; P_{EN} = probability of normal level of estrus expression; P_{HD} = probability of high level of estrus expression; Se_{ij} = estrus detection sensitivity for the estrus expression level i (discreet, normal, and high) and for the parity j of the cow; CIF = conditions of insemination fixed by the farmer (estrus detected after the voluntary waiting period and beyond 17 d after the last estrus, and the number of services per cow was less than 6); CP_{basic} = basic conception probability according to the daily milk production, DIM, 21-d conception rate of the herd (CR_{21}; i.e., proportion of cows pregnant 21 d after insemination), and herd sensitivity of estrus detection by the farmer (Se_H); FE = fertilization parameter calculated in the genetic compartment of the ECOMAST model, its definition as a success after an AI and including early embryonic death; EF_{OVn} = effect of number of ovulation after calving on the conception probability; EF_{Pi} = parity effect on the conception probability; EF_{CPD} = postpartum reproductive disorders effect on the conception probability; EF_{HDj} = health disorders effect on the conception probability; EF_{food} = negative energy balance effect on the conception probability; PL_{120} = probability of pregnancy loss between d 21 and 120 of pregnancy; F_{abort} = probability of abortion between d 120 and 275 of pregnancy.

with the values of P_{MYt} truncated between [0.005 – 0.15] (Dezetter et al., 2017).

The probabilities of ovulation with discreet (event 2.1.1, Figure 1) and normal (event 2.1.2, Figure 1) estrus expression were modeled using the parameters P_{ED} and P_{EN}, respectively. Like P_{EW}, the values of these parameters depend on the number of ovulation after calving and the number of estrus post-AI (Table 2).

Table 1. Definition and values of parameters used in ECOMAST stochastic simulation model of reproductive and economic performance in dairy herds to simulate the cow reproductive cycle

Parameter	Value[1]	Reference
Calving to first ovulation interval (CFOI; d)		Derived from Cutullic et al., 2011
Primiparous cows	$X \sim N(31, 100)$[2] with $X > 15$	
Multiparous cows	$X \sim N(26, 49)$[2] with $X > 15$	
Probability of a prolonged postpartum anovulation		
Average probability (CFOI = 45 d)	$1.2 \times (2.9 \times 10^{-5}) \times (MY_{305} - 5{,}000)$	Derived from Ledoux et al., 2011, and Cutullic et al., 2011
[minimum, maximum]	[0.05, 0.25]	
High probability (CFOI = 75 d)	$6.5 \times (2.9 \times 10^{-5}) \times (MY_{305} - 5{,}000)$	Dezetter et al., 2017
[minimum, maximum]	[0.28, 1]	
CFOI (d) in case of prolonged postpartum anovulation (primiparous and multiparous)	$X \sim N(75, 100)$[2] with $X > 50$	Derived from Ledoux et al., 2011, and Cutullic et al., 2011
No. of days to the resumption of ovarian cyclicity after abortion	$X \sim N(35, 16)$[2] with $X > 15$	Dezetter et al., 2017
Length of ovarian cycle (d)	$X \sim N(22, 12)$[2] with $17 < X < 29$	Dezetter et al., 2017
Probability of delay after 1st and 2nd postpartum ovarian cycles	$1.1 \times (1.4 \times 10^{-5}) \times (MY_{305} - 5{,}000)$	Derived from Ledoux et al., 2011, and Cutullic et al., 2011
[minimum, maximum]	[0.05, 0.15]	
No. of days in the interval between the first and second or between the second and third ovulation when the first or second postpartum ovarian cycle is delayed	$X \sim N(40, 100)$[2] with $X > 26$	Derived from Ledoux et al., 2011, and Cutullic et al., 2011
Length of pregnancy (d)	$X \sim N(282, 4)$[3]	Dezetter et al., 2017
Cumulated probability of pregnancy loss between d 21 and 120 of pregnancy (PL_{120})	0.15	Humblot, 2001; Grimard et al., 2006
Cumulated probability of abortion between d 120 and 275 of pregnancy (F_{abort})	0.015	Humblot, 2001; Grimard et al., 2006

[1] MY_{305} = milk yield in kilograms per cow over 305 d of lactation.

[2] $N(\mu, \sigma^2)$ = mean (μ) and variance (σ^2) parameters of truncated normal distribution.

[3] $N(\mu, \sigma^2)$ = mean (μ) and variance (σ^2) parameters of normal distribution.

Table 2. Definition and values of parameters used in ECOMAST stochastic simulation model of reproductive and economic performance in dairy herds to simulate the 3 levels of estrus expression (without expression, discreet, and normal expression) for each simulated ovulation according to parity, number of ovulation after calving, and number of estrus after AI of the cow

Item	Probability of estrus expression level at each simulated ovulation[1]		
	Without expression (P_{EWref})	Discreet (P_{ED})	Normal (P_{EN})
Primiparous			
1st ovulation	0.25	0.40	0.30
2nd ovulation	0.15	0.30	0.45
3rd ovulation and more	0.10	0.20	0.55
1st estrus after AI	0.15	0.30	0.30
2nd estrus and more after AI	0.10	0.20	0.40
Multiparous			
1st ovulation	0.25	0.35	0.35
2nd ovulation	0.15	0.25	0.50
3rd ovulation and more	0.05	0.15	0.60
1st estrus after AI	0.10	0.30	0.30
2nd estrus and more after AI	0.05	0.20	0.40

[1] All these parameters were computed from the expertise of the designers of the ECOMAST model (H. Seegers, INRA and ONIRIS, Nantes, France, personal communication).

The probability of ovulation with high expression of estrus (**P_{EH}**; event 2.1.3, Figure 1) was calculated as

$$P_{EH} = 1 - (P_{EW} + P_{ED} + P_{EN}). \quad [4]$$

At day t of simulated ovulation computed in step 1, the probability of attribution one level of estrus expression for this ovulation was randomly drawn using a multinomial law:

$$\text{level of estrus expression} \sim M\,(1;\ [P_{EW},\ P_{ED},\ P_{EN},\ P_{EH}]). \quad [5]$$

For cows that express estrus without ovulation (event 2.3, Figure 1), we assumed that this situation can occur if day t was less than CFOI or was between 2 successive ovulations. Estrus without ovulation was simulated in the model using Bernoulli's law, with P_{FO} as a parameter of this law (default value set at 0.05). We also assumed that all estrus without ovulation had a high level of estrus expression.

Step 3. Conception (Figure 1). Following estrus detection by the farmer, the cow could be inseminated (see the section on modeling herd management practices) and conceive (AI success and absence of early embryonic loss). If the cow actually ovulated (event 3.1, Figure 1), the probability of conception for a given cow was calculated. First, CP was calculated from the basic probability of conception (**CP_{basic}**). The latter was defined from the herd level of the 21-d conception rate (**CR_{21}**: default value set at 45%; i.e., proportion of cows pregnant 21 d after insemination), the daily milk yield and lactation stage of the cow and, to a lesser extent, from the herd sensitivity of estrus detection (**Se_H**: default value set at 50%), given its influence on DIM at AI. The CP_{basic} was defined for 2 levels of MY_t (low: ≤20 kg and high: 20–50 kg) and for 2 lactation stages [early: 50 DIM − 100 + (MY_t − 20) DIM; and late: ≥100 + (MY_t − 20) DIM]. For the early stage of lactation, CP_{basic} was calculated using the following formula (Grimard et al., 2006; Dezetter et al., 2017):

$$CP_{basic} = \begin{cases} CPref_{ijk} + \left[2.5 \times 10^{-3} \times (DIM - 30)\right] & \text{if } MY_t \text{ was low level} \\ CPref_{ijk} + \left[2.5 \times 10^{-3} \times (DIM - 30)\right] - \left[0.01 \times (MY_t - 20)\right] & \text{if } MY_t \text{ was high level.} \end{cases} \quad [6]$$

For the late stage of lactation, CP_{basic} was obtained by Grimard et al. (2006) and Dezetter et al. (2017):

$$CP_{basic} = \begin{cases} CPref_{ijk} & \text{if } MY_t \text{ was low level} \\ CPref_{ijk} - \left[7.5 \times 10^{-3} \times (MY_t - 20)\right] & \text{if } MY_t \text{ was high level.} \end{cases} \quad [7]$$

where $CPref_{ijk}$ is the reference value of the basic probability of conception for lactation stage i, 21-d conception rate j, and herd sensitivity of estrus detection k (Table 3). The values of $CPref_{ijk}$ were always assumed greater for late stage of lactation than for early stage of lactation.

Second, conception probability was calculated by multiplying CP_{basic} by fertilization parameter calculated in

Table 3. Reference values of the cow's basic conception probability parameter ($CPref_{ijk}$) used in the ECOMAST stochastic simulation model of reproductive and economic performance in dairy herds to simulate the 3 levels j (25, 45, and 70%) of the 21-d conception rate of the herd (CR_{21}), according to the lactation stage i, and the 3 levels k (20, 50, and 90%) of herd sensitivity of estrus detection by the farmer (Se_H)

21-d conception rate of the herd (CR_{21})	Lactation stage[1]	Se_H		
		20%	50%	90%
25%	Between 50 DIM and 100 + (MY_t − 20) DIM	0.213[2]	0.22[2]	0.234[2]
	≥ 100 + (MY_t − 20) DIM	0.30[2]	0.31[2]	0.33[2]
45%	Between 50 DIM and 100 + (MY_t − 20) DIM	0.397[2]	0.418[2]	0.45[2]
	≥ 100 + (MY_t − 20) DIM	0.556[2]	0.58[2]	0.63[2]
70%	Between 50 DIM and 100 + (MY_t − 20) DIM	0.60[2]	0.60[2]	0.70[2]
	≥ 100 + (MY_t − 20) DIM	0.90[2]	0.90[2]	0.99[2]

[1] MY_t = the daily milk yield in kilograms per cow at day t of lactation stage.

