A stochastic dynamic model of a dairy farm to evaluate the technical and economic performance under different scenarios

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ABSTRACT

Dairy farms need to improve their competitiveness through decisions that are often difficult to evaluate because they are highly dependent on many economic and technical factors. The objective of this project was to develop a stochastic and dynamic mathematical model to simulate the functioning of a dairy farm to evaluate the effect of changes in technical or economic factors on performance and profitability. Submodels were developed for reproduction, feeding, diseases, heifers, environmental factors, facilities, management, and economics. All these submodels were simulated on an animal-by-animal and day-by-day basis. Default values for all variables are provided, but the user can change them. The outcome provides a list of technical and economic indicators essential for the decision-making process. Performance of the program was verified by evaluating the effects and sensitivity analysis of different scenarios in 20 different dairy farms. As an example, a case study of a dairy farm with 300 cows producing 40 L/d and a 12% pregnancy rate (PR) was used. The effect of using a time-fixed artificial insemination (TFAI) protocol in the first insemination at 77 d in milk, with 45 and 40% conception rates for first-lactation and older cows, respectively, and a cost of €13 was explored. During the 5-yr simulation, the TFAI increased PR (12 to 17%) and milk yield per milking cow (39.8 to 41.2 L/d) and reduced days to first AI (93 to 74), days open (143 to 116), and the proportion of problem cows (24.3 to 15.9%). In the TFAI, cows were dried 30 d earlier, resulting in more dry cows, and a smaller difference in milk yield by present cows (35.5 vs 36.0 L/d for control and TFAI, respectively). A longer productive life (2.56 vs. 2.79 yr) with shorter lactations in TFIA resulted in less first-lactation cows (42 vs 36%), 32 more calvings per year, and, therefore, more cases of postpartum dis-

eases. Total (32.5 to 29.9%) and reproductive (10.5 vs 6.8%) culling rates decreased in TFIA. Overall, the net margin was €245 and €309/cow per year in control and TFIA, respectively. The net margin of applying TFAI decreased as PR of the farm increased, with limited benefit of TFAI at a PR of 30%. The model provides a powerful web-based tool to explore the short- and medium-term consequences of technical and economic decisions on the economic sustainability of dairy farms. **Key words:** stochastic model, dairy farm simulation, technical and economic performance

INTRODUCTION

Dairy farms are constantly facing changes in the economic and technical scenarios that challenge their profitability. In the last 20 yr, major transformations in the sector have occurred, where the number of farms has been greatly reduced and the size of farms and productivity of animals increased (Eurostat, 2015; USDA, 2016). In the European Union, dairy farms are currently facing major challenges due to the abolition of the production quota system. Although the elimination of the quota offers an opportunity to increase production per farm, it may also increase the supply-demand balance that will likely reduce the farm-gate price of milk. In this scenario, competitiveness of the production is essential for the economic sustainability of farms. The need to improve competitiveness requires strategic decisions that are difficult to assess because they depend on numerous technical and economic factors that are dependent on local conditions, such as milk and raw material prices, labor costs, farm size, current technical performance, and their interactions. Questions exist to which answers are not always obvious. For example, the profitability of an estrus or ovulation synchronization program depends on the cost of treatment, the average level of production, milk price, and current reproduction performance (Giordano et al., 2012). Voluntary culling rate depends on the price of milk, the slaughter price of the culled cow, and the

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cost and production potential of the incoming heifer (Sorge et al., 2007). In addition, the return of many of these actions does not come immediately, and the time required to improve the technical indexes and economic balance varies. The complexity of these interactions requires the integration of all this data into mathematical models (Mayer et al., 1998). These models simulate the consequences of the changes occurring in a system under different scenarios proposed by the user. A technical and economic evaluation before any decision that needs to be taken is becoming an essential part of dairy herd management. Models can be used (a) to take decisions in complex situations where many variables interact dynamically over time; (b) to analyze the effect of future circumstances on farm performance and profitability; (c) to assess risks and uncertainties through sensitivity analysis; and (d) to make decisions about areas in which little information is available. Many different areas of the dairy production system have already been modeled, such as diseases (Østergaard et al., 2005; Bruijns et al., 2010), reproductive strategies (Giordano et al., 2011, 2012; Shahinfar et al., 2015), replacement policies (Cabrera, 2010), feeding strategies (Cabrera and Kalantari, 2016), and interactions between genotype and environment (Bryant et al., 2005; Kaniyamattam et al., 2016), among others. However, in most cases, these models are limited to simulate the consequences of 1 specific problem and do not account for the potential interactions with other areas of the farm. Furthermore, most of them are not easily accessed by scientist and consultants to verify results or simulate farm-specific conditions.

The vision of the present project was to develop a cross-sectional framework model that includes major areas of a dairy farm that would allow users to input data related to their specific conditions and to evaluate the consequences of 1 or more technical or economic changes on farm performance and economic sustainability. Such application is available on the web (www.dairyfarm.es), where users will be able to use the model to test different scenarios. Therefore, the objective of our research was to develop an intensive dairy farm model that integrates the current knowledge of different areas of dairy cattle and farms to explore the technical and economic consequences of changes in the conditions of the farm, and present it in a web-based interface to facilitate wider use.

