Economic comparison of reproductive programs for dairy herds using estrus detection, timed artificial insemination, or a combination

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ABSTRACT

The objective of this study was to compare the economic outcome of reproductive programs using estrus detection (ED), timed artificial insemination (TAI), or a combination of both (TAI-ED) using a stochastic dynamic Monte-Carlo simulation model. Programs evaluated were (1) ED only; (2) TAI: Presynch-Ovsynch for first AI, and Ovsynch for resynchronization of open cows at 32 d after AI; (3) TAI-ED: Presynch-Ovsynch for first AI, but cows underwent ED and AI after first AI, and cows diagnosed open 32 d after AI were resynchronized using Ovsynch. Evaluated were the effect of ED rate (40 vs. 60%; ED40 or ED60), accuracy of estrus detection (85 vs. 95%), compliance with the timed AI protocol (85 vs. 95%), and milk price (\$0.33 vs. 0.44/kg). Conception rate to first service was set at 33.9% and then decreased by 2.6% for every subsequent service. Abortion was set at 11.3%. Cows were not AI after 366 d in milk, and open cows were culled after 450 d in milk. Culled cows were immediately replaced. Herd size was maintained at 1,000 cows, and the model accounted for all incomes and costs. Simulation was performed until steady state was reached (3,000 d), and then average daily values for the subsequent 2,000 d were used to calculate profit/cow per year. Net daily value was calculated by subtracting the costs (replacement, feeding, breeding, and other costs) from the daily income (milk sales, cow sales, and calf sales). The ED40 models resulted in greater profits than the TAI-85 model but lower profits than the TAI-95 model. Both ED60 models resulted in greater profits than the TAI-95 model. Combining TAI and ED increased profits within each level of accuracy or compliance. Adding TAI to ED would increase overall profit/cow per year by \$46.8 to \$74.7 with 40% ED, and by \$8.9 to \$30.5 with 60% ED. Adding ED to TAI would increase profit/cow per year

by \$64.2 to \$99.4 with 85% compliance and by \$31.8 to \$59.7 with 95% compliance. Although combining TAI and ED increased profits within each level of accuracy or compliance, when evaluated separately, ED60 with 95% accuracy or TAI with 95% compliance were as profitable as or more profitable than TAI-ED with low ED, accuracy, or compliance. Therefore, producers can improve their profits by combining TAI and ED as reproductive management; however, if a herd can achieve high ED with high accuracy or have high compliance with injections, using only ED or TAI might be more profitable than trying to do both.

Key words: economics, reproductive program, dairy cow

INTRODUCTION

Reproductive performance is a key determinant of dairy cow profitability (Britt, 1985; Meadows et al., 2005; De Vries, 2006; De Vries et al., 2006). Several parameters affect reproductive performance, such as voluntary waiting period (VWP), service rate (SR), conception rate (CR), and pregnancy loss. Pregnancy rate (PR) is the combination of SR and CR, and is believed to be one of the most comprehensive measures of reproductive performance. Depending on the dairy, one or more of these factors may be a problem. Traditionally, at the end of the VWP, cows would be AI upon detection of estrus, and cows not AI up to a predetermined DIM would be presented for veterinary evaluation and treated according to findings in the ovaries or uterus. Artificial insemination upon natural estrus is still the main method to breed cows (54.7 and 39.6% for first and subsequent services, respectively; USDA, 2009); however, with the advent of synchronization of ovulation for timed AI (Pursley et al., 1995; Moreira et al., 2001), dairies are increasingly adopting these protocols as part of their reproductive programs (Caraviello et al., 2006; USDA, 2009). For the most part, synchronization protocols are used in combination with estrus detection (Caraviello et al., 2006; USDA, 2009).

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Nonetheless, in an attempt to tightly control SR and to eliminate the need for estrus detection, many herds (9.9 to 13.2% for first and subsequent services, respectively) are opting for the use of timed AI exclusively (USDA, 2009; Giordano et al., 2011).

Although several studies have evaluated CR and time to conception using different reproductive programs (Pursley et al., 1997a; Cerri et al., 2004; Tenhagen et al., 2004), very few have evaluated the economic benefits of using such programs (Tenhagen et al., 2004; Giordano et al., 2011). Because of the wide variation in factors that affect reproductive efficiency of a given program such as SR, accuracy of estrus detection, and compliance with the timed AI (**TAI**) protocol, simulation models are an attractive option to evaluate different scenarios (Inchaisri et al., 2010). Stochastic dynamic dairy herd simulation models have been used to evaluate the economic benefit of different treatments for cystic ovarian disease (De Vries et al., 2006). Similar models could be used to compare the economic benefit of different reproductive programs in different scenarios (Marsh et al., 1985; Sørensen et al., 1992; Plaizier et al., 1997). To our knowledge, only one study has evaluated the economics of combining ED and TAI, although using a deterministic model (Giordano et al., 2011). Therefore, the objective of this study was to compare the economic benefits of different reproductive programs that use ED only, TAI only, or a combination of both (**ED-TAI**) using a stochastic dynamic simulation model. Of particular interest was the effect of SR (40 vs. 60%), accuracy of ED (85 vs. 95%), compliance with the timed AI protocol (85 vs. 95%), and milk price (\$0.33 vs. 0.44/kg).

MATERIALS AND METHODS

Simulation Model

An individual-based model of a dairy herd was developed to evaluate the technical and economic performance of different reproductive programs that use ED, TAI, or ED-TAI. The model tracks the daily reproductive status and milk production of each cow in the herd subject to a given reproductive protocol and a sequence of events including estrus, estrus detection, insemination, diagnostics, and calving. Stochastic elements were incorporated in the occurrence and detection of estrus, success of AI, occurrence of pregnancy loss, occurrence of involuntary culling, and occurrence of death. The model was implemented in the freeware agent-based modeling environment Netlogo (Wilensky, 1999; <http://ccl.northwestern.edu/netlogo>). The model structure and order of events are summarized in the Appendix in the form of pseudo-code.