[2] All the values of $CPref_{ijk}$ were determined by iteration, using the approximate Bayesian computation rejection algorithm (Appendix A) to obtain the 3 simulated values of the proportion of cows pregnant 21 d after insemination (CR_{21}; 25, 45, and 70%) depending on the 3 values of Se_H.

the section "Modeling the Individual Genetic Value of the Cow" (see above) and by several coefficients known to influence fertility (Table 4): (1) parity ($\mathbf{EF_{Pi}}$); (2) number of ovulation after calving ($\mathbf{EF_{OVn}}$); (3) negative energy balance ($\mathbf{EF_{food}}$; see above the section modeling feeding plan and negative energy balance); (4) CPD ($\mathbf{EF_{CPD}}$); and (5) health disorders ($\mathbf{EF_{HDj}}$).

If a cow that expresses estrus without ovulation (event 3.4, Figure 1) was inseminated, the value zero was systematically assigned to the conception probability in the model.

Once the conception probability was calculated, the transition of the cow to pregnancy status was randomly drawn using Bernoulli's law, with the setting of this law being the conception probability.

Step 4. Pregnancy (Figure 1). If the cow conceived, the day of calving (event 4.1, Figure 1) was simulated in the model by a random draw in the normal distribution (Table 1). The sex of the future calf was also randomly drawn, using Bernoulli's law, where the probability of this law was set by default at 0.50. However, pregnancy could be interrupted (event 4.2, Figure 1) due to embryonic or fetal loss (between d 21 and 120 of pregnancy), or to an abortion (between d 120 and 275 of pregnancy). The risk of interruption of pregnancy was modeled by an exponential law (with decreased risk over time) and a Bernoulli law for pregnancy loss until 120 d and abortion, respectively. The probabilities used to simulate the occurrence of these 2 events were pregnancy loss until 120 d ($\mathbf{PL_{120}}$) and abortion (Table 1).

Modeling of Herd Management Practices

Reproductive Management. The probability of ovulation detection (event 2.1.5, Figure 1) was first determined by the Se_H (default value set at 50%) and then modulated by cow characteristics. The interaction between the level of estrus expression and ovulation detection by the farmer (Disenhaus et al., 2010) was taken into account, by assigning for each level i of estrus expression (discreet, normal, and high) and for each parity j an eigenvalue of estrus detection sensitivity ($\mathbf{Se_{ij}}$), which is the probability of ovulation

Table 4. Definition and values of parameters used in the ECOMAST stochastic simulation model of reproductive and economic performance in dairy herds to simulate the effect of parity, number of ovulation after calving, negative energy balance, reproductive disorders, and health disorders on the cow's conception probability

Parameter	Value	Reference
Parity effect[1]		Dezetter et al., 2017
3rd lactation	0.95	
4th lactation and more	0.93	
Effect of number of ovulation after calving		Dezetter et al., 2017
1st ovulation	0.90	
2nd ovulation	0.95	
Negative energy balance effect	0.90	Dezetter et al., 2017
Postpartum reproductive disorders effect	0.70	Derived from Ledoux et al., 2011
Health disorders effect	0.90	Fourichon et al., 2000

[1] We assumed that the value of conception probability was not different between cows in first and second lactation according to Grimard et al. (2006).

detection by farmer for a cow that actually ovulates. For cows ovulating without heat expression (event 2.2, Figure 1), Se_{ij} was set to zero, which means that these cows were never detected by the farmer. The use of Se_{ij} as Bernoulli's law parameter allows a random draw of the detected or undetected ovulation status. In addition, we assumed that all estrus expression without ovulation (event 2.3, Figure 1), whatever the cause, was detected by the farmer. Consequently, in this model, the parameter $1 - P_{FO}$ corresponds to the specificity of estrus detection (default value set at 0.95).

The voluntary waiting period for first insemination post calving was set at 50 d by default, whatever the season. After the voluntary waiting period, cows with $MY_t > 50$ kg were not inseminated until their daily milk yield was below 50 kg per day. Moreover, cows that express estrus within 17 d after the last detected estrus were systematically not inseminated by the farmer. The maximum number of services per cow was set to 6 (events 3.1, 3.2, 3.3, and 3.4, Figure 1).

Managerial Goals. Two MG were simulated in the model: keeping a constant number of cows or delivering a given volume of milk to the dairy each year. The MG "constant number of cows" corresponds to the situation where the farmer decides to maintain a fixed number of cows for the whole year; this strategy may be chosen by farmers when housing capacity or roughage resources or both are limited. Otherwise, the MG "constant volume of milk sold" consists of delivering a fixed volume of milk per farm and per year, this volume being defined by contracts with dairy companies. In both strategies, the farmer could manage situations with too many or too few cows (constant number of cows) and over- or underproduction (constant volume of milk sold) by adjusting decisions on the replacement, culling, sale, and purchase of animals.

Herd Replacement. Male calves were sold at 14 d old. The farmer could decide to either keep all or sell some 14-d-old female calves among those born of cows with the lowest milk production level. To fulfill the replacement needs relative to the MG chosen, the sale or purchase or both of pregnant heifers or lactating cows could be decided with a maximum value fixed in terms of the percentage of animals concerned.

Managing Herd Size by Culling. Voluntary culling was simulated for different reasons. For each cow, a culling candidacy score was calculated every 15 d, using the equations of Dezetter et al. (2017). This score depended on the multiplication coefficients defined according to the MY_{305} level, parity, reproductive, and health status. Poor reproductive and milk production performances were highly penalized by the values of these coefficients. A high score means that a cow was more likely to be culled (Dezetter et al., 2017). Cows with a score above a defined threshold (default value set at 60) were systematically and immediately culled. Other cows with a score below the threshold were classified into 3 groups: (1) 15% of the highest scores, (2) between 15 and 55% of the highest scores, and (3) the remaining cows. When culling was needed due to constraints related to the MG (over-production or too many cows), cows in the first group were culled in priority, whereas those in the third group were never culled. At day t (every 15 d) of calculation of culling candidacy score, a prediction of the annual herd milk production and of the mean of herd size were estimated for the rest of the year ($365 - t$) to assess the culling needs at this day; see Dezetter et al. (2017) for more details.

Cows older than 13 yr were systematically culled. If the DIM was beyond 300 d, nonpregnant cows with 3 or more failed AI were systematically culled when their MY_t was less than 6 kg. However, if these nonpregnant cows had a MY_t higher than 6 kg, they were systematically culled after 600 DIM. This long period of 600 d after calving was used to simulate the situation of infertile cows with an extended lactation before culling (Gates, 2013).

Random mortality and involuntary culling were simulated by using binomial law, regardless of the farmer's choices, constraints related to the MG, or to the effect of health disorders.

Model Output

Indicators of Herd Reproductive Performance. Six indicators were calculated each year: the CIN, the calving to first insemination interval (**CFII**), the calving to conception interval (**CCI**), the average amount of milk produced in kilograms per cow per year (**AMY_{cow}**), the number of cows being the mean number of cows in the herd over the year, the annual replacement rate (**ARR**), and the annual culling rate for infertility (**CRI**).

Indicators of Farm Economic Performance. The indicator used to evaluate the economic performance of dairy farms was basically the annual gross margin of the herd excluding premiums in euros (**AGM**):

$$\text{AGM} = \text{revenues} - \text{costs} + \text{inventory change}. \quad [8]$$

The revenues are earned from the sale of milk, cows, heifers, and calves. The costs are expenses for feedstuffs (roughage and concentrates), insemination, purchase of cows or heifers, and other costs (e.g., treatment of reproductive disorders, prevention, and treatment of IMI). The inventory change refers to the variation in the number (and price) of animals in the dairy farm between the beginning and the end of the year.

In addition, the gross margin was expressed per 1,000 L of milk produced per year (**AGM$_{1,000L}$**) and per cow per year (**AGM$_{cow}$**).

Model Exploitation

Initial Dairy Herd. A Holstein dairy herd of 60 cows, with the following average phenotypic traits for milk production: MY$_{305}$ = 8,000 kg/cow-year, milk fat content in grams per kilogram over 305 DIM = 39.6 g/kg, and milk protein content in grams per kilogram over 305 DIM = 32.2 g/kg, and which corresponded to the observed average of the Holstein dairy herds in France (AGRESTE, milk control data 2014), was simulated. The economic calculations were based on agricultural economic data collected in France in 2014 [for more details, see Dezetter et al. (2017)].