MATERIALS AND METHODS

Structure of the Model

Figure 1 shows a schematic representation of the animal model. Each cow in the farm was assigned a

theoretical milk yield potential. The biological factors (lactation curves, growth, nutrient requirements and supplies, biology of reproduction, and so on) are described and affected by environmental and management factors (e.g., heat stress, 3× milking, grouping strategies), diseases (e.g., mastitis, ketosis, lameness), and nutrient supply. The resulting effects of these external factors interact with the theoretical milk yield potential to determine the actual production. During this process, fixed and variable costs (feed, labor, utilities, health, debt, and so on) and income (sales of milk, calves, culled cows, and so on) are accounted for. This process is repeated daily for each animal (heifers and cows) during the simulation period.

Biological Factors

Milk Production. Milk yield was determined based on Wood's lactation curve equations (Wood, 1967):

$$Y(t) = A \times t^b \times e^{-ct},$$

where Y_t = milk yield (L/d) at time t (DIM), A = initial milk yield (L/d), e = Neper number; t = time of lactation (DIM), b = rate of increase until the peak is reached (d^{-1}), and c = rate of decline after peak production (d^{-1}); constants b and c change with the number of lactation. Values for A (A , $1.54 \times A$, and $1.47 \times A$), b (0.208, 0.179, and 0.209), and c (0.002, 0.003, and 0.0036) are applied for first, second, and third and older lactations, respectively (Wood, 1967). When a new farm is generated at random, each cow is randomly assigned a theoretical maximum mature 305-d standard milk production (defined as the 305 DIM milk production in the third lactation) around the farm average $\pm 2,000$ L/cow per year. When individual actual cows are uploaded from farm data, the program uses predicted 305-d mature production if available, or it is calculated from current lactation 305-d predicted production, milk yield from the last 7 d, or the last test-day milk yield, adjusted for lactation number and DIM, in a priority order of decreasing reliability.

Reproduction. After calving, cows return to cyclicity 35 ± 4 DIM and, thereafter, the estrous cycle is repeated every 21 ± 2 d. Insemination occurs after the voluntary waiting period set by the user (50 DIM by default), and depending on estrus detection index (50% by default). Pregnancy will depend on conception rate (35% by default) and lasts 278 ± 5 d. Pregnancy losses (lost pregnancy after positive diagnosis at 30 d postinsemination) is programmed by default at 11% (Wiltbank et al., 2016). Potential effects of environmental conditions, management factors, and disease incidence (i.e., heat stress, lameness) on the onset of the estrous

Figure 1. General structure of the animal model. Each cow in the farm is assigned a theoretical milk yield potential. The biological factors (lactation curves, growth, nutrient requirements, biology of reproduction, and so on) are described and affected by environmental and management factors (e.g., heat stress, 3× milking, grouping strategies), diseases (e.g., mastitis, ketosis, lameness), and nutrient supplies. The resulting effects of these external factors determine the actual production. During this process, fixed and variable costs (feed, labor, utilities, health, debt, and so on) and income (sales of milk, calves, culled cows, and so on) are accounted. This process is repeated daily for each animal (heifers and cows) during the simulation period.

cycle after calving, heat detection rate, and conception rate can be programmed in their respective sections. Synchronization of ovulation can be implemented as fixed-timed AI, set by default at 77 DIM, with a conception rate of 45 and 35% for primiparous (**PP**) and multiparous (**MP**) cows, respectively; and at 400 d of life and a conception rate of 60% for heifers, and a treatment cost of €13 (Astiz and Fargas, 2013; Lopes et al., 2013; Sahu et al., 2015). Semen use is assigned a specific cost and an impact on the genetic potential of the offspring. By default, calves inherit their mother's production potential plus 0.75%. This value has been calculated from the 1.5% average increase in milk yield per cow per year in the United States in the last 20 yr (USDA, 2016), assuming that half of the improvement is due to genetic factors and the other half to nongenetic factors. However, the user may assign a different value depending on the genetics used on the farm. The proportion of females is set to 50%; however, to accommodate the use of sexed semen, this ratio can be changed. When sexed semen is used, the strategy should

be defined, including how many heifers or adult cows are inseminated with sexed semen, the production level of selected cows, the conception rate, the number of attempts, and the months of the year when it is applied. As an example, in the default, sexed semen is applied to the top 15% of heifers and 5% of cows inseminated between October and May with a conception rate that is 0.85 of the average farm conception rate at a cost of €50 per dose and a 90% chances of female (McCulloch et al., 2013; Butler et al., 2014; Seidel, 2014) and a genetic improvement that is the same as normal insemination (0.75% improvement above the dam production potential) unless otherwise indicated. The use of sexed semen insemination is only applied 2 times to the same cow before it goes into a normal insemination protocol. Embryo transfer can also be programmed under similar conditions, where the type of animals selected for transfer, expected conception rate, expected milk yield potential of the offspring, months of the year of use, cost, and number of attempts need to be defined (Hasler, 2001; Vasconcelos et al., 2006). Default values

for reproduction variables in the program are shown in Supplemental Table S1 (<https://doi.org/10.3168/jds.2017-12980>).