Reproductive Parameters and Programs

The reproductive parameters were modeled as a sequence of discrete events, each with their own probability, timing, and outcome. The parameters evaluated were estrus occurrence, estrus detection, AI, conception, pregnancy loss, and calving. The reproductive programs evaluated were as follows: ED = AI upon estrus detection; TAI = first AI after a Presynch-Ovsynch protocol (Pursley et al., 1995; Moreira et al., 2001), and subsequent AI after an Ovsynch protocol; TAI-ED = first AI after a Presynch-Ovsynch protocol, and subsequent AI upon estrus detection, or TAI if not AI upon estrus detection up to the scheduled day of TAI. The first estrus after calving followed a log normal distribution with mean (SD) of 19 d (11 d) truncated at 2 d (De Vries et al., 2006). The second and subsequent estruses followed a normal distribution with mean (SD) of 21 d (2.5 d). Return to estrus after TAI also followed a normal distribution with mean (SD) of 21 d (2.5 d). As previously reported (Giordano et al., 2011), the VWP for the ED group was set at 50 DIM; however, the VWP for the TAI and TAI-ED groups were set at 72 DIM. At the end of the VWP, all cows in the ED group were AI upon estrus detection, and all cows in the TAI and TAI-ED were timed AI for the first time. Pregnancy diagnosis was scheduled at 32 d after AI, and pregnant cows were reconfirmed at 91 and 200 d after AI. Accuracy of pregnancy diagnosis was set at 100%. Conception probability for AI upon accurate estrus detection was set at 33.9% for the first AI and then decreased by 2.6% for every subsequent AI (De Vries, 2004, 2006; Norman et al., 2009; Hertl et al., 2010). Conception probability for AI upon inaccurate estrus detection was set at 6.2% of the conception probability for accurate estrus detection. This assumption was based on data from Galvão et al. (2007), Santos et al. (2010), Giordano et al. (2012a), and Ribeiro et al. (2012). In total, 2,070 cows had plasma progesterone concentrations on the day of AI; of those, 1,929 had progesterone concentration <1 ng/mL and 141 had progesterone concentration ≥1 ng/mL. Conception risk was 33.9% (654/1,929) for cows accurately AI based on progesterone concentration (<1 ng/mL), and 2.1% (3/141) for cows inaccurately AI; therefore, conception risk for inaccurate AI was 6.2% of accurate AI (2.1/33.9). Conception probability for AI following the complete Ovsynch protocol was set at 85.6% of the conception probability for AI upon accurate estrus detection (33.9% × 0.856 = 29.0%). This assumption was based on data from Burke et al. (1996), Pursley et al. (1997a,b), and Tenhagen et al. (2004), where the CR for the Ovsynch protocol without presynchronization was compared with conception risk at detected estrus

in a total of 2,891 AI. Overall, the conception risk for Ovsynch was 38.8% (633/1,631 AI) and conception risk for estrus detection was 45.3 (571/1,260 AI); therefore, the conception risk for Ovsynch was 85.6% (38.8/45.3) of the conception risk for estrus detection. Missing any injection of the Ovsynch protocol resulted in conception probability of 18.1% of a complete Ovsynch ($29.0\% \times 0.181 = 5.2\%$). This assumption was based on data from Moreira et al. (2001), Galvão et al. (2004), Galvão and Santos (2010), and Santos et al. (2010), where conception risk was evaluated based on synchrony of ovulation after the last GnRH injection of the Ovsynch protocol. In total, 1,473 cows were evaluated, and of those, 1,258 had the ovulation synchronized after the last GnRH injection and 215 did not. Conception risk was 43.6% for cows with synchronized ovulation and 7.9% for unsynchronized ovulations; therefore, conception risk for cows with unsynchronized ovulations was 18.1% (7.9/43.6) of the conception risk for cows with synchronized ovulations. Conception probability following a complete Presynch-Ovsynch protocol was 29.8% higher than Ovsynch alone ($29.0\% \times 1.298 = 37.6\%$). This assumption was based on data from Moreira et al. (2001), El-Zarkouny et al. (2004), and Navanukraw et al. (2004), where the benefit from presynchronization was evaluated. In total, 1,428 cows were evaluated, and of those, 715 were presynchronized and 713 were not. Conception risk was 48.3% for presynchronized cows and 37.2% for cows not presynchronized; therefore, the conception risk was 29.8% greater ($48.3/37.2 = 1.298$ or 29.8%) for presynchronized cows. If one of the prostaglandin injections of the Presynch protocol was missed, 50% of the benefit was lost, and if both were missed, 100% of the benefit was lost. One would assume that the second prostaglandin injection is more important than the first but, because of lack of hard data, and for simplicity, equal weight was given to each injection.

Cows diagnosed not pregnant were managed according to each reproductive program: no intervention (ED) or were started on the Ovsynch protocol for timed AI (TAI and TAI-ED). Cows were allowed to be AI up to 366 DIM and allowed to be enrolled in the Ovsynch protocol up to 356 DIM so the last TAI would occur at 366 DIM. The period of 366 d was chosen to allow a total of 8 AI for the TAI groups, with the last AI at 366 DIM. Pregnant cows were dried off at 220 d of gestation, and gestation length was set at 280 d; therefore, the dry period was set at 60 d. Pregnancy loss was set at 11.3%, with 9.6% occurring from 32 to 90 d of gestation and 1.7% occurring from 90 d of gestation to term (based on data from Santos et al., 2004; McClure, 2007; Brick et al., 2012). After an abortion, cows in the ED and TAI-ED groups returned to estrus following a log normal distribution with mean (SD) of 19 d (11

d), based on data from Parmigiani et al. (1978) and Kastelic and Ginther (1989). Cows in the TAI group were re-enrolled in the Ovsynch after nonpregnancy diagnosis at 91 or 200 d after AI. Stillbirth probability was set at 6.5% according to previous reports (Bicalho et al., 2008; Schuenemann et al., 2011).

Milk and Fat Production

Daily milk yield (MY) was calculated using Wood's (1967) incomplete gamma function with adjustments for pregnancy as previously reported (De Vries, 2001; De Vries et al., 2006). Mathematically,

$$\text{MY (kg/d)} = a \times \text{DIM}^b \times \exp(-c \times \text{DIM}) \times [1 + (\text{DPREG}/d)^2]^{-1},$$

where DPREG is the number of days pregnant, and a, b, c, and d are parameters of the function. Parameters a through d for first parity were 16.27, 0.19, 0.001425, and 509.3; for second parity, 23.81, 0.1652, 0.002208, and 393.2; and for third and greater parities, 21.83, 0.2210, 0.003002, and 355.7, respectively.