For reproductive management, calving was simulated throughout the year. The annual incidence of clinical mastitis was 40 cases per 100 cow-years, which is the average observed in dairy herds in France (Fourichon et al., 2001; Idele, 2013). The annual incidence of other health disorders in the initial herd was set at 40 per 100 cow-years. The probabilities of culling and mortality following a health disorder (HD$_{cull}$ and HD$_{death}$) were 0.075 and 0.01, respectively. The annual probabilities of random mortality and involuntary culling simulated for this initial herd were 0.03 (Perrin et al., 2010). The expected average of daily milk yield used to set the feeding plan (distributed for the simulated initial herd) was fixed according to the lactation curve presented in Dezetter et al. (2017). In this curve, the milk production peak was 42 kg at 45 DIM. As such, we used a threshold of 45 DIM to determine the 2 feeding plan periods. Then, we fixed the maximum amount of concentrate and roughage distributed for each cow for the simulated initial herd (Dezetter et al., 2017) at 15 kg of DM of roughage per day as well as 9 kg of DM per day of concentrate with an increment of 1.5 kg per week, when DIM was less than 45 d (period 1) and 15 kg of DM of roughage and 4.5 kg of DM of concentrate per day, when DIM was between 45 d after calving and 60 d before next calving (period 2).

Simulated Scenarios. The effects of the intrinsic characteristics of cows related to reproduction, namely CPD, fertility, and pregnancy, as well as the farmer's strategies for management of reproduction, production, and animal replacement, on the reproductive and economic performance of dairy cattle herds were tested by varying the values (within the range of possible values found in the literature) of the 6 following parameters of the model:

21-d Conception Rate of the Herd. Although the CR$_{21}$ was not an input parameter of the model (it was calculated by dividing the number of cows pregnant 21 d after insemination by the total number of cows inseminated), we parameterized the CPref$_{ijk}$, using the approximate Bayesian computation (**ABC**) rejection algorithm (Appendix A) to obtain the expected CR$_{21}$ values presented in Table 3. Three CR$_{21}$ values were simulated: (1) 25% (low; Cartmill et al., 2001a; Demetrio et al., 2007; Inchaisri et al., 2010); (2) 45% (average; Dhaliwal et al., 1996; Fricke et al., 1998); and (3) 70% (high; derived from the upper bound of the 95% CI of conception rate estimated by Drost et al. (1999) and from the 21-d pregnancy rate estimated by Chebel et al. (2003) and Inchaisri et al. (2010; Table 3).

Pregnancy Loss Until 120 Days. Three values of the parameter PL$_{120}$ were simulated: (1) 3% (low; Silke et al., 2002), (2) 15% (average), which was the reference value used by default in the model (Grimard et al., 2006; Table 1), and (3) 43% (high; Cartmill et al., 2001b).

Calving to First Ovulation Interval. As for the CR$_{21}$, the CFOI was not an input parameter of the model. Therefore, we parameterized the probability of a prolonged postpartum anovulation (p1) to obtain scenarios with expected CFOI values presented in Table 1. Two values of this parameter were simulated: 45 d (average), which is the reference value used by default in the model; and 75 d (high; Ledoux et al., 2011; Table 1).

Herd Estrus Detection Sensitivity. Although the Se$_H$ is not an input parameter of the model, the variation in the Se$_H$ was simulated by setting the Se$_{ij}$ values (individual sensitivity of each cow) for each expected simulated Se$_H$ scenario. The values of Se$_{ij}$ for each simulated Se$_H$ scenario were obtained using the ABC rejection algorithm (Appendix A). Three values of this parameter were simulated: (1) 20% (low) (Roelofs et al., 2005; Palmer et al., 2010); (2) 50% (average), which corresponds to the visual detection (Rutten et al., 2014); and (3) 90% (high), which may corresponds to the situation where an automated estrus detection device is used by the farmer (Østergaard et al., 2005; Roelofs et al., 2005).

Managerial Goals. Both MG were tested: delivery of a given volume of milk to the dairy, set at 480,000 L per year (reference MG) and keeping a constant annual average number of cows at 60 cows (lactating and dry cows) in the herd. The tolerated annual variation for the 2 MG was more or less than 5%.

Management of Purchase and Sale of Animals by the Farmer. Two management of purchase and sale of animals by the farmer (**MPS**) scenarios were simulated: closed or open herd. In the closed herd scenario, the purchase and sale of animals (cows and heifers) from or to another farm were not allowed. The exit of cows related to MG constraints (in case of too many cows or over-production) was simulated only by culling cows, with a candidacy score above a defined threshold (default value set at 60), which corresponds to cows with high prevalence of health disorders and poor milk production performances. For open herd scenario (reference MPS), in addition to culling strategy, the farmers under MG constraints could purchase (cows and pregnant heifers in situation with too few cows or under-production) and sell animals (cows and heifers in situation with too many cows or over-production). The maximum allowed percentage of animals purchased or sold per year was set at 20 and 40% of the herd size, respectively (Appendix B).

Simulation Run. Two simulation plans were run: the first consisted in varying the value of a single parameter while fixing the others in the reference values, whereas the second consisted of varying the values of the 6 parameters tested simultaneously.

In simulation plan 1, a total of 10 scenarios were simulated to estimate the relative difference in the reproductive and economic performances between different values of a single factor (Table 5). A complete factorial plan (simulation plan 2) was implemented to quantify the weight of the 6 factors studied and their interactions on the reproductive and economic outputs of the model, with a total of 216 simulated scenarios. A sensitivity analysis, using sensitivity indices (**IS**), was used to compute the weight of each individual factor on this complex simulated system (Zhu et al., 2017). These IS were estimated from the variance decomposition in the ANOVA test. Two IS were calculated: the main sensitivity indices (**$\mathbf{IS_p}$**), which allowed to quantify the proportion of j model output variability explained by the effect of the factor i; and the interaction sensitivity indices (**$\mathbf{IS_i}$**), which allowed to quantify the proportion of j model output variability explained by the effect of the interaction between 2 factors i and z. These 2 indices were calculated with the R software (R Development Core Team, 2016) using the following formulas (Brun et al., 2006; Courcoul et al., 2011):

$$\mathrm{IS_p} = \mathrm{V_{(i)}}/\mathrm{V_{(j)}}, \tag{9}$$

$$\mathrm{IS_i} = \mathrm{V_{(i,z)}}/\mathrm{V_{(j)}}, \tag{10}$$

where $\mathrm{V_{(i)}}$ is the variance of factor i, $\mathrm{V_{(i,z)}}$ is the variance of the interaction between factor i and z, and $\mathrm{V_{(j)}}$ is the variance of j model output.

Table 5. Definition of the 10 scenarios for simulation plan 1 obtained by individual variation of a single factor among the 6 factors studied

	Scenario ID									
Factors studied	1[1]	2	3	4	5	6	7	8	9	10
21-d conception rate of the herd[2] (%)	45	25	70	45	45	45	45	45	45	45
Probability of pregnancy loss between d 21 and 120 of pregnancy (%)	15	15	15	3	43	15	15	15	15	15
Calving first ovulation interval (d)	40	40	40	40	40	75	40	40	40	40
Herd sensitivity of estrus detection by the farmer (%)	50	50	50	50	50	50	20	90	50	50
Management of purchase and sale of animals by the farmer	Open herd	Open herd	Open herd	Open herd	Open herd	Open herd	Open herd	Open herd	Closed herd	Open herd
Managerial goals	Constant volume of milk sold	Constant volume of milk sold	Constant volume of milk sold	Constant volume of milk sold	Constant volume of milk sold	Constant volume of milk sold	Constant volume of milk sold	Constant volume of milk sold	Constant volume of milk sold	Constant number of cows

[1] Scenario 1 is the baseline scenario of simulation plan 1.

[2] Proportion of cows pregnant 21 d after insemination.

A factor or the interaction between 2 factors was considered important when the value of the IS (IS_p, IS_i) was greater than or equal to 5%.

Each scenario was simulated for 10 yr, with 250 repetitions. Data from the first 5 yr of simulation were not used in our study as they were used to calibrate the stochastic simulation model. Results were therefore produced from the average over the last 5 yr of the indicators of herd reproductive and farm economic performance.

RESULTS

Effect of a Change to a Single Factor on Reproductive and Economic Performance (Simulation Plan 1)

The mean ± standard deviation of 250 replicates of the indicators from the baseline scenario (scenario 1 in Table 5) and their relative difference for the other scenarios (scenarios 2 to 10 in Table 5) are shown in Table 6.

Indicators of Herd Reproductive Performance

The simulation results for the baseline scenario yielded a CFII of 87.5 ± 1.6 d, a CCI of 139 ± 4.7 d, and a CIN of 414.3 ± 5.1 d. The average number of cows was 59 ± 0.9. The AMY_{cow} was 8,376 ± 112.6 kg. The ARR and CRI were 35.2 ± 2.7% and 4.6 ± 1.4%, respectively.

The decrease in the CR_{21} (i.e., proportion of cows pregnant 21 d after insemination) from 45 to 25% (scenario 2) induced on average an increase of 32 d in the CCI, 24 d in the CIN and 12% in the CRI. Increasing the CR_{21} from 45 to 70% (scenario 3) reduced the CCI by 20 d, the CIN by 18 d, and the CRI by 3.4%. The effect of the CR_{21} on reproductive performance depended on the initial fertility status of the herd: a 10-percentage-point increase in the CR_{21} when the initial CR_{21} was low was associated with a reduction of 12 d in the CIN; however, when the initial CR_{21} was average, it was associated with a decrease of 7.2 d in the CIN.