Dry Period. Cows are dried 60 d before the expected calving date, although dry period length will be affected by the actual gestation length (278 ± 10 d). However, if production is below a minimum value (15 L/d by default), cows are either dried if pregnant or sent to slaughter if not pregnant. The effects of short dry periods on the following lactation performance have been modeled based on data from Annen and Collier (2005), Steeneveld et al. (2013, 2014), Santschi et al. (2011), and Timms (2004), and are presented in Figure 2. If the dry period length of multiparous cows falls below 30 d, a 0.8% daily reduction in milk yield occurs during the following lactation for each day below 30 d dry, resulting in a 24% less production in the following lactation if no dry period occurs. For primiparous cows, the daily milk yield of the following lactation starts decreasing when the dry period falls under 45 d, with a reduction of 0.7% per day under 45 d, resulting in a 31.5% reduction in production for the following lactation if no dry period occurs.

Calves and Heifers. The capacity of the farm for heifers is set at 60% of adult animals by default. If no replacements are grown in the farm, the user may set up replacement capacity to 0. In this condition, when the farm occupation falls under the lower capacity limit defined by the user (see Farm Capacity and Overcrowding section), the farm buys a ready-to-calve heifer. At calving, all males are sold. Females are born with 40 kg of BW and 75 cm of height. When colostrum is not provided, the incidence of respiratory diseases and diarrhea in calves is multiplied by 3 during the first 60 d of life (Weaver et al., 2000; Tyler et al., 1999). Puberty is defined at a BW of 300 kg. Conditions for insemination are determined by the user and set at a minimum of 400 d of life and 360 kg f BW by default. After calving, primiparous cows continue to grow at a fixed rate of 0.350 kg/d for the following 305 d for a total increase of 106 kg during the first lactation. Default values for most relevant variables related to calves and heifers are shown in Supplemental Table S1 (<https://doi.org/10.3168/jds.2017-12980>).

Nutrient Requirements and Supplies. Energy (NE_L for cows or ME for heifers) and CP requirements were calculated based on the NRC (2001). For calves and heifers, DMI and energy and protein requirements were calculated with the assumptions used in Tables 10–1, 10–2, 10–4 and 11–3 in the NRC (2001). Growth may be affected by environmental conditions, management and disease incidence; different feeding groups may be defined by the user based on age or BW. The user should define the target growth rate and the diet

Figure 2. Model used for determining the effect of the length of the dry period on production performance in the following lactation for primiparous (dashed line) and multiparous (solid line) cows (summarized from Annen and Collier, 2005; Steeneveld et al., 2013, 2014; Santschi et al., 2011; Timms, 2004).

profile (energy and protein content, and cost) to calculate actual growth and cost of heifer rearing.

For milking cows, equation [1–2] from NRC (2001), based on BW, FCM, and week of lactation, was used for calculating DMI in cows. Energy for maintenance is 0.08 Mcal of NE_L /kg of metabolic BW, and energy requirements for milk yield are based on equations [2–16] of the NRC (2001) that considers milk fat and protein content. Protein requirements for maintenance were calculated based on the NRC (2001). Protein requirements for milk yield were calculated based on protein yield and an average efficiency of protein utilization of 26% (Huhtanen and Hristov, 2009). Daily milk yield was calculated from the theoretical milk yield curves of each cow adjusted for lactation number and DIM and modified by the external factors (environment, management, and diseases). The dietary energy and protein-allowable milk yield was calculated based on nutrient supplies (actual DMI $\times$ nutrient content). Actual milk yield was the lowest of the comparison between cow's daily milk yield and the dietary allowable production. However, to account for the contribution of mobilized energy and recovery of body fat reserves, a provision for the loss of 1 point of BCS in the first 60 d of lactation was introduced in the program. One point of BCS loss in an average cow provides 385 and 450 Mcal of NE_L for PP and MP cows, respectively, and the gain of 1 point of BCS requires 459 and 535 Mcal of NE_L for PP and MP cows, respectively (NRC, 2001). Therefore, the program has an allowance of 6.4 and 7.6 Mcal of NE_L /d of extra-energy during the first 60 DIM for PP and MP cows, respectively. During DIM 150 to 300 an additional 3.0 and 3.5 Mcal of NE_L /d for PP and MP cows, respectively, were added to requirements. The underlying assumption was that changes in BCS occur

within the limits of a generally defined healthy cow and that the energy balance at the end of the lactation cycle is zero.

Diseases

The disease submodel was designed with a high degree of flexibility. A matrix of potential effects for any disease has been developed and default values for most common diseases are provided (Supplemental Table S2; <https://doi.org/10.3168/jds.2017-12980>). Diseases described by default include mastitis, laminitis, retained placenta, metritis, ketosis, hypocalcemia, displaced abomasum, and diarrhea in calves. Disease may be programmed to account for the cost of clinical treatment and effects on milk yield and composition, intake, reproduction, SCC, growth, abortion, risk of culling, and interactions with other diseases. The immune response associated with a disease results in the repartitioning of glucose and energy toward the immune system, reducing energy available for production and feed efficiency (Kvidera et al., 2017). Cheeke and Dierenfeld (2010) suggested that the energy diverted to the immune reaction during sickness represents 10 to 15% of the requirements. In the current model, the user may reduce milk yield without affecting DMI, thus reducing feed efficiency; however, users may also reduce DMI to reduce milk yield without affecting feed efficiency. Although it is often difficult to assess the direct effect of a disease on intake or milk yield, the user has the option of determining if the primary effect is on milk yield or feed intake. This may be relevant because the consequences are different. In addition, interactions with other diseases may also be programmed as odd ratios. For example, a cow with hypocalcemia has a 3× increased risk of displaced abomasum (Chapinal et al., 2012; Martinez et al., 2012). New diseases can be added at the level of disaggregation desired by the user as long as the incidence and effects are described. For example, mastitis is currently defined as a single entity by default, but users may create different types of mastitis (i.e., environmental vs. contagious, or *Staphylococcus aureus* vs. *Escherichia coli*). Literature is highly variable on the definitions and the quantitative description of the effects of diseases, making it very difficult to assign default values. However, average incidence and default values for the effects of these diseases are provided to guide users as a starting point, but users are cautioned on evaluating the conditions of the farm being simulated.