Daily fat percentage in milk (fat %) and FCM were modeled, for all lactations, as previously described (De Vries, 2001; De Vries et al., 2006). Mathematically,

$$\text{Fat \%} = 12.86 \times \text{DIM}^{-1.081} \times \exp[0.0926 \times (\ln \text{DIM})^2] \times (\ln \text{DIM})^{1.107}$$

$$\text{FCM (kg/d)} = 0.4 \times \text{MY} + 0.15 \times \text{Fat \%} \times \text{MY}.$$

BW

Body weight was modeled as previously described (van Arendonk, 1985; De Vries, 2001; De Vries et al., 2006).

$$\begin{aligned} \text{BW (kg)} = & A \times \{1 - [1 - (B/A)^{1/3}] \\ & \times \exp(-C \times \text{AGE})\}^3 - (P1/P2) \times \text{DIM} \\ & \times \exp(1 - \text{DIM}/P2) + P3^3 \times \text{DPC}^3, \end{aligned}$$

where AGE is the cow's age in days, and DPC is 0 to 50 d of gestation (calculated by subtracting 50 from the gestation days). The parameters mature liveweight (kg; A), birth weight (kg; B), growth rate parameter (C), maximum decrease of liveweight during lactation (P1), time during the lactation with minimum liveweight (P2), and pregnancy parameter (P3) for first parity were 600, 42, 0.0039, 20, 65, and 0.0187, and for second

and greater parities were 600, 42, 0.0060, 40, 75, and 0.0187.

DMI

Dry matter intake (kg/d) for lactating cows was calculated as recommended by the NRC (2001), as previously reported (De Vries et al., 2006):

$$\text{DMI} = 0.372 \times \text{FCM} + 0.0968 \times \text{BW}^{0.75} \\ \times \{1 - \exp[-0.192 \times (\text{DIM}/7 + 3.67)]\}.$$

Dry cows were assumed to consume 12 kg of DM/d, as previously reported (De Vries et al., 2006).

Culling and Replacements

Cows were culled if the income from milk sales was lower than the cost of production (feeding cost + other costs) or if they were not pregnant by 450 DIM. Furthermore, a probability of involuntary culling was set at 0.1%/d for the first 60 DIM, and 0.03%/d for the remaining of the lactation and dry period (based on data from Dechow and Goodling, 2008; Pinedo and De Vries, 2010). The probability of death was set at 0.05%/d for the first 60 DIM, and 0.0076%/d for the remaining of the lactation and dry period (based on data from Dechow and Goodling, 2008; Pinedo and De Vries, 2010). For each cow that was culled or died, a pregnant heifer (730 d old; 280 d pregnant) was immediately purchased as replacement. Therefore, herd size remained constant.

Costs and Incomes

Estrus detection cost in all lactating cows was set at \$0.15/cow per day, assuming an employee makes \$15/h and can observe 100 cows for signs of estrus in 1 h. Price of GnRH was set at \$2.40/dose, and that of PGF_{2α} was set at \$2.65/dose (average commercial prices in July 2012). The price range for GnRH was \$2.00 to \$2.80 and for PGF_{2α} was \$2.30 to \$3.00. Injection cost was set at \$0.25/injection, assuming an employee makes \$15.00/h and can give 60 injections per hour. Semen cost was set at \$10.00/straw. Cost of AI was set at \$5.00/AI. Pregnancy diagnosis cost was set at \$3.00/diagnosis. Calf price (average for male and female) was set at \$140/calf. Milk price was modeled at \$0.33 and \$0.44/kg. Dry matter price was set at \$0.25/kg for lactating cows and at \$0.15/kg for dry cows. Cull price was modeled at \$0.65/kg of live weight with milk price at \$0.33 and \$0.44/kg or at \$1.65/kg of live weight with milk price

at \$0.44/kg to evaluate conditions of low milk price and low cull price, high milk price and low cull price, and high milk price and high cull price. Replacement heifer price was set at \$1,600.00/heifer. Other variable and fixed costs were set at \$2.50/cow per day.

Experimental Design

Four factors that could affect the economic benefits of the 3 different reproductive programs were compared: estrus detection (40 vs. 60%), accuracy of estrus detection (85 vs. 95%), compliance with each injection of the synchronization protocol (85 vs. 95%), and milk price (\$0.33 vs. \$0.44/kg). Values for estrus detection followed previous reports (De Vries et al., 2006). Values for accuracy of estrus detection were extracted from a review by Heersche and Nebel (1994). The values for compliance with each injection of the synchronization protocol matched the values for accuracy of estrus detection. Milk price was modeled to represent \$15 or \$20 per 100 lbs. This design would generate 28 scenarios: 8 scenarios for ED [40 (**ED40**) or 60% (**ED60**) estrus detection, 85 or 95% accuracy of estrus detection (**ED40-85** or **ED40-95**), and \$0.33 or 0.44/kg of milk], 4 scenarios for TAI [85 or 95% compliance (**TAI-85** or **TAI-95**) with injections, and \$0.33 or 0.44/kg of milk], and 16 scenarios for TAI-ED (40 or 60% estrus detection, 85 or 95% accuracy of estrus detection, 85 or 95% compliance with injections, and \$0.33 or 0.44/kg of milk). However, for TAI-ED only, the extremes for accuracy of estrus detection and compliance with injections were compared (85% for both vs. 95% for both; TAI-ED40-85, TAI-ED40-95, TAI-ED60-85, and TAI-ED60-95). Therefore, 20 different scenarios were evaluated. For the ED40-85 and ED40-95 models, 34 and 38% of the AI were accurate, respectively. For the E60-85 and ED60-95 models, 57 and 51% of the AI were accurate, respectively.

For each reproductive program, all the combinations of probability of estrus detection, accuracy of estrus detection, and compliance with each injection were run separately for \$0.33/kg of milk and then for 0.44/kg of milk. For each set of parameters, 100 simulations for a herd of 1,000 cows were run for 5,000 d. In the beginning of the simulation, each herd was composed of 33.3% of the cows each in the first, second, and third lactations. Age of first-lactation cows was set at 730 d, second lactation at 1,155 d, and third lactation at 1,580 d, assuming a calving interval of 425 d. Simulation started with cows in their first day of lactation. Usually it took between 1,500 and 2,000 d for each herd to reach steady state (determined by visual observation; Figure 1); therefore, the first 3,000 d were excluded

Table 1. Calculation of service rate (SR), conception rate (CR), and pregnancy rate (PR) for the timed AI model with 95% compliance with each injection