The decrease in the PL_{120} from 15 to 3% (scenario 4) induced on average a decrease of 10 d in the CCI and 2% in the CRI. Increasing the PL_{120} from 15 to 43% (scenario 5) increased the CCI by 28 d, the CIN by 19 d, and the CRI by 7.5%.

Increasing the CFOI from 45 to 75 d (scenario 6) increased the CFII by 19 d, the CCI by 19 d, and the CIN by 20 d. However, the increase in the CFOI from 45 to 75 d decreased the ARR by 2.5%.

The decrease in the Se_H from 50 to 20% (scenario 7) induced on average an increase of 47 d in the CFII, 69 d in the CCI, 48 d in the CIN, and 6.2% in the CRI. Increasing the Se_H from 50 to 90% (scenario 8) reduced the CFII by 16 d, the CCI by 25 d, the CIN by 23 d, and the CRI by 3.2%. The effect of the Se_H on the reproductive performance depended on the initial sensitivity of estrus detection by the farmer: a 10-percentage-point increase in the Se_H when the initial Se_H was low was associated with a reduction of 16 d in the CIN; however, when the initial Se_H was average, it was associated with a decrease of 5.7 d in the CIN.

Scenarios with MPS "closed herd" (scenario 9) and MG "constant number of cows" (scenario 10) had an effect on the ARR only, and they reduced this indicator by 6 and 7%, respectively.

Farm Economic Performance

The simulation results for the baseline scenario yielded an AGM of €114,288 ± 2,264, an $AGM_{1,000\text{ L}}$ of €234.8 ± 4.5 and an AGM_{cow} of €1,934 ± 50.3. The sale of milk (€178,349 ± 1,588.5) represented approximately 88% of the revenues (€202,175 ± 3,164). However, the cost of feed (€60,983 ± 1,018) for fodder and concentrates represented around 70% of the costs (€87,513 ± 1,692) of the farm.

The decrease in the CR_{21} from 45 to 25% (scenario 2) induced on average a decrease of €8,000 in the AGM, €9.4 in the $AGM_{1,000\text{ L}}$, and €124 in the AGM_{cow}. This decrease was explained by the increase in costs related to the purchase of animals (€5,722.5) and AI (€1,766.8). However, increasing the CR_{21} from 45 to 70% (scenario 3) increased the AGM by €2,286, the $AGM_{1,000\text{ L}}$ by €2.3 and the AGM_{cow} by €55.7. The effect of the CR_{21} on economic performance depended on the initial fertility status of the herd: a 10-percentage-point increase in the CR_{21} when the initial CR_{21} was low was associated with an increase of €62.2 in the AGM_{cow}; however, when the initial CR_{21} was average, it was associated with an increase of €22.3 in the AGM_{cow}.

The decrease in the PL_{120} from 15 to 3% (scenario 4) induced on average a decrease of €668.3 in the cost of the purchase of animals. Increasing the PL_{120} from 15 to 43% (scenario 5) decreased the AGM_{cow} by €77.4 and increased the costs related to AI and the purchase of animals by €605.8 and €2,088.5, respectively.

Increasing the CFOI from 45 to 75 d (scenario 6) decreased the AGM_{cow} by €58. This decrease was due to lower revenues from the sale of animals (−9%) and an increase in animal purchase costs (+15%).

The decrease in the Se_H from 50 to 20% (scenario 7) resulted on average a decrease of €3,429 in the AGM and €105 in the AGM_{cow}. Increasing the Se_H from 50 to 90% (scenario 8) increased the AGM by €1,143 and the AGM_{cow} by €50. However, improving the estrus detec-

Table 6. The mean and SD of the 250 replicates of the indicators of reproductive and economic performance simulated by the model for the baseline scenario (simulation plan 1) and the relative difference (%) of the mean of these indicators when changing the value of a single factor among the 6 factors studied compared with the baseline scenario

	Baseline scenario (scenario 1)		CR_{21}[1]		PL_{120}[2]			Se_H[4]			
Indicator	Mean	SD	25% (scenario 2)	70% (scenario 3)	3% (scenario 4)	43% (scenario 5)	CFOI[3] = 75 d (scenario 6)	20% (scenario 7)	90% (scenario 8)	MPS[5] "closed herd" (scenario 9)	MG[6] "constant number of cows" (scenario 10)
Reproductive indicator											
No. of cows present per year	59	0.9	0	−1	−1	1	1	3	−2	5	6
CFII[7] (d)	87.5	1.6	−2	0	0	0	22	54	−18	1	1
CCI[8] (d)	139	4.7	23	−14	−7	20	14	50	−18	4	5
CIN[9] (d)	414.3	5.1	6	−4	−2	5	5	11	−5	2	1
AMY_{cow}[10] (kg)	8,376	112.6	−3	2	1	−2	−2	−6	3	−1	0
ARR[11] (%)	35	2.7	−3	3	2	−3	−7	−2	1	−17	−20
CRI[12] (%)	4.6	1.4	259	−74	−43	164	9	136	−70	14	−12
Economic indicator (€)											
Annual gross margin (AGM)	114,288	2,264	−7	2	1	−3	−2	−3	1	2	3
$AGM_{1,000\,L}$[13]	234.8	4.5	−4	1	1	−2	−1	0	0	−2	−3
AGM_{cow}[14]	1,934	50.3	−6	3	2	−4	−3	−5	3	−3	−3
Revenues	202,175	3,164	−2	0	0	−1	−2	−1	0	1	1
Sale of milk	178,349	1,506	−2	0	0	−1	0	−1	0	3	4
Sale of animals	23,826	2,444	−1	1	1	−1	−9	0	0	−19	−17
Costs	87,513	1,501	5	−3	−1	2	−1	1	−1	−1	0
Ration cost	60,983	1,018	−4	0	0	−1	−2	−1	0	4	5
AI cost	5,048	199	35	−25	−6	12	−5	−20	5	3	4
Purchase of animals	4,177	1,310	137	−21	−16	50	15	91	−15	−100	−86
Other costs	17,305	420	−3	−1	0	−1	0	−4	−3	4	5
Inventory change	−374	1,652	−107	44	22	−16	−36	105	0	43	−62

[1] 21-d conception rate of the herd (i.e., proportion of cows pregnant 21 d after insemination).

[2] Probability of pregnancy loss between d 21 and 120 of pregnancy.

[3] Calving to first ovulation interval.

[4] Herd sensitivity of estrus detection by the farmer.

[5] MPS = management of purchase and sale of animals by the farmer.

[6] MG = managerial goals.

[7] CFII = calving to first insemination interval.

[8] CCI = calving to conception interval.

[9] CIN = calving interval.

[10] AMY_{cow} = milk yield in kilograms per cow per year.

[11] ARR = annual replacement rate.

[12] CRI = annual rate of culling for infertility.

[13] Gross margin in euros per 1,000 L of milk produced per year.

[14] Gross margin in euros per cow per year.

tion was associated with an increase (+5%) in the cost of AI and a decrease (−15%) in the animal purchase costs. The effect of the Se_H on the reproductive performance depended on the initial sensitivity of estrus detection by the farmer: a 10-percentage-point increase in the Se_H when the initial Se_H was low was associated with an increase of €35 in the AGM_{cow}; however, when the initial Se_H was average, it was associated with an increase of €12.5 in the AGM_{cow}.

Scenarios with MPS "closed herd" (scenario 9) and MG "constant number of cows" (scenario 10) had almost the same effect on economic performance. In both scenarios, we observed on average an increase of €2,286 and €3,429 in the AGM and a decrease of €4.7 and €7 in the $AGM_{1,000\ L}$, respectively. Similarly, a decrease of €58 in the AGM_{cow} was also observed in both scenarios. The increase in the AGM was explained by the increase in the sale of milk as a result of the high number of cows within the herd per year (+5%: 3 more cows in both scenarios) compared with the baseline scenario. As a corollary, the feed cost increased from 4 to 5% compared with the baseline scenario, and consequently, the AGM_{cow} decreased by 3%. Despite the increase in the sale of milk, the effect of the 2 factors MPS and MG on the AGM was mitigated by the decrease (between −17 and −19%) in the revenues related to the sale of animals. This decrease was a consequence of a low ARR (between −17 and −20%) compared with the baseline scenario.

Quantification of the Weight of the 6 Factors and Their Interactions on Reproductive and Economic Performance (Simulation Plan 2)

Figure 2 shows that the Se_H and the CR_{21} had an important effect on the CIN. The increase in the Se_H and the CR_{21} were associated with a decrease in the CIN. However, the decisions to purchase and sale of animals had no important effect on the effect of the Se_H and the CR_{21} on the CIN. Figure 3 shows that, in addition to the positive effect of the increase in the Se_H and the CR_{21} on the AGM, the decisions to purchase and sale of animals had an effect on the effect of the Se_H and the CR_{21} on the AGM.