For infectious diseases, it is possible to simulate endemic or outbreak scenarios. For the endemic occurrence, it can be programmed to have different incidence in different seasons of the year (e.g., higher incidence of

respiratory problems in winter) or time in the lactation cycle (e.g., mastitis incidence may be higher in the first month of lactation) by assigning different incidence values (Supplemental Table S2; <https://doi.org/10.3168/jds.2017-12980>). In the outbreak mode, the model assumes that the disease enters in the farm through a single infected animal and requires the definition of the number of infectious days and rate of disease transmission (new infected animals per day; Supplemental Table S2). An infected animal will suffer the consequences described for the disease. Vaccinations can be programmed for all infectious diseases and are defined in terms of degree of protection, reduction of effects if infected while vaccinated, duration of protection, frequency of vaccination, and cost of vaccination (Supplemental Table S2). As an example, Figure 3 shows the expected evolution of cases of an infectious disease in a herd where an infected animal enters the herd at the beginning of the second year of simulation, sheds the microbial agent during 5 d, infects 0.5 cows/d, and, after infection, acquires immunity for 6 mo. If the infected animal enters a herd treated with a vaccine that protects 80% of the cows, the cases are greatly reduced. Although about 20% of the vaccinated cows may become infected, the effects will be reduced by 50% compared with the nonvaccinated expression of the disease. Full immunity after vaccination lasts for 6 mo and then it is linearly reduced from 100 to 0% in another 6 mo. This structure of data input can also be applied to other preventive measures, such as the application of calcium boluses to prevent hypocalcemia or propylene glycol to prevent ketosis, as long as the treatment is applied systematically to all cows and information is provided on the effects of such treatments.

Management and Environmental Factors

Many different management decisions and environmental factors can be incorporated into the program following the same structure described for diseases. Some management conditions have been preprogrammed by default because they are common in dairy farms and to illustrate how to use this utility to incorporate additional strategies to be used in the model.

Feeding Groups. By default, cows belong to either the production or the dry group. Users may create different feeding groups as long as each group has a diet description (NE_L, CP, and the cost per kilogram of diet) and the criteria for grouping, which may include DIM, lactation number, reproductive status (pregnant, not pregnant, or both) and range of milk yield (Supplemental Table S3; <https://doi.org/10.3168/jds.2017-12980>). However, changing cows to a new group may cause stress and reduce performance. Cabrera and Kalantari

Figure 3. Example of the default incidence of a respiratory disease syndrome in cows during 3 yr without (dashed line) or with (solid line) vaccination. Incidence is higher in winter and an infectious outbreak occurs in January 2018.

(2016) reviewed literature and reported that moving cows from groups has small and short-lived effects on milk yield, suggesting an overall reduction of 5% in milk yield during 5 d. This effect has been programmed by default. If primiparous cows are grouped separately, milk yield of primiparous cows is increased 8% based on Grant and Albright (2001).

Heat Stress. Heat stress is also modeled by default based on the temperature-humidity index. The negative effects on intake, milk yield and composition, and reproduction performance can be calculated based on St-Pierre et al. (2003) and programmed in a month-by-month basis. In the default, heat stress results in a reduction (multiplier) in DMI (0.80), milk yield (0.80),

milk fat and protein content (0.92), heat detection rate (0.5), and conception rate (0.5; Supplemental Table S3, <https://doi.org/10.3168/jds.2017-12980>). The intensity and effects of heat stress can be changed by the user and be applied at different time-periods (months).

3× Milking. The effects of 3× milking can be modeled by defining its effects on milk yield, milk component changes, SCC, and any potential interactions. The effects and default values have been defined based on reviews by Erdman and Varner (1995) and Smith et al. (2002; Supplemental Table S3, <https://doi.org/10.3168/jds.2017-12980>). Milk yield, milk fat and protein content, and SCC are affected by a factor of 1.09, 0.94, 0.99, and 0.85, respectively. Feed intake will increase automatically due to higher production. The increase in labor costs or milking parlor costs should be assigned in their respective areas.

Farm Capacity and Overcrowding. The user defines maximum and minimum capacity of the farm in terms of feed bunk space. When the farm capacity is exceeded, the program culls a cow based on theoretical milk yield, DIM, and pregnancy status (see Culling Strategies section). If the number of cows falls below the minimum capacity defined by the user, the program buys a heifer just about to calve. For feed bunk space, a reduction in DMI of 0.40 and 0.25% for each percentage point above 125 and 140% of capacity for PP and MP cows, respectively, has been programmed based on data from Grant and Albright (2001; Figure 4). There is not sufficient data in literature to provide default values for stall overcrowding, but provision for effects have been built in.

Figure 4. Effect of overcrowding in the feed bunk on DMI in primiparous (dashed line) and multiparous cows (solid line; adapted from Grant and Albright, 2001).