Cycle	Eligible, no.	AI, no.	SR, %	Pregnant, no.	CR, %	PR, %
1	1,000	1,000	100	329	32.9	32.9
2	671	0	0	0	—	—
3	671	671	100	169	25.2	25.2
4	502	0	0	0	—	—
5	502	502	100	122	24.3	24.3
6	380	0	0	0	—	—
7	380	380	100	91	23.9	23.9
8	289	0	0	0	—	—
9	289	289	100	67	23.2	23.2
10	222	0	0	0	—	—
11	222	222	100	49	22.1	22.1
12	173	0	0	0	—	—
13	173	173	100	38	22.0	22.0
14	135	0	0	0	—	—
15	135	135	100	28	20.7	20.7
Total	5,744	3,372	58.7	893	26.5	15.5

from the technical and economic analysis. Steady state is reached when the mean and variance do not change when shifted in time or space. Net daily value was calculated by subtracting the costs of replacement heifers, feeding costs, breeding costs, and other costs from the daily income from milk sales, cow sales, and calf sales. The net daily value was averaged for the last 2,000 d of simulation and profit/cow per year was calculated. To evaluate reproductive parameters such as SR, CR, PR, median days open (MDO), and proportion of pregnant

cows at 366 DIM (**PP366**), the models were run 100 times for 366 d without culling, deaths, abortion, or calving. The number of eligible cows, number of cows AI, and number of cows that conceived were calculated for every 21 d cycle after the end of the VWP (50 DIM for ED, and 72 DIM for TAI and TAI-ED). The total number of cows eligible, AI, and pregnant were used to calculate SR, CR, and PR at the end of the breeding period (Table 1). Proportion of pregnant cows in each day was averaged for the 100 runs, and the day the pro-

Figure 1. Graphic interface of NetLogo (<http://ccl.northwestern.edu/netlogo>) using a model that combined timed AI (TAI) and estrus detection (ED) as an example in a 5,000-d run. VWP = voluntary waiting period. From top to bottom: milking, pregnant, open, in VWP, and dry. Color version available in the online PDF.

portion of pregnant cows reached 50% was considered as MDO. Proportion of pregnant cows at 366 DIM was averaged for 100 runs.

Statistical Analysis

Data obtained after 100 runs for each scenario such as daily number of cows pregnant, lactating, culled and died, milk yield, estrus detection cost, synchronization cost, AI cost, diagnostic cost, feeding cost, replacement cost, other cost, milk income, calf sales income, cow sales income, and net income were exported into an Excel spreadsheet (Microsoft Corp., Redmond, WA) for data organization in preparation for statistical analysis. The cumulative yearly profits for each scenario were compared by ANOVA using the GLM procedure of SAS (SAS Institute Inc., Cary, NC). Differences with P -value ≤ 0.05 were considered statistically significant.

RESULTS AND DISCUSSION

Overview

Herein, we used a stochastic dynamic dairy herd simulation model to evaluate the technical and economic performance of different reproductive programs that use ED, TAI, or a combination of both. An advantage of the stochastic model compared with a deterministic model is the ability to evaluate variability in the outcomes of interest. Also, this is the first time that important factors for reproductive success such as accuracy of ED and compliance with the injections for the TAI protocol are evaluated. Using the NetLogo platform to build the model also allowed real-time evaluation of several components of the model, such as proportion of pregnant, nonpregnant, lactating, or dry cows, milk yield, culling, and profit. Figure 1 shows the TAI-ED model after a run for 5,000 d. It can be observed that the model stabilizes after approximately 2,000 d.

Effect of Different Reproductive Programs on Reproductive Parameter Outcomes

Reproductive parameter outcomes are shown in Table 2. Observed SR was very close to the specified ED rate set for the ED models. Although in the TAI model, cows were AI every other cycle, SR was close to 60% because of the large effect of the first AI, when all cows were AI, and also to a lesser extent because the breeding period ended with all cows being AI one last time (Table 1). The combination of TAI and ED (TAI-ED) resulted in the highest SR.

Both accuracy of ED and compliance with each injection affected CR; however, compliance with injection

Table 2. Reproductive parameter outcomes for 3 reproductive programs that used estrus detection only (ED), timed AI only (TAI), or a combination of both (TAI-ED), under different ED rates (40 or 60%; ED40 or ED60), accuracy of ED (85 or 95%), and compliance (85 or 95%; TAI-85 or TAI-95) with each injection of the TAI program¹

Parameter ²	ED40-85	ED40-95	ED60-85	ED60-95	TAI-85	TAI-95	TAI-ED40-85	TAI-ED40-95	TAI-ED60-85	TAI-ED60-95
SR, %	39.1 $\pm$ 0.7 ⁷	39.1 $\pm$ 0.7 ⁷	58.7 $\pm$ 1.0 ⁴	58.7 $\pm$ 1.0 ⁴	57.0 $\pm$ 0.9 ⁶	58.7 $\pm$ 1.0 ⁴	79.5 $\pm$ 0.8 ³	80.2 $\pm$ 0.8 ²	90.6 $\pm$ 0.9 ¹	90.6 $\pm$ 1.1 ¹
CR1, %	29.2 $\pm$ 2.4 ⁵	32.3 $\pm$ 2.3 ⁴	32.4 $\pm$ 2.3 ³	32.4 $\pm$ 2.3 ³	24.9 $\pm$ 1.4 ⁹	32.9 $\pm$ 1.4 ¹	25.2 $\pm$ 1.3 ⁸	32.6 $\pm$ 1.3 ²	25.4 $\pm$ 1.1 ⁷	32.6 $\pm$ 1.2 ²
CR2, %	28.9 $\pm$ 2.0 ⁵	31.9 $\pm$ 2.3 ¹	31.5 $\pm$ 2.4 ²	31.5 $\pm$ 2.4 ²	19.4 $\pm$ 1.4 ¹⁰	25.2 $\pm$ 1.7 ⁹	28.0 $\pm$ 2.7 ⁸	31.1 $\pm$ 2.7 ⁴	28.3 $\pm$ 2.5 ⁷	31.3 $\pm$ 2.5 ³
CRav, %	28.0 $\pm$ 1.0 ⁵	31.1 $\pm$ 1.1 ¹	30.7 $\pm$ 1.0 ²	30.7 $\pm$ 1.0 ²	20.0 $\pm$ 0.7 ¹⁰	26.5 $\pm$ 0.8 ⁷	23.4 $\pm$ 1.0 ⁹	28.7 $\pm$ 1.1 ⁴	24.3 $\pm$ 1.1 ⁸	29.5 $\pm$ 1.4 ³
PR, %	10.9 $\pm$ 0.5 ¹⁰	12.2 $\pm$ 0.5 ⁸	18.0 $\pm$ 0.7 ⁵	18.0 $\pm$ 0.7 ⁵	11.4 $\pm$ 0.4 ⁹	15.5 $\pm$ 0.4 ⁷	18.6 $\pm$ 0.7 ⁴	23.0 $\pm$ 0.8 ²	22.1 $\pm$ 0.9 ³	26.8 $\pm$ 1.2 ¹
MDO, d	171 ¹⁰	159 ⁸	120 ⁴	120 ⁴	156 ⁹	114 ⁷	133 ⁶	114 ²	117 ³	113 ¹
PP366, %	82.0 $\pm$ 1.4 ⁷	85.3 $\pm$ 1.2 ⁶	94.3 $\pm$ 0.7 ³	94.3 $\pm$ 0.7 ³	81.2 $\pm$ 1.3 ⁸	89.4 $\pm$ 0.9 ⁵	92.3 $\pm$ 0.9 ⁴	95.5 $\pm$ 0.7 ²	95.5 $\pm$ 0.7 ²	97.3 $\pm$ 0.5 ¹

¹Each model was run 100 times without culling, deaths, abortion, or calving. Values are means $\pm$ SD for 100 runs, except for MDO, which also includes the median for 100 runs.