The IS of the 6 factors studied and their interactions are displayed in Table 7. The Se_H was the factor that had the greatest effect on the variability of most reproductive indicators. The Se_H explained 89.8, 61.5, 58.9, and 53.7% of the variability of the CFII, CCI, CIN, and AMY_{cow}, respectively; and only 7.5% of the AGM (Table 7). The CR_{21} was the factor that had the greatest effect on the economic outputs of the model, which explains 54.4% of the variability of the AGM. In addition, the CR_{21} was the second factor that affected the reproductive indicators, which explains 23, 19.8, and 19.5% of the variability of the AMY_{cow}, CCI, and CIN, respectively. The second factor related to cow characteristics that had an effect on economic performance was PL_{120}, which explained 7.6% of AGM variability (Table 7).

The other factors (CFOI, MPS, and MG) and all possible interactions studied did not have an important effect on the variability of reproductive and economic indicators, except for the interaction between the CR_{21} and the MPS, which had a slight effect on the AGM (IS = 6.7%; Table 7). Figure 4 shows that the AGM was higher in an open herd than in a closed herd when the CR_{21} was 25 or 45% (low or average fertility). However, when the CR_{21} was 70%, the AGM became higher in closed than in open herds.

DISCUSSION

In this study, the calculated sensitivity indices from the simulation of 216 scenarios with 250 repetitions, for a range of possible values of the parameters reported in the literature, showed that the management of estrus detection had a greater effect than the fertility of cows on the reproductive performance indicators (IS_p of Se_H > IS_p of CR_{21}) of Holstein dairy herds. However, the fertility of cows was the most influential factor for economic performance indicators. In the previous simulation models (particularly the epidemiological models), the effects on output parameters of large values of input parameters [e.g., use of 95% for the sensitivity of estrus detection by Rutten et al. (2014)] or of noninformative distributions of input parameters [e.g., use of an uniform distribution (10–80%) for the submission rate by Hudson et al. (2014)] were tested in a classical sensitivity analysis. However, in this study, our aim was to use a range of values that were more realistic and documented in the literature. Our approach was chosen because the calculation of the sensitivity indices in this study was based on the variance decomposition method, which was itself sensitive to the values of the model input parameters, and allowed us to calculate with a high degree of precision the respective weight of each input parameter studied.

The effect of the increase of the Se_H on the shortening of the CIN (increasing the Se_H from low (20%) to average (50%) levels and from average to high (90%) levels reduced the CIN by 48 and 23 d, respectively) was mainly due to the shortening of the CFII. This effect is consistent with the data simulated in the literature (Inchaisri et al., 2010; Rutten et al., 2014). Rutten et al. (2014) reported a reduction of 16 d in the CIN for an increase in estrus detection sensitivity from 50 to 80% (Rutten et al., 2014), whereas Inchaisri et al. (2010) showed by simulation that the increase in estrus detection sensitivity from 30 to 50% and from 50 to 70% was associated with a reduction in the CIN of 100 and 45 d, respectively. However, in the latter study, the different levels of estrus expression and the correlation between estrus expression level, parity, and estrus detection sensitivity were not taken into consideration in the model, which could explain these higher effects compared with our results.

The high Se_H level that we tested (90%) could be attained by using the milk progesterone assay (Østergaard et al., 2005), which is considered as the gold

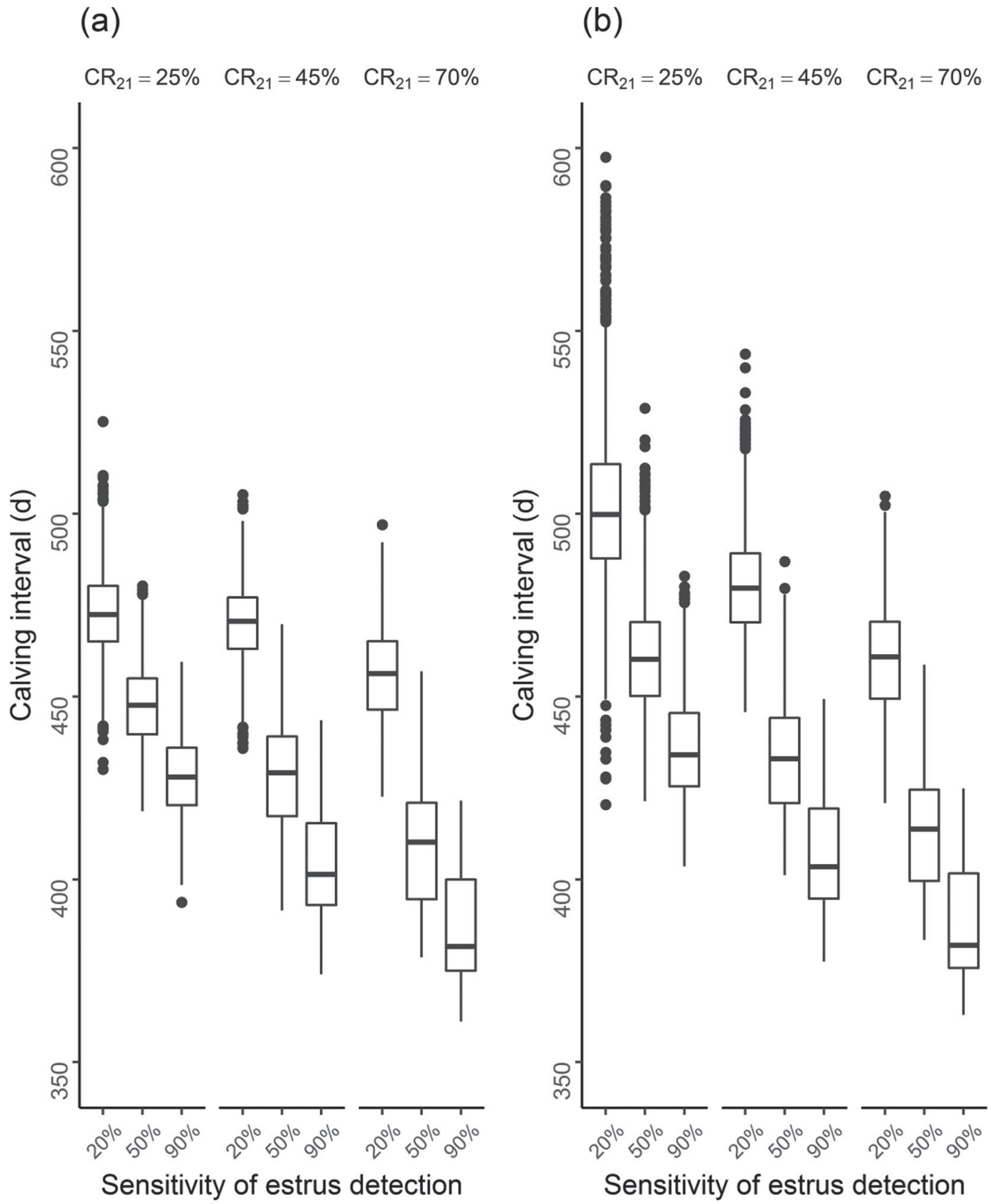

Figure 2. Effect of the interaction between 21-d conception rate of the herd, sensitivity of estrus detection by the farmer, and management of purchase and sale of animals on the calving interval in simulation plan 2. (a) Scenarios with management of purchase and sale of animals "open herd: farmers can buy and sell animals"; (b) scenarios with management of purchase and sale of animals "closed herd: the purchase and sale of animals (cows and heifers) from or to another farm was not allowed"; CR_{21} = 21-d conception rate of the herd (i.e., proportion of cows pregnant 21 d after insemination). The boxes identify interquartile ranges (quartile 1–quartile 3), the solid black mid line indicates the median, whiskers end at the lowest and highest values that are not extreme values, and dots represent extreme values.

standard method for the detection of ovulation (Roelofs and Der Kooij, 2015), regardless of the level of estrus expression. However, this high value of Se_H could be difficult to reach by visual detection and could also be considered as too optimistic when estrus detection is realized with an accelerometer or pedometer. In fact, the expression of estrus by Holstein cows is relatively discreet, with about 60% of ovulations not accompanied by standing heat (Van Eerdenburg et al., 1996; Kerbrat and Disenhaus, 2004; Roelofs et al., 2005). Isobe et al. (2004) reported in the study carried out on 32 Holstein cows that incidences of silent ovulations