Culling Strategies. Cows may exit the farm due to accidental death (5% in default; Garry, 2008), disease (where the risk of culling is defined within each disease), or a combination of low production and low conception rate. By default, if a cow is not pregnant at 300 DIM it is no longer inseminated and culled at the end of lactation, based on Giordano et al. (2012). However, a more complex decision-making strategy taking into account the lactation number (PP vs. MP), DIM, pregnancy status, actual milk yield, and the genetic potential has been programmed (Supplemental Table S4; <https://doi.org/10.3168/jds.2017-12980>). Therefore, overall culling rate and the productive life of a cow is not predetermined, but it is the result of these interactions.

Economics, Labor, Facilities, and Equipment

Input is required for prices of different items (e.g., feed, milk, bonus-penalties for milk quality, calf and heifer prices, culled cow prices), labor costs, utilities (e.g., water, electricity, phone), rent, taxes, and debt (e.g., facilities, equipment), among others (Supplemental Table S5; <https://doi.org/10.3168/jds.2017-12980>). When a new farm is generated, default values for all these costs are calculated from the average cost based on Observatori de la llet (2016), but the user may modify them. Labor is defined by default for an average of approximately 50 cows per person, but it can also be changed.

Table 1. Average results of the main production performance indexes of the simulations after 5-yr simulation of the control herd and the same herd after the implementation of a time-fixed artificial insemination (TFAI) program

Item	Control	TFAI
Milk yield milking cows (L/d)	39.8	41.2
Milk yield total cows (L/d)	35.5	36.0
Heat detection rate (%)	46	55
Conception rate (%)	26	31
Pregnancy rate (%)	12	17
Days to first insemination	93	74
Days open	143	116
DIM	225	197
Problem cows (>150 DIM not pregnant, %)	24.3	15.9
Pregnant cows (%)	46.2	56.5
Average lactations (no.)	2.56	2.79
Culling rate (%)	32.5	29.9
Reproduction culling rate (%)	10.5	6.8
First-lactation cows (%)	42	36
Total cows (no.)	292	294
Dry cows (no.)	31	37
Days dry	58	58
DIM at dry off	368	338
Milk production at dry off (L/d)	31.4	32.8
Calvings (no.)	262	294

Table 2. Average results of the incidence of diseases simulations after 5-yr simulation of the control herd and the same herd after the implementation of a time-fixed artificial insemination (TFAI) program

Item	Control	TFAI ¹
Retained placenta (%)	9.6	10.5
Metritis (%)	13.9	13.9
Clinical ketosis (%)	4.1	3.7
Subclinical ketosis (%)	25.0	31.0
Clinical hypocalcemia (%)	0.8	3.1
Subclinical hypocalcemia (%)	23.3	28.6
Displaced abomasum (%)	3.1	4.4
Postpartum mastitis (first 60 d, %)	12.0	14.3
Mastitis (except first 60 DIM, %)	9.9	9.9
Lameness (%)	22.6	22.1
Calf diarrhea (%)	15.2	15.2

Simulation, Output Files, and Verification

Simulations can be run from 1 mo and for as long as needed. However, because errors accumulate, simulations longer than 5 to 7 yr are generally not recommended or the number of replications should be increased. The stochastic nature of the program requires that simulations be repeated. Repetitions will depend on the size of the herd and years simulated. A test to determine the optimal number of replications required for the stability of results was conducted. A default scenario in farms of different sizes (50 to 1,000 cows) was replicated 5 to 1,000 times and results of repetitions were used to calculate the average and standard deviation. A coefficient of variation below 1% for total net margin was used as a threshold to define the optimal number of replications.

Results are provided in different time periods (months, trimester, semester, or year) in table and graphic format (Tables 1, 2, 3; Figures 5, 6, 7, 8; Supplemental Table S6, <https://doi.org/10.3168/jds.2017-12980>). This numerical information is organized in areas of interest: demographics, production, reproduction, replacement heifers, diseases, and economics.

Table 3. Average results of the main average economic analysis (€) of the 5-yr simulation of the control herd and the same herd after the implementation of a time-fixed artificial insemination (TFAI) program

Item	Control	TFAI ¹	Difference
Income from milk sales	1,257,210	1,283,957	26,747
Income from calf sales	10,613	12,436	1,823
Income from cows sales	27,347	19,558	-7,716
Feeding costs cows	714,031	717,988	3,959
Feeding costs calves and heifers	108,990	111,684	2,694
Heifer purchase costs	30,873	23,928	-6,945
Veterinary-health costs	15,559	17,833	2,274
Total income	1,295,097	1,315,951	20,854
Total costs	1,223,342	1,224,839	-1,497
Net margin	71,755	91,112	19,357

Figure 5. Evolution of pregnancy rate in the 5-yr simulation of the control (black solid line) herd and the same herd after the implementation of a time-fixed artificial insemination program (dashed line).

