Un enfoque de dinámica de sistemas para el modelado de hatos lecheros considerando un escenario de inseminación artificial a plazo fijo

A system dynamics approach for dairy herd modeling considering fixed-term artificial insemination scenario

John H. Davila D Yony Fernando Ceballos
Universidad de Antioquia, Colombia

German Sánchez Torres
Universidad del Magdalena, Colombia

Recibido: 16/04/2022
Aceptado: 01/07/2022
Publicado: 03/10/2022

Correspondencia de autores:
John.davila@udea.edu.co

Resumen

Objetivo: Diseñar un modelo de simulación continúa basado en Dinámicas de Sistemas para analizar los parámetros reproductivos considerando políticas de inseminación artificial y reproductivas orientadas a la sostenibilidad en un hato lechero. **Metodología:** El procedimiento se clasifica en cuatro etapas: (I) Análisis del comportamiento del hato lechero y definición del problema, (II) Descripción de procesos y contextualización de un modelo, (III) Generación del modelo preliminar, verificación, validación y (IV) Análisis de resultados. **Resultados:** Se mostró que mediante herramientas de simulación es posible modelar los procesos al interior del hato lechero. Las detecciones efectivas de periodos de calor constituyen un factor determinante en la aplicación de políticas de inseminación artificial y en general en la sostenibilidad del hato. Por lo que utilizar un protocolo de biotecnologías reproductivas, como la sincronización de celo y la inseminación artificial a tiempo fijo son políticas que mitigan los problemas asociados a problemas reproductivos. **Conclusiones:** El uso de la dinámica de sistemas nos permitió tener un abordaje holístico del problema considerando todas las variables relevantes para evaluar políticas de mejora. El modelo presentado en el desarrollo de la investigación permitió evaluar diferentes políticas asociadas al manejo animal, explotación de carne en vacas secas, y políticas de revisión continua sobre situaciones asociadas a la eficiencia en la identificación de vacas en celos.

Palabras clave: Dinámica de sistemas, hato lechero, sostenibilidad, inseminación artificial a plazo fijo.

Abstract

Objective: To design a continuous simulation model based on System Dynamics to analyze reproductive parameters considering artificial insemination and reproductive policies aimed at sustainability in a dairy herd. **Methodology:** The procedure is classified into four stages: (I) Analysis of the behavior of the dairy herd and definition of the problem, (II) Description of processes and contextualization of a model, (III) Generation of the preliminary model, verification, validation and (IV) Analysis of results. **Results:** It was shown that using simulation tools it is possible to model the processes within the dairy herd. The effective detections of periods of heat constitute a determining factor in the application of policies of artificial insemination and in general in the sustainability of the herd. Therefore, using a reproductive biotechnology protocol, such as heat synchronization and fixed-term artificial insemination, are policies that mitigate the problems associated with reproductive problems. **Conclusions:** The use of system dynamics allowed us to have a holistic approach to the problem considering all the relevant variables to evaluate improvement policies. The model presented in the development of the research allowed evaluating different policies associated with animal management, meat exploitation in dry cows, and policies of continuous review on situations associated with the efficiency in the identification of cows in heat.

Keywords: System dynamics, dairy herd, sustainability, fixed-term artificial insemination.

Como citar (IEEE): J. Davila., F. Ceballos., y G. Sanchez. "Un enfoque de dinámica de sistemas para el modelado de hatos lecheros considerando un escenario de inseminación artificial a plazo fijo". Investigación e Innovación en Ingenierías, vol. 10, n°2, 93-105, 2022. DOI: https://doi.org/10.17081/invinno.10.2.5283

Introduction

The continuous increase in the human population together with the changes in ***dietary patterns*** derived from *Changes* in *economic* development transfers strong restrictions to the global food system and requires continuous changes to supply the demand [1].

For the dairy sector, environmental changes also impose strong restrictions on the profitable production of derived products. For some areas, the ***reduced water availability*** and the grazing areas decreased limit large-scale production and constitute direct factors that have changed the dynamics of the sector [2]. An alternative to satisfy the demand while maintaining profitability is the increase of small-scale dairy production systems and the improvement in the efficiency of the existing ones [3,4] through the adoption of practices that incorporate technological improvements, good management and optimal financial management [5].