²SR = service rate; CR1 = conception rate to first service; CR2 = conception rate to second service; CRav = average conception rate for all services; PR = pregnancy rate; MDO = median followed by mean days open; PP366 = proportion of pregnant cows at 366 DIM.

Superscript numbers (1–10) within each row rank each parameter from the best to the worst value.

tions had a greater detriment to CR because of the compounded effect (e.g., $0.85 \times 0.85 = 0.73$ and $0.85 \times 0.85 \times 0.85 = 0.61$), where the chance of a cow receiving all injections for the presynchronization was only 73%, and the chance of a cow receiving all injections for the Ovsynch was only 61% for the TAI-85 model. For the TAI-95 model, the values would be 90 and 85%, respectively. On the other hand, although the CR after inaccurate ED (2.1%) was lower than the CR after missing an injection of Ovsynch (5.2%), it affected a lower proportion of cows (2% for ED40-95 to 9% for ED60-85). This can be clearly observed in the TAI-ED models with 85% accuracy and 85% compliance, where the first service was lower than the second service. The highest mean CR was observed for the ED models with 95% accuracy and the lowest mean CR for the TAI-85 model. However, the TAI models with 95% compliance had the highest first-service CR because of the beneficial effect of presynchronization.

Pregnancy rate was low for ED40 models (lowest for the ED40-85 model) and for the TAI-85 model because of low SR and low CR, respectively. Pregnancy rates increased by increasing SR in the ED60 models (highest for the TAI-ED60-95 model) and by increasing CR in the TAI-95 model. Compliance with each injection had a greater effect on PR than accuracy of ED. Although PR increased from 11.8% (from 16.1 to 18.0) to 11.9% (from 10.9 to 12.2) by going from 85 to 95% accuracy in the ED40 and ED 60 models, PR increased by 36% by going from 85 to 95% compliance in the TAI models. Therefore, compliance with injections is crucial for the success of programs that rely solely on TAI.

Median days open was shorter for TAI-85 than for the ED40 models and shorter for TAI-95 than for the ED60 models (Table 2). Nonetheless, mean days open were longer for TAI-85 compared with ED40-95 and for TAI-95 compared with the ED60 models. This is mainly because of the long and fixed re-insemination interval (42 d) leading cows to have either 156 or 198 d open in the TAI-85 model or 114 or 156 d open in the TAI-95 model. The survival curves are shown in Figure 2. Although ED40-85 had the lowest PR, PP366 was actually slightly higher than the TAI-85 model because of the shorter VWP for the ED models, and the long re-insemination interval and the lower CR for the TAI models, especially that with 85% compliance. Therefore, although the models with TAI achieved a higher proportion of pregnant cows after the first service, all the ED models achieve a higher proportion of pregnant cows by the end of the breeding period than the TAI-85 model. Furthermore, the ED60-85 and ED60-95 models achieved a higher proportion of pregnant cows by the end of the breeding period than the TAI-95 model. In

summary, combining TAI and ED increased PR, decreased MDO, and increased PP366.

Effect of Different Reproductive Programs on Technical and Economic Results

Technical and economic results for the 3 reproductive programs with milk price set at \$0.33/kg and \$0.44/kg are shown in Table 3. First, the technical and economic results for the models with milk at \$0.33/kg are in line with previous reports (De Vries, 2006; De Vries et al., 2006). Nonetheless, others have reported much higher profits per cow per year (Giordano et al., 2011). This is

Figure 2. Proportion of nonpregnant cows for 3 reproductive programs that used estrus detection only (ED), timed AI only (TAI), or a combination of both (TAI-ED), under different ED rates (40 or 60%), accuracies of ED: (panel a) 85% and (panel b) 95%, and compliance: (panel a) 85% and (panel b) 95%, with each injection of the TAI program.

partly because in the model by Giordano et al. (2011) fixed and other variable costs were not accounted for, thereby decreasing the cost of production by \$912.5/yr. Furthermore, milk price and cull price were slightly higher. The ED40 models resulted in greater profits than the TAI-85 model but lower than the TAI-95 model. Both ED60 models resulted in greater profits than the TAI-95 model. In herds that use only ED, adding TAI would increase overall profit/cow per year by \$46.8 (TAI-ED40-85 vs. ED40-85) to \$68.8 (TAI-ED40-95 vs. ED40-95), and by \$8.9 (TAI-ED60-85 vs. ED60-85) to \$26.9 (TAI-ED60-95 vs. ED60-95). Our findings corroborate with the observations by Giordano et al. (2011), where profits were increased if TAI was combined with ED at any level of ED (from 10 to 80% ED). Adding ED to a TAI program is effective because it increases SR and decreases the interbreeding inter-

val. As expected, the benefit from adding TAI to an ED program was highest when ED was lowest (Tenhagen et al., 2004). In herds that use only TAI, adding ED would increase profit by \$64.2 (TAI-ED40-85 vs. TAI-85) to \$96.3 (TAI-ED60-85 vs. TAI-85), and by \$31.8 (TAI-ED40-95 vs. TAI-95) to \$59.7 (TAI-ED60-95 vs. TAI-95). Adding ED to a TAI program has the greatest effect when compliance is poor (85%), even with low SR (40%) and poor accuracy (85%). This is because CR is higher for ED with poor accuracy than for TAI with poor compliance.