Finally, validation of the model is very difficult in field conditions because many factors change simultaneously and continuously. Therefore, the model was submitted to a verification process and a sensitivity analyses. Data from 20 commercial dairy farms (farm size from 50 to 800 milking cows) were selected from different areas of Spain and uploaded into the model. A set of different scenarios was selected [implementation of a time-fixed AI program, the comparison of pedometers vs. time-fixed AI, delay first insemination in PP and MP cows,

no insemination in the hot months of summer, use of sexed semen, embryo transfer, accelerated growth programs in calves and heifers, contracted heifer growth vs. traditional heifer raising program, robotic milking vs. parlor milking, 2× vs. 3× milking, standard versus short dry periods, expansion and either buying cows to fill it up vs. grow with own heifers, effects of heat stress and effect of mitigation of heat stress (ventilation and sprinklers), increased voluntary culling rate, reduction of the incidence of diseases (lameness and

Figure 6. Evolution of milk yield in the 5-yr simulation of the control herd and the same herd after the implementation of a time-fixed artificial insemination program (TFAI). Milk yield in liters per day per milking cow: control (black solid line) and TFAI (black dashed line); milk yield in liters per day per total cows: control (gray solid line) and TFAI (gray dashed line).

Figure 7. Evolution of the numbers of dry cows in the 5-yr simulation of the control (solid line) herd and the same herd after the implementation of a time-fixed artificial insemination program (dashed line).

mastitis), vaccinating or not against bovine respiratory syndrome, preventive treatment of hypocalcemia and ketosis with systematic use of Ca boluses and propylene glycol, respectively, among others]. At least one of these scenarios was tested in each farm and simulated for a 5-yr period. Sensitivity analyses were used to verify that the model responded in a reasonable way to different magnitudes of these changes. All simulations results were evaluated for consistency with expected outcomes by 3 researchers and 4 external dairy consultants. These tests were used to identify model limitations and errors, and were amended.

Web Application

The web application is available at www.dairyfarm.es. Users have free access to a demo farm, but should register an account to save and manage their own farms. At the start of the simulation, the farm is either generated at random or by uploading a file from a specific farm. A Microsoft Excel (Microsoft Corp., Redmond, WA) template available for download provides the required information to upload actual data from a farm. The information required is easily accessible from most commercial management software and should include

Figure 8. Evolution of the monthly net margin in the 5-yr simulation of the control (solid line) herd and the same herd after the implementation of a time-fixed artificial insemination program (dashed line).

cow identification, age, number of lactation, DIM, days pregnant, milk yield, milk composition, and SCC. When data of a cow are missing, the farm average is used. Body weight and height, if not provided, is assigned based on standard curves for Holstein (Penn State Extension, 2017). The program checks internally all input data to verify that number are within the expected range. The remaining variables are assigned an average default value, but the user may change them if needed. The user should also select a specific context. A context is a set of default values for a defined situation. Contexts describe the average conditions of a country, a region, a production system, or any local characteristic of a set of farms. For example, a context could define the organic production in Spain, and any farm generated under this context uploads default values that describe this type of farms. A user may have several farms within 1 context, and several contexts within the same account.

Three focus groups with 10 to 15 veterinarians and consultants were conducted in different locations in Spain. Each focus group was presented with the program in a morning session and simulated a scenario in a dairy farm in an afternoon session to test the usability of the software. Suggestions were collected and implemented to improve the usability of the simulator and the web application.

A Modeling Example

To illustrate the potential of the model, a case study used in the verification process is presented. A case of implementing reproduction programs has been selected because several published models can be used to compare results and because many consequences are well established, making the evaluation process easier to explain. A 300-adult cow dairy farm (average of 40 L/milking cow per day) with the corresponding replacement heifers was used. The farm had an average voluntary waiting period of 50 d, a heat detection rate of 46%, a conception rate of 26%, a milk price of €320/t, and a labor efficiency 43 cows/person. Incidence of major diseases was 25% mastitis, 20% lameness, 12% retained placenta, 14% metritis, 3 and 30% for clinical and subclinical hypocalcemia, 5 and 30% for clinical and subclinical ketosis, 4% displaced abomasum, 20% calf diarrhea, and 5% calf accidental deaths. Age at first calving was 27.7 mo. Total debt was €600,000. Diets were designed to provide nutrients in excess of requirements (NRC, 2001). Default values for all other variables were used (see Supplemental Tables S1 to S6; <https://doi.org/10.3168/jds.2017-12980>). The question of the suitability of using a time-fixed artificial insemination (TFAI) protocol was raised. The TFAI was

planned only for the first insemination at 77 DIM, with a 45% conception rate for first-lactation cows and 40% for older cows, and a cost of €13 per treatment. Cows observed in heat before the TFAI were inseminated. The model was used to help in the decision-making process. A sensitivity analysis of the returns based on pregnancy rates was conducted.

RESULTS AND DISCUSSION

The model was developed based on data obtained in confined intensive systems and should be applied to these conditions. Models for grazing systems have been developed, but will not be discussed here (Shalloo et al., 2004). Most models are developed for a specific objective, but do not account for potential interactions or herd dynamics. For example, Carabaño et al. (2016) developed a model to evaluate the effect of heat stress on milk yield, but ignored the potential effect on reproduction performance or the incidence of diseases (Polsky and von Keyserlingk, 2017). Other models have addressed the effect of reproductive strategies on herd performance without considering the effect of heat stress and diseases on reproduction (Giordano et al., 2011). The reduced fertility in summer months not only affects the decision of using ovulation synchronization programs, but also affects herd dynamics in terms of seasonal changes of calvings, milk production, and so on, which is relevant for the planning of the herd. In addition, improvements in technical indexes may not necessarily improve economic returns due to different prices of milk and feeds, among others, which in many cases requires access to the models to introduce the actual farm information. Although it is possible to access to some model applications for use (Østergaard et al., 2005; Schils et al., 2007), other models cannot be used by scientists or consultants to verify results or accommodate specific farm conditions (Shalloo et al., 2004; Dezetter et al., 2017). Access to models is important because the conclusions on the suitability of implementing a specific action is highly dependent on the economic and technical context of each farm.