A mechanism to increase the efficiency of production systems is related to the precise determination of the reproductive cycles of cows. The Estro determination is related to the increase in milk production [6], however, it is difficult to determine this state because the production environment has an impact on the natural manifestations of behavior [7]. Some studies in this direction are described in [8].

Artificial insemination has been a strategy used to increase the efficiency of the production systems of the sector. However, the precise identification of the optimal moment for the execution of artificial insemination is still a challenge in non-industrialized settings with few studies available in that direction [9, 10].

The dairy sector in Colombia produces an average of 300 million liters of milk annually, around nine million liters per day, which directly generates jobs for around 736,873 people. This sector has approximately 400,000 producers and contributing to the 0.80% of the Colombian Growth Domestic Product (GDP) [11]. Of the five administrative districts in the Medellin municipality, the district of Santa Elena ranks third in agricultural production with 37% of the working population. Of the total agricultural activities, 82% are crop activities, 8% livestock activities, and 10% in Agricultural and Livestock Service [12].

The dairy sector conditions are defined by variables associated with the reproduction of animals and milk production. In the livestock sector, reproduction is a factor that directly influences the productivity and profitability of the herd, so it is clear that by having greater animal fertility, there will be a greater number of calves by year and with this, a greater number of lactations during life useful of the animal [13].

To achieve this ideal model, which permits one calf per cow per year, it is necessary to carry out orderly nutritional, medical, and biosecurity management. In addition, an administrative reproductive control should be done to obtain data that allow a reproductive, productive, and economic evaluation of the herd regularly, managing to acquire records that allow making decisions about the productive unit management to achieve the desired performance at the economic and animal level [14].

The objective of this study is to analyze the reproductive parameters of the Paysandú productive unit located in the municipality of Santa Elena Antioquia; to correlate the results obtained with those reported in the literature, this is done to perform a detailed analysis and build a simulation model that allows the application of various policies aimed at sustainability.

Methodology

Systems dynamic is a modeling and simulation tool that enables systems to be represented and their past and future behaviors simulated. A system is the perception of reality that the modeler wants to represent and this may be different depending on the purposes. Once the system is defined, a model that reproduces the global behavior is built through the interrelated operation of the partial mechanisms that compose it, to have a tool that allows simulating the impact of different strategies on the variables of interest. The main objective of Systems Dynamic is to understand the structural causes that cause generate the behavior of the system [15]. This implies increasing the knowledge about the role of each belonging element, and studying how different actions, carried out, accentuate or attenuate implicit behavioral tendencies.

As differentiating characteristics from other tools, it can be said that it is not intended to predict future behavior in detail [16]. The study of the system and the testing of different policies on the conceptual model will enrich the knowledge of the real world, checking the consistency of the proposed hypotheses and the effectiveness of the different policies.

For the construction of the diagrams, the information of the Paysandú farm owned by the Universidad Nacional de Colombia - Medellín is used, the data collected in visits to the farm are presented in Table 1.

Tabla 1. General characteristics of the farm.

Property	Description
Farm Name	Hacienda Paysandú.
Location	Department of Antioquia, district of Santa Elena.
Owner	Universidad Nacional de Colombia
Farm size	140 hectares of which 38 are for dairy cattle, 32 for the BON program, and 70 for forest reserves.
Activities	Species: Cattle (Bos taurus), dairy, and meat-type livestock.
Breeds	Holstein, Cruces de Holstein con BON (F1), BON y Angus.
Feeding	Species: Cattle (Bos taurus), dairy and meat-type livestock, Kikuyo meadows with the rotation of paddocks, harvest concentrates, and milk production.
Description	The average temperature is 14 ° C, it is located at an altitude of 2500 m.a.s.l., the Soils have a loamy-sandy texture and the topography of the area is undulating.
Daily milk production	24 liters/day time from June 2018 to June 2019.