Although compliance is critical for the success of TAI and TAI-ED programs, it is often overlooked. One might think of compliance simply as missing injections for cows on a list, and as such, 85% compliance might seem very low. Nonetheless, compliance starts with manufacturing the correct list. The authors have

Table 3. Steady-state technical and economic (\$/cow per year) results for 3 reproductive programs that used estrus detection only (ED), timed artificial insemination only (TAI) or a combination of both (TAI-ED), under different ED rate (40 or 60%; ED40 or ED60), accuracy of ED (85 or 95%), and compliance (85 or 95%; TAI-85 or TAI-95) with each injection of the TAI program with milk price set at \$0.33/kg (top row for each parameter), followed by results when milk price was set at \$0.44/kg (bottom row of each parameter)

Item	ED40-85	ED40-95	ED60-85	ED60-95	TAI-85	TAI-95	TAI-ED40-85	TAI-ED40-95	TAI-ED60-85	TAI-ED60-95
Pregnant, % ^{a,A}	45.6	47.8	53.3	55.2	46.0	52.4	54.5	58.3	57.2	60.4
Lactating, % ^{b,B}	45.8	48.0	53.6	55.5	46.2	52.7	54.8	58.9	57.6	60.8
Culling, % ^{c,C}	84.8	84.1	82.9	82.6	83.8	82.0	81.9	81.1	81.3	80.9
	89.2	88.6	87.4	86.9	88.6	87.0	87.0	86.1	86.3	85.6
Milk, kg/d ^{d,D}	40.3	38.3	34.2	33.0	38.6	32.8	31.4	28.8	29.4	27.5
	40.5	38.7	34.5	33.4	38.9	33.1	31.7	28.9	29.6	27.8
Milk sales ^{e,E}	33.8	34.0	34.4	34.5	33.8	34.4	34.5	34.8	34.7	35.0
	33.2	33.3	33.7	33.9	33.2	33.6	33.8	34.1	34.0	34.2
Milk sales ^{e,E}	3,450.5	3,441.0	3,431.0	3,433.3	3,414.9	3,391.2	3,404.9	3,400.0	3,402.3	3,405.2
	4,750.9	4,743.9	4,730.0	4,724.5	4,718.5	4,693.9	4,719.2	4,712.3	4,713.6	4,705.5
Cows sales ^{f,F}	132.3	124.5	108.7	104.2	126.0	103.7	97.8	87.6	90.0	82.6
	133.1	126.0	109.7	105.1	127.2	104.4	99.0	88.2	90.8	83.7
Calf sales ^{g,G}	122.4	123.4	126.2	127.7	120.9	123.2	124.4	126.9	125.9	128.4
	123.1	124.0	127.2	128.6	121.7	124.0	125.3	128.0	126.8	129.4
Replace costs ^{h,H}	645.2	613.3	547.5	528.4	618.0	525.3	502.1	460.6	470.2	439.2
	647.5	619.3	552.6	534.0	622.7	529.0	506.5	462.4	473.4	444.5
Breeding costs ^{i,I}	91.1	88.7	97.2	94.1	104.1	91.6	136.1	126.5	131.9	123.0
	93.8	91.5	100.0	96.6	104.8	92.0	139.8	130.0	135.5	126.3
Feeding costs ^{j,J}	1,801.9	1,795.5	1,784.2	1,782.0	1,790.0	1,773.1	1,774.9	1,767.6	1,770.1	1,766.3
	1,851.0	1,846.2	1,834.3	1,829.6	1,843.9	1,829.4	1,832.8	1,824.5	1,827.1	1,819.3
Other costs ^{k,K}	912.5	912.5	912.5	912.5	912.5	912.5	912.5	912.5	912.5	912.5
Profit ^{l,L}	254.6 ⁹	278.8 ⁸	324.6 ⁵	348.3 ²	237.2 ¹⁰	315.5 ⁶	301.4 ⁷	347.3 ³	333.5 ⁴	375.2 ¹
	1,502.2 ⁹	1,524.4 ⁸	1,567.9 ⁵	1,585.5 ³	1,483.4 ¹⁰	1,559.5 ⁶	1,552.0 ⁷	1,599.1 ²	1,582.8 ⁴	1,616.0 ¹

^{a-l}Lowercase superscripts indicate differences when milk price was set at \$0.33/kg; ^aall values differ ($P < 0.001$; SE = 0.04); ^ball values differ ($P < 0.001$; SE = 0.04), except TAI-95 vs. TAI-ED40-85 ($P = 0.12$); ^call values differ ($P < 0.01$; SE = 0.08), except ED60-95 vs. TAI-95 ($P = 0.08$); ^dall values differ ($P < 0.001$; SE = 0.005), except ED60-85 vs. TAI-95 ($P = 0.43$); ^eall values differ ($P < 0.05$; SE = 1.62), except TAI-ED40-85 vs. TAI-ED60-85 and TAI-ED60-95 ($P > 0.25$), TAI-ED40-95 vs. TAI-ED60-85 ($P = 0.31$), and TAI-ED60-85 vs. TAI-ED60-95 ($P > 0.21$); ^fall values differ ($P < 0.001$; SE = 0.25), except ED60-95 vs. TAI-95 ($P = 0.15$); ^gall values differ ($P < 0.02$; SE = 0.10), except ED40-95 vs. TAI-95 ($P = 0.23$); ^hall values differ ($P < 0.01$; SE = 1.2), except ED60-95 vs. TAI-95 ($P = 0.08$); ⁱall values differ ($P < 0.001$; SE = 0.07); ^jall values differ ($P < 0.03$; SE = 0.51), except TAI-ED40-95 vs. TAI-ED60-95 ($P = 0.09$); ^kall values are equal (fixed cost); ^lall values differ ($P < 0.001$; SE = 1.26), except ED60-95 vs. TAI-ED40-95 ($P = 0.59$).

^{A-L}Uppercase superscripts indicate differences when milk price was set at \$0.44/kg; ^Aall values differ ($P < 0.001$; SE = 0.04); ^Ball values differ ($P < 0.05$; SE = 0.03), except ED40-95 vs. TAI-85 ($P = 0.10$), ED60-95 vs. TAI-95 ($P = 0.18$), and TAI-95 vs. TAI-ED40-85 ($P = 0.51$); ^Call values differ ($P < 0.05$; SE = 0.07); ^Dall values differ ($P < 0.001$; SE = 0.004), except ED40-85 vs. TAI-85 ($P = 0.30$); ^Eall values differ ($P \leq 0.05$; SE = 1.76), except TAI-85 vs. TAI-ED40-85 ($P = 0.77$), and TAI-ED40-96 vs. TAI-ED60-85 ($P = 0.59$); ^Fall values differ ($P < 0.001$; SE = 0.25), except ED60-95 vs. TAI-95 ($P = 0.06$); ^Gall values differ ($P < 0.001$; SE = 0.09), except ED40-95 vs. TAI-95 ($P = 0.97$); ^Hall values differ ($P < 0.04$; SE = 1.2); ^Iall values differ ($P < 0.001$; SE = 0.07); ^Jall values differ ($P < 0.02$; SE = 0.43), except ED60-95 vs. TAI-95 ($P = 0.77$); ^Kall values are equal (fixed cost); ^Lall values differ ($P < 0.001$; SE = 1.50), except ED60-95 vs. TAI-ED60-85 ($P = 0.21$).

troubleshoot reproductive problems in herds and discovered that only 70 to 75% of the cows were AI for the first service in a 100% TAI program because of missing cows when generating the AI list. Even in herds with good compliance, only approximately 95 to 97% of the cows are AI upon completion of a TAI protocol, either because cows are missed or because the AI technician decided not to AI the cow (e.g., cows with purulent discharge, cow with certain diseases such as mastitis, cows in which the cervix cannot be passed, cows with uterine adhesions). Other issues with list manufacturing include entering incorrect information for AI or pregnancy diagnoses that lead to nonpregnant cows not being re-enrolled in the program, cows that were AI not coming up for pregnancy diagnosis, or pregnant cows receiving prostaglandin. Even if the list is correct, usually not all the cows are found for hormone administration, especially in large herds; therefore, the diligence of the person responsible for hormone administration dictates how high or low compliance is. Often, mistakes also occur when ear tags are misread. Given these issues, herd managers who are risk averse might favor ED or even natural breeding over TAI (Overton, 2005; Lima et al., 2010).