The vision of the present project was to develop a framework model that would allow users to input data related to their specific conditions and explore the consequences of one or more technical or economic changes in the whole farm. This is a first step in an ongoing project that will progressively incorporate additional modules. However, at the current stage, it provides a comprehensive simulation of a dairy herd that includes major factors affecting performance. The cross-sectional (genetic, nutrition, reproduction, diseases, environment, management, heifers, economics, and any potential interactions) and dynamic nature of

the model presented in a web-based interface application is an innovative and interdisciplinary approach suitable to test a large variety of scenarios. The simulator has been built upon 5 principles: (1) it is dynamic and stochastic; (2) simulations run in day-by-day and cow-by-cow bases; (3) algorithms and default values of variables are supported by scientific evidence; (4) it is presented in a flexible web-based interface to facilitate its use; and (5) it is programmed with a structure to allow future improvements and additions.

Some algorithms in the current model have been simplified in an attempt to optimize the need of data input or the computational power (time of simulation). For example, the effects of nutrition consider only the energy and protein requirements and supplies, which is likely sufficient for most simulation needs. The underlying compromise in the development of the model is to balance scientific validity, completeness of the model, flexibility and usability of the computer application.

One of the problems of complex models is the amount of data input required. This concern has been resolved by generating specific contexts that contain default values that reflect the estimated average for each specific context. Contexts describe the average conditions of a country, a region, a production system, or any local characteristic of a set of farms. Furthermore, many questions do not require changing default values because they become common among the 2 comparisons, and, therefore, the change in the considered variable is sufficient to evaluate the consequences. For example, the accuracy of electricity cost may not be relevant for testing the effect of a TFAI, whereas labor costs may be relevant for short dry periods because the number of animals milking increases.

The stochastic nature of the simulation requires the repetition of the simulation several times to account for variability. The model uses the number of cows in the herd and the years simulated to calculate and recommend the required number of replicas to achieve a coefficient of variation below 1% in the net margin.

A true validation has not been conducted in field conditions because many factors change simultaneously and continuously. Furthermore, because the result is the average of a large number of repetitions, the variation associated with the measurements would require a test in many farms to achieve the objective. The verification of results through the simulation of effects in different scenarios (20 different farms across Spain) and testing all major areas of intervention allowed the identification of errors and fine tuning of algorithms. Projection and sensitivity analysis were compared with historical data of local farms provided by consultants and results were expected and consistent in the direction and the size of results in a dairy farm.

One of the cases studied to verify the model is presented to illustrate the analysis conducted and the potential use of the simulator. A reproduction case was selected because the effects of ovulation synchronization are well established and the effect on average performance and seasonal fluctuation of technical and economical indexes are well described. The farm had a pregnancy rate of 12% and was considering the use of a TFAI program to improve reproductive performance. Table 1 shows the result of the simulation in the control and TFAI scenarios. Heat detection rate and conception rate improved in the TFAI herd, as expected, and pregnancy rate increased from 12 to 17%. This improved pregnancy rate is within the range observed for similar scenarios by Galvao et al. (2013) and somewhat lower than Giordano et al. (2011); in the latter, however, resynchronization was used after the first insemination. The TFAI reduced the time at first insemination by 19 d, days open by 27 d, DIM by 28 d, and problem cows (>150 DIM not pregnant) by 8.3 percentage units. Milk yield increased 1.3 L/d per milking cow. However, because some cows got pregnant and were dried earlier, the number of dry cows increased and the improvement in milk yield per adult cow was considerably smaller (0.5 L/d). In fact, cows were dried off on average 30 d earlier with a milk yield 1.4 L/d higher. This is consistent with the 27-d reduction in days open and the theoretical higher milk yield at a 30-d earlier dry off.

The effects of heat stress in production and reproduction is reflected in the seasonal fluctuations in pregnancy rates (Figure 5), milk yield (Figure 6), calvings, the number of dry cows (Figure 7), and the net margin (Figure 8), as expected. The changes in the reproduction and production indexes due to TFAI were consistent with average changes in the region both in terms of averages as in terms of seasonal fluctuations, and similar to those reported for days open by Oseni et al. (2003). The total number of calving also increased in TFAI herd due to better reproduction, which resulted in more calves sold. Culling rate was reduced, resulting in longer productive life and less first-lactation cows in the TFAI herd, in agreement with Galvao et al. (2013). Although the reproduction culls were considerable lower (10.5 vs. 6.8 for control and TFAI herds, respectively), the effect in overall culling rate was much lower (reduction of 2.6 percentage units) due to an increase in the involuntary culling in the TFAI herd. This is due to an increase in the incidence of postpartum diseases. A longer productive life (4.6 mo more) with shorter lactations (30-d shorter) in the TFAI herd implies more calvings and, therefore, higher risk of postpartum diseases. Table 2 reflects this fact, where most postpartum diseases have a higher incidence, whereas diseases not

related to calving (lameness, mastitis after 60 DIM, and calf diarrhea) remained at a similar rate. This is, in fact, an important consequence of improving reproduction indexes with a TFAI protocol that should be considered in the analysis and that it is often difficult to assess.