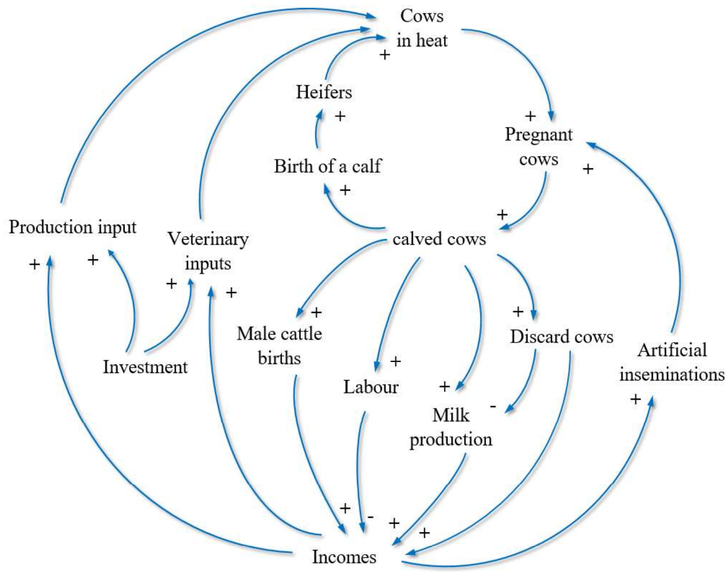
Source: Own elaboration

Dynamic hypothesis

First, a causal diagram is built which, as a conceptual construction, functions as a feedback structure for the system and fulfills the function of a dynamic hypothesis [17] (see Figure 1, and Figure 2).

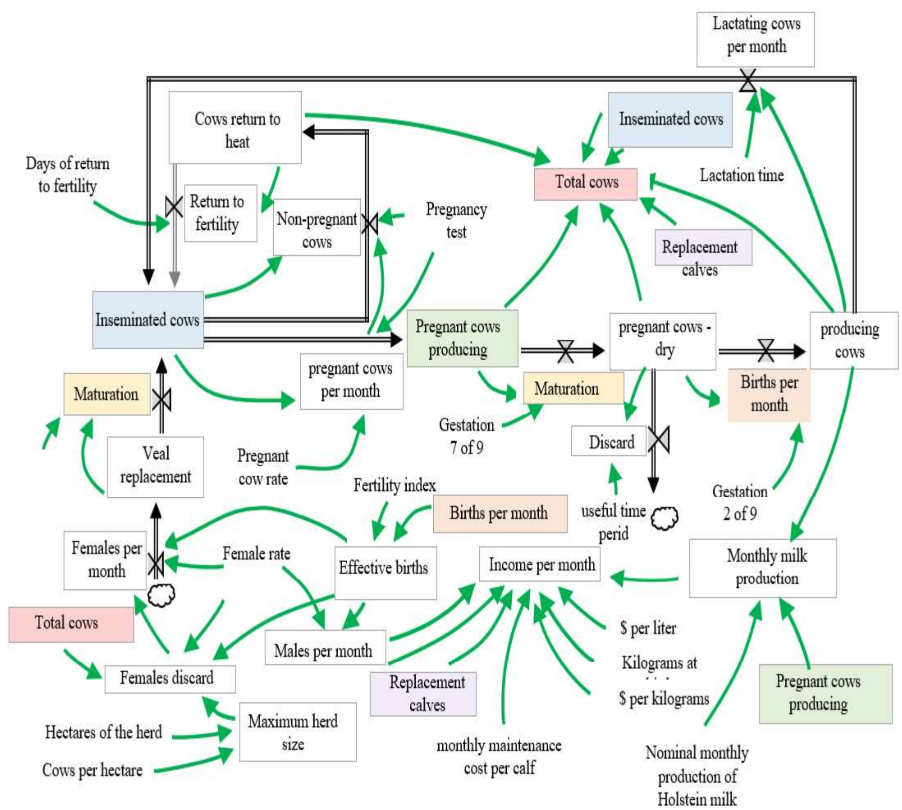
For the dairy herd problem, the main variables are described in Table 2, and the description of relevant variables equations are show in Table 3. The causal diagram starts in the variable incomes. These are calculated based on milk production and the number of calves births that are sold for the sausage production. These incomes are reinvested in inputs for production (labor, agricultural inputs) and veterinary inputs. By having more inputs for production and veterinary supplies, a higher percentage of pregnancy success can be achieved and therefore have more cows in heat. This increases the number of pregnant cows and after the delay associated with gestation, the number of calved cows increases where calving females are reused inside the dairy herd and they begin their productive life after 20,5 months as heifers in heat.