The technical results for the models with milk at \$0.44/kg are in line with previous reports (De Vries, 2006; De Vries et al., 2006); however, the profits were higher than in previous reports (De Vries, 2006; De Vries et al., 2006), because of higher milk prices, but were still lower than other reports (Giordano et al., 2011). In general, with higher milk prices, the proportion of lactating cows increased because there was no culling due to milk sales being lower than the cost of production; therefore, all cows that did not get pregnant remained in the herd until 450 DIM. As a consequence, milk yield was decreased. Economic results were similar to the models with milk price at \$0.33/kg, with the only change being that TAI-ED40-95 was slightly more profitable than ED60-95. Of greater importance is the fact that the percentage increase in profit when ED or TAI was added to a program that used only one was much greater when milk price was lower. When milk price was \$0.33/kg, the difference in profits for TAI-ED40-85 versus ED40-85 (\$46.8) and for TAI-ED40-95 versus ED40-95 (\$68.8) represented an increase in profit of 18.4 to 24.7%. When milk price was \$0.44/kg, the difference in profits for TAI-ED40-85 versus ED40-85 (\$49.8) and for TAI-ED40-95 versus ED40-95 (\$74.7) would represent an increase in profit of only 3.2 to 4.9%. The increase in profit would be even less significant if SR was good. The difference in profits for TAI-ED60-85 versus ED60-85 (\$14.9) and for TAI-ED60-95 versus ED60-95 (\$30.5) represents an increase

of only 0.9 to 1.9%. The difference in profits for TAI-ED60-85 versus ED60-85 (\$14.9) and for TAI-ED60-95 versus ED60-95 (\$30.5) represents an increase of only 0.9 to 1.9%. Therefore, reproductive performance is not as critical when milk prices are high as when milk prices are low. However, dairies should still strive for good reproductive performance because it cannot be improved as fast as milk prices can decrease.

Choosing the Most Profitable Program

Although adding ED or TAI to a program that uses either one only would increase profits, it was not always the program that showed the best reproductive parameters, such as PR, MDO, and PP366, and proportion of pregnant cows in the herd, that had the highest profits. In general, as the proportion of pregnant cows in the herd increased, milk yield increased, culling rate decreased, and proportion of lactating cows decreased. Although there is a benefit to improving reproductive performance by increasing milk yield and decreasing culling, it may be offset by a decreased proportion of lactating cows in the herd. Furthermore, although breeding costs decrease with increased reproductive performance for each program (ED, TAI, or TAI-ED), costs were higher for programs that used TAI or a combination of TAI and ED. Therefore, although PR and proportion of pregnant cows were higher for TAI-85 than for ED40-85, and higher for TAI-95 than for ED40-95, profits were lower. Likewise, although PR and proportion of pregnant cows in the herd were higher for TAI-ED40-85 than for ED60-85, for ED60-95, and for TAI-95, profits were lower. Similarly, profits were lower for TAI-ED60-85 than for ED60-95. These findings corroborate the observations by Tenhagen et al. (2004). They observed that although adding TAI to 2 herds that used ED improved reproductive performance (reduced interval to first AI, increased SR, reduced days open, reduced culling for infertility), it was only economically advantageous in the herd with 29% SR and not in the herd with 56% SR.

Regarding the comparison between TAI and ED, our results differed slightly from a previous report (Giordano et al., 2011), using data generated from one study in Wisconsin (Giordano et al., 2012b), where greater profits results for 100% TAI with resynchronization 32 d after AI than for 100% ED with 50% SR. After performing a sensitivity analysis, those researchers concluded that SR had to increase from 50 to 62% for the ED model to be more profitable than the TAI model. Herein, even the ED60-85 model, which had an overall SR of 58.6% (49.8% accurate and 8.8% inaccurate), had higher profits than TAI-95. The discrepancy

might have arisen from the assumptions for each model. Herein, we collected data from several published reports and calculated the weighted average of the effect of inaccurate AI, compliance, presynchronization, and Ovsynch itself on CR. In the model by Giordano et al. (2011), the first and subsequent services CR for the 100% TAI model were 45 and 30%, respectively, whereas for ED they were 33 and 30%, respectively. Based on data from Moreira et al. (2001), El-Zarkouny et al. (2004), and Navanukraw et al. (2004), we assumed that conception probability following a complete Presynch-Ovsynch protocol was 29.8% higher than Ovsynch alone ($29.0\% \times 1.298 = 37.6\%$), but conception probability for Ovsynch was assumed to be 85.6% of the conception probability for AI upon accurate estrus detection ($33.9\% \times 0.856 = 29.0\%$), based on data from Burke et al. (1996), Pursley et al. (1997a,b), and Tenhagen et al. (2004). After accounting for compliance, the CR for first service for the TAI-95 model was 32.9%, decreased to 25.2%, and then continued to decrease 2.6% for every subsequent service, whereas the first-service CR for the ED60 models ranged from 28.8 (ED60-85) to 32.4% (ED60-95) and then decreased 2.6% for every subsequent service.

A recent study using 55,372 AI from 23,695 lactations from 14,148 Holstein cows in 7 herds in New York State reported that CR for first service was 29%, decreasing to 26, 25, and 24% for second, third, and fourth subsequent services (Hertl et al., 2010). Although the authors stated that all cows in these 7 herds were enrolled in ovulation synchronization and planned breeding programs, they did not compare CR between AI performed after TAI or ED. A report from all the regions in the United States (Norman et al., 2009) showed that CR averaged 31% in 2006, with the lowest CR in the Southeast (26%) and the highest in the Northeast (33%) and Southwest (33%). If CR for TAI were increased to 45% for the first service with 100% compliance, profit would indeed be higher for TAI than for ED with 50% SR, 100% accuracy, and 33% CR, at either \$0.33/kg (\$423.3 vs. \$324.8) or \$0.44/kg (\$1,661.1 vs. \$1,564.5) milk price. Interestingly, with 50% SR, 100% accuracy, and 33% CR, profits were higher than those of TAI-95 at \$0.33/kg (\$324.8 vs. \$315.5) or \$0.44/kg (\$1,564.5 vs. \$1,559.5) milk price. Even with 50% SR, 95% accuracy, and CR for accurate ED of 33.9%, ED was more profitable than TAI-95 at \$0.33/kg (317.9 vs. \$315.5) or \$0.44/kg (\$1,561.7 vs. \$1,559.5) milk price. Therefore, if a given herd is achieving much higher CR using TAI than with ED, it should probably favor TAI; however, if CR for TAI are similar to those of ED, and SR is at least 50%, ED would be more profitable. Therefore, dairy farmers can make an informed decision based on the CR being achieved on their dairies.