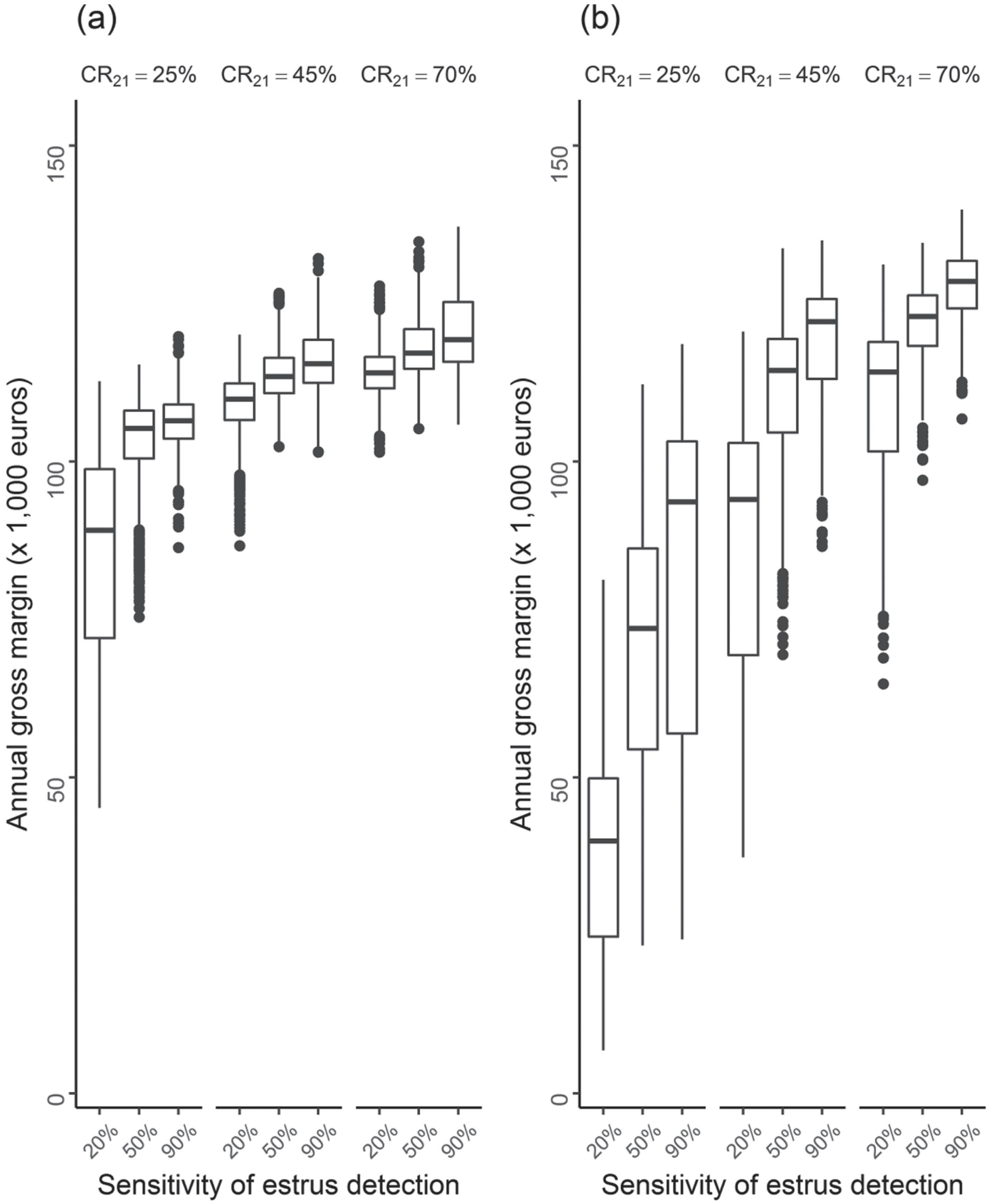

Figure 3. Effect of the interaction between 21-d conception rate of the herd, sensitivity of estrus detection by the farmer, and management of purchase and sale of animals on the annual gross margin in simulation plan 2. (a) Scenarios with management of purchase and sale of animals "open herd: farmers can buy and sell animals"; (b) scenarios with management of purchase and sale of animals "closed herd: the purchase and sale of animals (cows and heifers) from or to another farm was not allowed"; CR_{21} = 21-d conception rate of the herd (i.e., proportion of cows pregnant 21 d after insemination). The boxes identify interquartile ranges (quartile 1–quartile 3), the solid black mid line indicates the median, whiskers end at the lowest and highest values that are not extreme values, and dots represent extreme values.

Table 7. Sensitivity indices (%) of the 6 factors studied and their interactions calculated from simulation plan 2 for the indicators of reproductive and economic performance of the Holstein dairy farm

	Reproductive and economic indicator[1]				
Factor studied	CFII	CCI	CIN	AMY_{cow}	AGM
21-d conception rate of the herd (CR_{21})[2]	0	19.5	19.8	23	54.5
Probability of pregnancy loss between d 21 and 120 of pregnancy (PL_{120})	0	10.4	7.7	6.6	7.6
Calving to first ovulation interval (CFOI)	7.1	2	3.8	2.1	0.3
Herd sensitivity of estrus detection by the farmer (Se_H)	89.8	61.5	58.9	53.5	7.5
Management of purchase and sale of animals by the farmer (MPS)	0	1	1.4	0.6	0.1
Managerial goals (MG)	0	0	0	0	0.3
CR_{21} × PL_{120}	0	0	0.3	1.2	0.5
CR_{21} × CFOI	0	0	0	0	0
CR_{21} × Se_H	0	0.1	0.8	1.2	1.1
CR_{21} × MPS	0.1	0.7	0.7	0.4	6.7
CR_{21}× MG	0	0	0	0.1	0.2
PL_{120} × CFOI	0	0	0	0	0
PL_{120} × Se_H	0	0	0.5	0.3	0
PL_{120} × MPS	0	0	0.1	0	0.5
PL_{120} × MG	0	0	0	0	0
CFOI × Se_H	0	0	0.1	0.1	0
CFOI × MPS	0	0	0	0	0
CFOI × MG	0	0	0	0	0
Se_H × MPS	0.2	0.5	0.5	0.2	1.5
Se_H × MG	0	0	0	0	0
MPS × MG	0	0	0	0.1	1.5

[1] CFII = calving to first insemination interval; CCI = calving to conception interval; CIN = calving interval; AMY_{cow} = milk yield in kilograms per cow per year; AGM = annual gross margin.

[2] CR_{21} = proportion of cows pregnant 21 d after insemination.

at the first, second, third, and fourth ovulation postpartum were 83, 46, 13, and 0%, respectively. In the model settings, the percentage of cows with discreet ovulation varied between 15 and 40%, depending on the parity and number of ovulation after calving of the cow (Dezetter et al., 2017). These discrete ovulations are difficult to detect even by automatic devices, due to the negative correlation between the sensitivity of ovulation detection by the pedometer or accelerometer and the percentage of silent ovulations. Indeed, factors that decrease the expression of estrus during the real ovulation, such as the number of ovulation after calving, will also decrease the sensitivity of automated estrus detection devices (Roelofs and Der Kooij, 2015). For example, Ranasinghe et al. (2010) compared the data recorded by the pedometer and the progesterone assay of 161 Holstein cows and estimated that the sensitivity of ovulation detection by pedometer at the first, second, third, and fourth ovulation postpartum was 44.8, 76.2, 78.7, and 89.5%, respectively. It is well established that the low sensitivity of the estrus detection during the first ovulation, occurring during the voluntary waiting period, hardly affects the reproductive performance of the herd; however, if the number of cows that exhibit a prolonged postpartum anovulation increases (e.g., scenarios with CFOI of 75 d), the first ovulation may occur after the voluntary waiting period, and thus the performance of automated estrus detection devices will be negatively affected (Roelofs and Der Kooij, 2015).

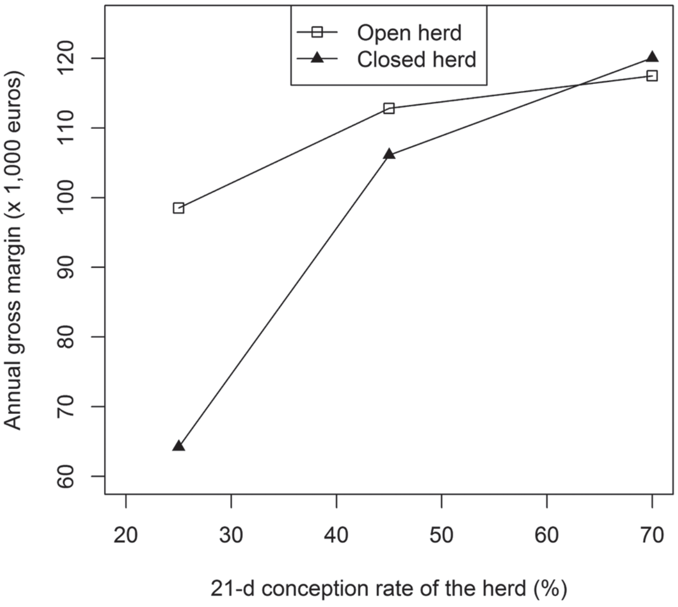

Figure 4. Mean effect of the interaction between 21-d conception rate of the herd and management of purchase and sale of animals by the farmer on the annual gross margin in simulation plan 2. 21-d conception rate of the herd = proportion of cows pregnant 21 d after insemination.

Although the sensitivity of a test is negatively correlated with its specificity (Dohoo et al., 2009), in this work we set the value of estrus detection specificity at 95% for different Se_H scenarios. In fact, we assumed that the farmer always visually checks any estrus detected by an automated estrus device (scenario with $Se_H = 90\%$), and any alert within 17 d after the last detected estrus was systematically rejected (assumed false alarm). In addition, any slight decrease in the specificity could lead to a marginal increase in the number of services per cow (if the day t of false positive alert was day of end of voluntary waiting period $\leq$ t $<$ CFOI or t $>$17 d after the last detected estrus), but would not affect the CCI or CIN. Indeed, the values of CCI and CIN were mainly influenced by the sensitivity of ovulation detection and the conception rate (common IS of Se_H and CR_{21} was 80% for these 2 indicators). The slight increase in the costs related to AI is the main economic effect resulting from the decrease in the specificity of estrus detection. However, according to several studies (Seegers et al., 2006; Rutten et al., 2013), the decrease in estrus detection specificity did not have a significant negative effect on the economic performance of dairy cattle farms.