Figure 1. **Causal diagram of a dairy herd**



Source: Own elaboration

Figure 2. Herd flow chart causal diagram



Source: Own elaboration

Tabla 2. Description of the process variables discriminated by type

Variable	Type	Description
Cost calf support month	Exogenous	Monthly cost of supporting a growing calf in the herd
First service time	Exogenous	Time elapsed between requesting an order and delivery time.
Hectares of the Hato	Exogenous	Dairy herd size (38 Hectares)
lifespan	Exogenous	Lifespan of a dairy cow (8 years, 6 calvings)
Breastfeeding time	Exogenous	Milk production time of a cow in the herd
Producing cows	State	Milk producing cows in the herd
Inseminated cows	State	Cows inseminated monthly in the herd (IATF)
Income per month	State	Monthly income due to the sale of male calves, discarded female calves, milk production and herd maintenance costs.
Replacement calves	State	Calves each month are retained in the herd to replace discard females.
Dry cows	State	Females, age being exploitative, do not generate revenue milk production
Cows return to heat	State	Females that were not successfully inseminated

Source: Own elaboration

Table 3. Description of relevant variables equations

Variable	Equation
Monthly milk production	$\left(Producer\ cows + Pregnant\ cows\ prod * \left(\frac{7}{9}\right)\right) * \mathrm{NMPM}$
Inseminated cows	$INTEG\ (Maturation + Return\ to\ fertility + Lactation\ cows\ per\ month - Pregnant\ per\ month - Non\ pregnant\ cows, 39)$
Income per month	$COP\ per\ kg * Kg\ calf\ at\ birth * (Males\ per\ month + Females\ discarded) + COP\ per\ liter * NMPM - Calf\ maintenance\ cost\ per\ month * Calves\ replacement$
Total cows	$Inseminated\ cows + Producer\ cows + Pregnant\ cows\ prod + Return\ to\ heat\ cows + Dry\ pregnant\ cows + Repositioning\ calves$

NMPM = Nominal monthly production of Holstein milk

Source: Own elaboration

Calved cows increase the need for labor and therefore income within the herd is reduced. These calved cows directly increase milk production since these are the ones used in the productive processes of a dairy farm. However, after a cow has her sixth calf she is considered Discarded as Infertile. On average, this happens 7 years after their productive period begins. Finally, these cows are sold to generate income in the dairy herd. A significant part of the income is used in insemination processes which are done artificially, increasing the rate of pregnant cows.

Flow and levels diagrams

Regarding the data of the variables used in the model, the details are given in visits to the farm. The optimal entry age to the first service for dairy cattle is between 18 and 20 months. In this case, the average is 20,5 months, which is the farm's reference value [18]. Some critical control points have been pointed out when cows join the service such as birth weight, weaning age, weaning weight, or DWG (Daily Weight Gain), and its variations have been related to risk factors such as the exploitation system and the farm location area, the time and racial predominance, in addition to the management practices that determine the quantity, quality and continuity of feeding, especially during pre and post-weaning periods.

It is important to mention that this is closely linked to the weight of the animal, where for a heifer it must be 55% of its live weight as an adult. For example, large breeds like Holstein should weigh between 320 and 340 kg. This weight is achieved with a good supply of improved grass and supplementation (multi-nutritional blocks, molasses-urea, protein banks, or concentrated feed) obtaining clear reductions in the incorporation age to the reproductive stage as a result of feeding [19].

For the effective pregnancy age and the first service age, which is where the animal presents optimal physiological and anatomical conditions to be pregnant for the first time, it is reported that the effective pregnancy of a heifer should not generally exceed 23 months of age because after this age each lost day has high economic losses. The average effective pregnancy age is 25,1 months in the visited dairy herd.

The average age at first calving is 34,1 months but it is conditioned by the feeding that is provided during the growth period and far from the nominal value of 24 months in dairy cattle such as the Holstein breed. Although, according to the Holstein Association of Colombia this value is within the recommended ranges, which considers that the ideal cow should have its first calving before reaching 36 months [14].

It can be inferred that the ideal open heifer period is zero (0) days, considering what is expected is that the specimen can conceive with the first insemination that is effectuated to achieve an age at first calving within the ideal range for their breed. Nevertheless, the results obtained after carrying out the reproductive evaluation were 209 days of the open period in a heifer. For this result we took into account 11 specimens of which 3 had an open period of zero days; 6 heifers still had to confirm effective pregnancy and 2 heifers had open days greater than 600 days, which may alter the results when evaluating the 17 heifers on the farm.