Possible Model Limitation

One particular aspect of the model is that the total number of cows (lactating plus dry) in the herd is maintained constant instead of the number of lactating cows. Some dairy farmers might try to keep the number of lactating cows constant to reduce idle capacity; however, variation in cow numbers does occur throughout the year, and farmers often cannot or do not try to adjust their lactating cow numbers. Herein, the model with the best reproductive performance (TAI-ED60-95) had 36 to 39 fewer lactating cows than the model with the worst performance (ED40-85). Having fewer lactating cows counteracted the positive effect that improved reproductive performance had on milk yield per lactating cow, so that milk income was actually lower for TAI-ED60-95 than for ED40-85. Ultimately, most of the benefit from improved reproductive performance was because of lower replacement costs. If the number of lactating cows were held constant, herds with better reproduction would have to make investments to house and feed more dry cows, and to purchase more lactating cows if numbers fell below a given threshold. It is also worth noting that introducing mainly primiparous cows into the herd to maintain lactating cow numbers would decrease the average milk yield for the herd; therefore, the differences in milk yield observed herein would also be decreased. One strategy that high-producing herds with good reproductive performance can take is to extend the VWP (Arbel et al., 2001; Sørensen and Østergaard, 2003; Tenhagen et al., 2003) or shorten the dry period (Watters et al., 2008, 2009; Santschi et al., 2011).

CONCLUSIONS

Accuracy of ED and compliance with injections for the TAI protocol both affected reproductive performance; however, the effect of compliance was greater. Combining TAI with ED resulted in increased reproductive performance and profits compared with either TAI or ED alone within each level of accuracy or compliance with injections. This trend was not altered by milk price; however, percentage increase in profits for improving reproductive performance was much greater when milk price was low. The greatest improvement from combining TAI and ED was observed when compliance with injections was poor (85%), even with low SR (40%) and poor accuracy (85%). Although combining TAI and ED increased reproductive performance and profits compared with either TAI or ED alone within each level of accuracy or compliance with injections, profits were not always increased with increased reproductive performance because of the decreased

proportion of lactating cows in the herd and increased breeding costs. Therefore, when evaluated separately, the ED60-85 and ED60-95 models and the TAI-95 model performed better than the TAI-ED40-85 model despite having worse reproductive performance. Likewise, the ED60-95 model performed similarly to the TAI-ED40-95 model and better than the TAI-ED60-85 model. Herds can improve their profits by combining TAI and ED as reproductive management. However, if a herd can achieve high SR with high accuracy or have high compliance with injections, using only ED or TAI might be more profitable than trying to do both.

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APPENDIX

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Initialization of model parameters (e.g. mean estrus duration, estrus detection (ED) accuracy, etc.)
Definition of variables holding information about daily totals (e.g. number of AI, number of pregnant cows, cost of AI, etc.)
Creation of individual cows and initialization of their attributes (e.g., age, weight, reproductive status, etc.)
For each day in the simulation
  Daily totals are initialized as zero
  For each individual cow the following functions are evaluated
    Estrus function
    Determines next estrus days for individual
    Determines if cow is in estrus at this particular day
    Estrus detection
    If the cow is in estrus, and past the voluntary waiting period (e.g. 50 DIM for ED model) but  $\leq 366$  DIM, then estrus is detected with a given probability (e.g. 40 or 60%)
    Cow is artificially inseminated
    Conception occurs with given probability (this probability varies depending on AI protocol, accuracy of ED, and number of services)
    Cow reproductive status is updated to "pregnant"
    Other related individual attributes are updated (e.g., number of service)
    Daily counters are updated (e.g., total number of AI)
    Synchronization protocol (if applies)
    If corresponds (cow is open, milking days appropriate, etc.) the cow is assigned to the corresponding injection for the synchronization protocol
    The corresponding injection is updated as "successful" with a given compliance probability.
    Cow is artificially inseminated if the cow is at the end of the protocol.
      Conception occurs with given probability (this probability varies depending on AI protocol, compliance with protocol, and number of services)
      Cow reproductive status is updated if corresponds
    Other related individual attributes are updated (e.g., number of service, injection received, etc.)
    Daily counters are updated (e.g., total number of AI, number of injections)
    Abortion
    If cow is pregnant abortion is determined with a given probability (this probability depends on the days pregnant)
    The reproductive status of the cow is updated to "not pregnant"
    A new estrus date is determined
    Other related individual attributes are updated (e.g., number of abortion since last calving event)
    Diagnostic
    Diagnostic takes place 32 days after AI in cows that have not been resinseminated.
    Daily counters are updated (e.g., total number of pregnancy checks)
    Dry Pregnant
    If the cow has being pregnant for 220 days its milking status is updated to "dry"
    Calving
    If the cow has being pregnant for 280 days its status is updated to "not pregnant" and "milking"
    Other related individual attributes are updated (e.g., number of lactations)
    Daily number of calves is updated
    Replace Cow
    Determines if a cow is to be replaced depending on pregnancy status (i.e. not pregnant) and days in milk (i.e. 450) or based on income over cost of production (income from milk sales is less than feeding cost plus other costs).
    Daily counters are updated (e.g., total number replaced cows)
    Death
    The cow is eliminated from the simulation with a given probability (daily mortality probability)
    Updated Cows
    Age of the cow is updated (one day older)
    Food intake is calculated
    If the cow is milking, its production is calculated
    Other related individual attributes are updated (e.g., number of days pregnant, number of days milking, etc.)
    Daily counters are updated (e.g., total number replaced cows)
  Evaluate next cow
  Buy Cows
  A number of cows equal to the total daily eliminated (i.e. culled or died) cows is created and initialized
  Daily Economic Calculations
  Daily cost variables are updated
Simulate next day

```

Figure A1. Pseudo-code showing model structure and order of events using the Netlogo modeling environment (<http://ccl.northwestern.edu/netlogo>).