The economic analysis reflects most of these observations, where the TFAI herd had more income from milk and sold calves, but less from selling culled cows, as expected. The higher yield and more heifers implied higher feeding costs, and the trend for a higher incidence of diseases resulted in higher veterinary-associated costs in the TFAI herd. In contrast, the control herd had to spend more money in purchasing heifers to maintain the size of the herd. Galvao et al. (2013) reported that one of the major benefits of improving reproductive performance was associated with a reduction in the replacement costs. However, the potential negative effect of a higher incidence of postpartum diseases was not considered. Overall, the TFAI farm had €19,357/yr more income than the control herd, as a results of in improved net margin from €245 to €309/cow per year in control and TFAI, respectively. Once again, the technical and economic consequences of the 2 scenarios are consistent with the expected outcomes. Data also indicated that the reduction in days open was a relevant technical index that started to decrease after 5 mo of the implementation of the program (data not shown), but actual economic returns was not relevant until 12 to 14 mo after the start of the program (Figure 8).

Giordano et al. (2011) compared the effect of a reproduction program based on visual heat detection to the use of 2 ovulation synchronization programs with resynchronization (programs A and B). Although the scenarios were not the same and technical and economical indexes reported differed from the ones in the present paper, the increase in average pregnancy rate (7 and 10 percentage units higher), the decrease in days open (20 and 15 d less), and the improved return per cow per year (\$45 and \$69 more) of synchronization programs A and B, respectively, compared with visual heat detection were in the same range as the results obtained in the current simulation. It should be kept in mind that some differences existed between the 2 simulations. In Giordano et al. (2011), the program included the resynchronization of cows after an unsuccessful pregnancy, and the effects of diseases and the effect of heat stress on production and reproduction were not accounted. No doubt heat stress has major effects on production, reproduction, and the incidence of some diseases (Polsky and von Keyserlingk, 2017), and the technical and economical implications of considering the effect of heat stress on the use of different reproduc-

tion programs is highly relevant (Oseni et al., 2003). Galvao et al. (2013) also reported the effect of different estrus synchronization programs on performance and economic returns. Although it is difficult to extrapolate absolute economic returns due to different economic scenarios, the improved profit per cow per year ranged from \$46 to \$68/cow per year, which is within the range of results observed in the current paper (€64/cow per year). In addition, the current model provides information on the seasonal fluctuations of technical and economic indicators.

Another relevant application of the model is the assessment of risks and uncertainties through sensitivity analysis. On one hand, results provide the average and standard deviation of the net margin, and the probability distribution of results is a helpful tool to assess these risks. In this case, net margin had a large standard deviation (€245 ± 92 and €309 ± 88/cow per year for control and TFAI herds, respectively), suggesting many factors may affect the final economic outcome. On the other hand, recommending the application of a TFAI program depends on the current reproductive performance of the herd. In the case study farm, where pregnancy rate was 12%, the reproduction program improved the net margin by €64/cow per year. However, the benefit followed the law of diminishing returns as pregnancy rates in the control herd increased, with the breakeven point for the use of TFAI was at a pregnancy rate of 30% (Figure 9). Tenhagen et al. (2004) observed that the economic benefit of implementing reproduction programs decreased as the control heat detection rates increased.

Finally, the development of such framework models is also dynamic by definition, and it will be improved and enlarged in the future. Therefore, this is a first step of an ongoing project that will progressively incorporate additional modules. In particular, some of the

Figure 9. Economic return of the implementation of a time-fixed artificial insemination (TFAI) program for the first insemination as a function of pregnancy rate (control = solid line; TFAI = dashed line).

limitations that are currently being addressed include the development of a more comprehensive nutritional module (currently based only on energy and protein balance), evaluation of the environmental impact of the farm, the connection between nutrition, condition score, metabolic diseases, and reproduction, or a more detailed description of the effects of diseases. However, at the current stage, the model provides a comprehensive simulation of a dairy herd sufficient for the simulation of many different scenarios that are important for research and dairy farm management. Although this qualitative and quantitative data provides useful information to take a decision, results of the simulation do not imply a prediction of results in a specific farm. Instead, the simulation will point to the direction (gain or loss), the size (what quantitative change to expect), and the nature (which indexes will be affected) of changes expected in all major technical and economic indexes with a prospective of time (how long will it take to observe a change). This data should help in the decision process and suggest potential interactions that should be considered during the decision-making process. In all cases, users are strongly cautioned to use the simulator and interpret results with the utmost caution and responsibility. Results of simulation models only reflect the consequences of the data input, and low-quality data will result in low-quality simulations. Simulation requires a good understanding of the model and, therefore, some training. Users should be careful and conscious of the quality of the data used and the implications of these data on the simulation and the intrinsic limitations of mathematical models.

CONCLUSIONS

A general framework of a stochastic, dynamic, and flexible dairy farm model has been developed. The verification of outputs in different farms and conditions and the sensitivity of the results to different conditions provide evidence of proper behavior. Although the stochastic nature of the program cannot provide a true prediction for a specific farm, it is a useful tool to point the direction, size, and type of responses expected under given circumstances and an evaluation of the interactions and risks involved. The model provides a powerful and useful tool to explore the short and medium term consequences of technical and economic decisions on the economic sustainability of dairy farms.

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