Although the IS for the Se_H for the indicators of economic performance were lower than those of the reproduction, the Se_H is the factor with the second highest effect on the AGM. The reduction in the CIN resulting from an improvement in the Se_H increased the AMY_{cow}, and consequently, it reduced the number of cows needed to achieve the MG "constant volume of milk sold." This chain reaction could explain the observed economic gain. The beneficial effect of the increase in the Se_H on the AGM_{cow} [increasing 10 percentage points of the Se_H from low (20%) to average (50%) levels and from average to high (90%) levels increased the AGM_{cow} by €35 and €12.5, respectively] was consistent with the results of several studies (De Vries and Conlin, 2003; Inchaisri et al., 2010). For example, an increase of 10 percentage points in the Se_H was associated with an increase in the AGM_{cow} of \$27 (De Vries and Conlin, 2003) and €26.5 (Inchaisri et al., 2010) when the initial Se_H was less than 50%, and between €5.5 (Inchaisri et al., 2010) and \$7.8 (De Vries and Conlin, 2003) when the initial Se_H was greater than 50%. It is worth indicating that the estimated effects in our work are greater than the values found in latter studies. This difference could be explained on the one hand by an overestimation of the positive economic effect of the increase in the Se_H, on the grounds that an improvement in the Se_H requires an investment in working time (e.g., increasing the Se_H from 20 to 50% for visual detection of estrus) or in automated estrus detection devices (e.g., increasing the Se_H from 50 to 90%). This investment will generate additional costs that were not included in our study. On the other hand, this difference could also be due to the different economic contexts simulated in each study. In our work, the economic calculations were based on agricultural economic data collected in France in 2014. In addition, 2014 was considered more favorable economically than the following years, which have seen an increase in the prices of concentrate and a stagnation of the milk price. Consequently, the economic results simulated in our study overestimated the current economic performance observed in dairy farms in France.

The economic effect of cow fertility simulated in our work [increasing the CR_{21} (i.e., proportion of cows pregnant 21 d after insemination) by 10 percentage points between the low (25%) and average (45%) levels and between the average and high (70%) levels increased the gross margin by €62.2 and €22.3/cow-year, respectively] was close to that simulated by Inchaisri et al. (2010) for dairy cattle farms in the Netherlands, who reported that the 10-percentage-point increase in the conception rate, when the initial value is lower than 50%, was associated with an average increase in gross margin per cow per year of €37.8, and that the 10-percentage-point increase in the conception rate over the reference value (50%) was associated with an increase of €8.35 in the gross margin per cow per year. In this study, although the effect of the CR_{21} on reproductive performance was lower compared with the Se_H, we noted that the CR_{21} was the parameter that had the greatest effect on economic performance of dairy farms. This result was consistent with the work of Inchaisri et al. (2010), and could be explained by a higher increase in milk sales revenue and by a greater reduction of AI and animal purchase costs, when improving the CR_{21} compared with the Se_H. Indeed, the success of AI (decreasing in the AI cost) and the self-sufficiency for the renewal of cows from heifers born in the herd (decreasing in the cost of animals purchase) were mainly linked to the improvement of conception rate of the cows.

The pregnancy loss until 120 d had an effect on the variability of economic performance of our dairy farm. The economic effect of this factor (increasing 1 percentage point in the PL_{120} decreased the gross margin by €2/cow-year) was close to that calculated by Inchaisri et al. (2010) for dairy cattle farms in the Netherlands, who noted that an increase of 1 percentage point in the embryonic death rate decreased the gross margin by €4/cow-year.

In this study, the 2 factors whose interaction had an effect on the economic performance of the dairy farms were the CR_{21} and the MPS. In fact, decisions to buy and sell animals had an effect on the ARR, because closed farms (no sale or purchase of animals) had a low turnover rate (van Schaik et al., 1998). In addition, the reduction in the ARR combined with the culling of cows having low milk production, as well as the selection of heifers from cows with high milk production levels could increase the economic performance of dairy farms (Lopez-Villalobos and Holmes, 2010). Therefore, farmers who chose to reduce the ARR by adjusting their decisions for buying and selling animals, in reaction to the degradation of the CIN, could reduce the negative effect of poor reproductive performances on the economic performances of their farms.

The other management and cow factors studied (CFOI, MG, and MPS) did not have a major effect on the reproductive and economic indicators, but the magnitude of their effects was consistent with the previously reported data (Sørensen et al., 1992; van Schaik et al., 1998). The calculated economic results of a closed herd scenario (MPS) were similar to those reported by van Schaik et al. (1998), who determined that the closed farms had an increase of 5% in the net income compared with open herds. In our study, the scenarios with the MG "constant number of cows" had a higher economic performance than scenarios with the MG "constant volume of milk sold," which is similar to the results of Sørensen et al. (1992).

Other factors related to farming systems (compact or continuous calving, milk production level, cows breed, herd size, and so on), which are known to have an effect on the reproductive and economic performance of dairy farms (Lucy, 2001), have not been studied in our work. Therefore, not taking into consideration the farming system in this study could have over- or underestimated the calculated effect of the Se_H on the reproductive and economic performance of dairy farms.

In this study, we uses the ECOMAST model (Dezetter et al., 2017), as it is more appropriate to simulate more realistic and refined data for dairy herds. However, the high number of parameters of this model showed that it is more complex compared with those proposed in the literature (Østergaard et al., 2005; Cabrera, 2012; Rutten et al., 2014). This complexity could be behind some difficulties in implementing this model, such as (1) the values of some parameters were set from the experience of the authors (Dezetter et al., 2017); (2) the stochasticity of the simulated processes made the calibration of the simulated scenarios more difficult (Hofmann, 2005) and required a longer computation time; and (3) the high number of parameters in our model did not enable us to achieve a global sensitivity analysis to quantify the weight of each input parameter on the model outputs. Despite this, the complexity of the model allowed us to simulate the reproduction of cattle, which is a complex biological phenomenon, and to obtain data closer to reality and consistent with the literature.

The partial sensitivity analysis carried out showed that a large part of the variability of the reproductive and economic outputs was explained by the Se_H and the $CR_{21,}$ respectively. The calibration of the model to reproduce a given context with high precision requires more precise knowledge of the values of the Se_H and the CR_{21} than the values of any of the other parameters of the model.

Due to the lack of data, particularly for the key parameters, Se_H and CR_{21}, external validation of the model with real data remains difficult to achieve. However, other validation techniques, such as the face validity technique, could be used. In this technique, the adequacy of the results of the scenarios tested is checked, either with real data or with the results expected or observed in the literature (Haffke et al., 2015). In our work, the results of the scenarios in which we varied the Se_H, CR_{21}, CFOI, and PL_{120} of the cows were consistent with the expected results and with the data in the literature (Inchaisri et al., 2010; Rutten et al., 2014). Similarly, the median distribution of reproductive indicators CIN (405 d), CFII (94 d), and CCI (139 d), observed for French Holstein dairy herds with 60 cows (Bekara et al., 2016), were close to the means and medians of the simulated distributions of the corresponding indicators in the baseline scenario in simulation plan 1 (the baseline scenario medians not shown in Table 6 were 414, 88, and 139 d for CIN, CFII, and CCI, respectively).

CONCLUSIONS

In this study, the sensitivity indices calculated on simulated outputs, for a possible range of variations in the values of the factors studied, showed that the herd management practices, essentially estrus detection, had a greater effect than the intrinsic characteristics of the cows on reproductive performance. Conversely, the intrinsic characteristics of the cows (conception rate, and to a lesser extent, pregnancy loss until 120 d) had a greater effect than the herd management practices on the economic performance of dairy cattle farms. However, the effect of improving the sensitivity of estrus detection and the conception rate on reproductive and economic performance was not uniform, and was even higher when the reproductive performance of the herd was poor. The effect of the interaction between herd management practices (management of purchase and sale of animals) and the intrinsic characteristics of the cows (conception rate) on the economic benefit of dairy cattle farms was demonstrated in this study. With a low conception rate, open herds had lower economic losses than closed herds. In addition, without interaction, closed herds or farms with constant number of cows had economic losses of around €58/cow-year, compared with open herds or to farms with constant volume of milk sold. Altogether, our results suggest that, in a typical French dairy farm, farmers' efforts on estrus detection will be more profitable when associated with improvement of the conception rate of the cows.

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APPENDIX A

Approximate Bayesian Computation Rejection Algorithm

The ABC rejection algorithm was used to estimate the values of 2 input parameters of the ECOMAST model: (1) the sensitivity of estrus detection for the estrus expression level i (discreet, normal, and high) and for the parity j of the cow (Se_{ij}), and (2) the reference value of the basic conception probability of the cow ($CPref_{ijk}$). This step was necessary before performing the simulations, because the 2 important factors, the 21-d conception rate of the herd (CR_{21}; i.e., proportion of cows pregnant 21 d after insemination) and the herd estrus detection sensitivity (Se_H), which were used to define the simulation plan 2, were themselves the output parameters of the model and their values were determined from the values of Se_{ij} and $CPref_{ijk}$. The ABC method estimates the values of Se_{ij} and $CPref_{ijk}$ by analyzing the similarity between the expected and the simulated data obtained by the model. The principle of this method consists of sampling sets of values of the input parameters to be estimated, and then performing the simulations with each set of parameters. If $\boldsymbol{x}$ output values among $\boldsymbol{y}$ simulated output values were close to the expected data, then the set of values of input parameters used to simulate these $\boldsymbol{x}$ data were very close to the real unknown values of the parameters that we are trying to estimate (Toni et al., 2009). However, the probability of generating simulated data with a small distance to the expected data decreases rapidly when the data quantity increases. To circumvent this difficulty, the widely used approach, which consists of replacing the simulated and the expected data with a reduced size set of summary statistics, was used (Sunnåker et al., 2013).

The algorithm of ABC rejection used in this work consists of 6 steps (Toni et al., 2009):

(1) Sampling of 100 values of Se_{ij} and $CPref_{ijk}$ parameters from uniform distribution [0–1].

(2) Simulating a data set for each sampled value of Se_{ij} or $CPref_{ijk}$ or both (number of replicates = 10). The values of other input parameters such as CFOI, pregnancy loss, MG, and MPS were fixed from their baseline value. The time horizon of simulation was 10 yr. However, data from the first 5 yr of simulation were not used on the grounds that they were used to calibrate the stochastic simulation model.

(3) Calculating the summary statistics (herd size = 60 cows; milk yield = 8,000 kg/cow-year; Se_H = 20, 50, and 90%; and CR_{21} = 25, 45, and 70%) for the expected or observed data $S(X_O)$ and for the simulated data $S(X^*)$, for each value and for each replicate, from the average over the last 5 yr of simulation.

(4) Computing the distance (d) between $S(X_O)$ and $S(X^*)$ for each value and for each replicate. In this work, we used the Euclidean distance:

$$d\left[S\left(X_O\right),S\left(X^*\right)\right]=\sum_{j=1}^{S}\left(\frac{S_j\left(X^*\right)-S_j\left(X_O\right)}{k_j}\right)^2, \quad [A1]$$

where k_j is the empirical standard deviation of j (j = 1, ..., S) summary statistics of the simulated data $S_j(X^*)$.

(5) Setting the value of the tolerated distance ε. The tolerated distance is determined by the proportion of conserved simulations (pε) with little distance. In this work, we set the value of pε to 5%.

(6) Estimating the median of Se_{ij} or $CPref_{ijk}$ or both, which are input parameters of the model, only from the values that produced the conserved simulations in step 5. The ABC algorithm described above was used to estimate the Se_{ij} and $CPref_{ijk}$ parameters as follows: first, we estimated simultaneously the values of Se_{ij} and $CPref_{ijk}$ that will be used to simulate the baseline scenario of this work (Se_H = 50% and CR_{21} = 45%). Then, the values of $CPref_{ijk}$ were fixed and the ABC algorithm was used twice to estimate the values of Se_{ij} for the other 2 scenarios of Se_H (20 and 90%; Table A1). Finally, this algorithm was used 8 times to estimate the values of $CPref_{ijk}$ that will be used to simulate the 3 scenarios of CR_{21} (25, 45, and 70%) and their interaction with the 3 scenarios of Se_H (20, 50, and 90%).

The ABC algorithm was performed in this work using the "abc" package of the software R (R Development Core Team, 2016).

APPENDIX B

Simulation Algorithms of Management of Purchase and Sale of Animals by the Farmer

Every 15 d, the decision to buy and sell the animals is simulated in the model together with the culling candidacy score computation. This decision depends on the management of purchase and sale of animals by the farmer and on the MG constraints.

Constant Herd Size

Under the MG constraint "maintaining a constant annual average number of cows (N)," we used the following algorithm to simulate the purchase and sale of animals for open herd:

Table A1. Median estimated by the approximate Bayesian computation (ABC) rejection algorithm of the sensitivity of estrus detection (Se_{ij}) according to the estrus expression level i, the parity j, the number of ovulation after calving, and the number of estrus after AI of the cow

	Se_{ij} depending on estrus expression level[1]								
	Se_H[2] = 20%			Se_H = 50%			Se_H = 90%		
Item	Discreet	Normal	High	Discreet	Normal	High	Discreet	Normal	High
Primiparous									
1st ovulation	0.045	0.10	0.20	0.10	0.30	0.35	0.84	0.88	0.95
2nd ovulation	0.09	0.13	0.25	0.20	0.40	0.60	0.89	0.93	0.99
3rd ovulation and more	0.18	0.23	0.36	0.40	0.80	0.95	0.89	0.94	0.97
1st estrus after AI	0.22	0.26	0.36	0.50	0.70	0.95	0.89	0.94	0.97
2nd estrus and more after AI	0.09	0.14	0.23	0.20	0.40	0.57	0.84	0.89	0.89
Multiparous									
1st ovulation	0.05	0.11	0.25	0.12	0.29	0.35	0.85	0.88	0.95
2nd ovulation	0.10	0.15	0.28	0.21	0.43	0.62	0.89	0.93	0.99
3rd ovulation and more	0.19	0.24	0.39	0.43	0.82	0.96	0.90	0.95	0.98
1st estrus after AI	0.24	0.29	0.42	0.51	0.73	0.97	0.90	0.94	0.98
2nd estrus and more after AI	0.095	0.17	0.25	0.22	0.41	0.58	0.84	0.90	0.91

[1] All these values were computed using the ABC algorithm.

[2] Se_H = herd estrus detection sensitivity.

Step 1

Calculating the number of cows present at day t ($NBCW_t$) after culling those with a culling candidacy score >60.

Step 2

Step 2.1. If $NBCW_t < (N \times 0.95)$, the purchase of cows and pregnant heifers was allowed. The needed expected number of animals to be purchased at day t (ENP_t) was calculated by the following formula:

$$ENP_t = N - NBCW_t. \quad [B1]$$

However, the needed effective number of animals to be purchased at day t (NP_t) was calculated by

$$NP_t = \begin{cases} ENP_t & \text{if } ENP_t \le (0.2 \times N) - NP_{t-15} \\ (0.2 \times N) - NP_{t-15} & \text{if } ENP_t > (0.2 \times N) - NP_{t-15} \end{cases}, \quad [B2]$$

where NP_{t-15} was the total number of animals purchased between d 1 and day t − 15 of the year.

Step 2.2. If $NBCW_t > (N \times 1.05)$, the sale of pregnant heifers and cows (cows ranked in the first and second group of culling candidacy score) was authorized. The needed expected number of animals for sale at day t (ENS_t) was calculated by the following formula:

$$ENS_t = NBCW_t - N, \quad [B3]$$

whereas the needed effective number of animals for sale at day t (NS_t) was calculated by

$$NS_t = \begin{cases} ENS_t & \text{if } ENS_t \le (0.4 \times N) - NP_{t-15} \\ (0.4 \times N) - NS_{t-15} & \text{if } ENS_t > (0.4 \times N) - NP_{t-15} \end{cases}, \quad [B4]$$

where NS_{t-15} was the total number of sold animals between d 1 and day t − 15 of the year.

Step 2.3. If $(N \times 0.95) \le NBCW_t \le (N \times 1.05)$, the purchase and sale of animals were not allowed.

Constant Volume of Milk Sold

Under the MG constraint "fixed milk production level (delivery contracted)," we used the following algorithm to simulate the purchase and sale of animals for open herd:

Step 1

At day t, the prediction of the expected quantity of herd milk production ($EMP_{365\text{-}t}$) for the rest of the year (365 − t) was realized. The $EMP_{365\text{-}t}$ was calculated as the sum of the projection of the lactation Wood curve of each cow present in the herd at day t, adjusted by the effect of dry period, probability of health disorders, and probability of culling.

Step 2

At day t, the prediction of the expected annual herd milk production throughout the current year of simulation (EMP_n) was calculated, as the sum of total milk production of the herd between d 1 and day t and $EMP_{365\text{-}t}$.

Step 3

Calculating the variation indicator of milk production (delta) using the following formula:

$$\text{delta} = (\text{EMP}_{\text{n}} - \text{delivery contracted}). \qquad [\text{B5}]$$

Step 4

Step 4.1. If delta < (−0.05 × delivery contracted) (under-production situation), the purchase of cows and pregnant heifers was allowed. The needed expected number of animals to be bought at day t (ENP_{t}) was calculated by the following formula:

$$\text{ENP}_{\text{t}} = (|\text{delta}|/\text{MY}_{305}) + 0.50, \qquad [\text{B6}]$$

where MY_{305} was the milk yield in kilograms per cow over 305 d of lactation. The value of ENP_{t} was rounded to the nearest integer number.

However, the needed effective number of animals to be bought at day t (NP_{t}) was calculated using equation [B2].

Step 4.2. If delta > (0.05 × delivery contracted) (over-production situation), the sale of pregnant heifers and cows (cows ranked in the first and second group of culling candidacy score) was allowed. The needed expected number of animals for sale at day t (ENS_{t}) was calculated by the following formula:

$$\text{ENS}_{\text{t}} = (\text{delta}/\text{MY}_{305}) + 0.50. \qquad [\text{B7}]$$

The value of ENS_{t} was rounded to the nearest integer number.

The needed effective number of animals for sale at day t (NS_{t}) was calculated using formula [B4].

Step 4.3. If (−0.05 × delivery contracted) ≤ delta ≤ (0.05 × delivery contracted), the purchase and sale of animals were not allowed.