The calving to insemination interval is a physiological indicator given by the bovine female's ability to return to estrus after calving, but it also has a management component considering that operational management is involved, since it is necessary to detect the cow in heat. In the analysis case, it was found within the reference range with an average of 78.6 days in which data from 39 animals were analyzed compared to what is reported in the literature, which indicates that before performing the first service it is recommended at least 50 days have passed after the delivery to obtain optimal fertility and thus an ideal postpartum first service between 70 and 80 days.

The obtained data after the reproductive evaluation was the following, with a total of 39 specimens evaluated for this aspect, 52,5% of them returned to heat after the first postpartum insemination. The literature reports that the return values to heat after postpartum insemination should be less than 50%, showing a return rate on the farm [14].

The number of animals that return to heat after the first insemination is mainly related to the management factor since the female must be given adequate time and must be waited to have a sufficient uterine evolution, which ranges from 50 to 60 days approximately. On the farm, the reproductive analysis of open cycle days was of 147 days in which 51 cows were taken into account. This increase in days open is directly related to repeat service cows and protocols for confirming pregnancy and heat.

The management factor is of vital importance, both in the ability to detect heat and in the time that elapses between heat detection and insemination. The insemination moment is important due to its short period as well as the technique used and timing, considering that very early postpartum services are less fertile.

As mentioned above, nutritional management is also one of the most important factors for bovine fertility [20]. An ideal value for milk-producing cows is considered between 1,8 and 2,8 services per conception.

The interval between deliveries consists of the sum from delivery to the conception or open days plus the gestation period and this considerably affects the performance throughout the cow's life, determining the number of total deliveries per cow. In this lies the importance of having a short open period and good regulation of the dry cow period.

For the percentage of pregnant cows, a value of 63,6% was found after the reproductive evaluation, indicating that the farm has a medium reproductive index approaching the lower allowed index. This may be due to two aspects such as low specimen fertility or poor planning and development of the farm's reproductive programs (heat detection, insemination program).

The empty cows percentage (not pregnant or producing) has a result of 34,4%, this is in the maximum limit allowed for the empty cows percentage on a farm, which is not the best. According to the literature the normal values of empty cows are between 25% and 35%.

Regarding the birth index, this consists of the number of calves born in a year with respect to the number of cows suitable for reproduction, which is inversely related to the open period. In Colombia, cattle ranches have birth rates of 52% to 66%. The reproductive evaluation results showed that the herd fertility is 74,5%; according to Sanchez, the ideal total fertility index is between values of 60% to 65% and the farm is above the cited reference values. This is favorable because fertility is guaranteed in females as well as a good gestation percentage [13].

The average time in milk production was 300 days with a great variation between cows because some of them had up to 365 days in production. Comparing with what is reported in the literature, this is within the normal average that is 305 days [21].

All the found and evaluated data in visits to the farm are adapted to a monthly scale in the model and a simulation horizon of 10 years is proposed.

Results

The base scenario represents the policy of having natural breeding, it is that the cows are always with a bull, and the heat physiological cycle is no altered or adapted. In other hand, artificial insemination is used when the cow goes into heat, for which it is necessary an accuracy heat detection method. Then, artificial insemination is carried out without cycle alterations.

In the fixed-term artificial insemination scenario (FTAI), the cow estrous cycle is manipulated. Initially, some females that are going to enter into heat are identified, after, it uses different hormones to sync, so it possible that the artificial insemination can be carried out in all at the same time or in predefined batches [22, 23, 24, 25].

The identification of heat in cows can be synchronized through the application of hormones, it becomes the insemination process is highly successful and easily controllable. Inside the farm, the rate of return to heat will be identified in conjunction with the new cows that can enter service, achieving high coverage in the dairy herd. One of the interesting characteristics of this scenario is that the number of employees is not increased, since traditionally, the employees who were originally designated to identify jealousy move to perform this procedure.

These employees carry out the insemination process monthly according to the size of the herd. Synchronizing the insemination dates for all cows makes it possible to stabilize the expenditure curve due to the concentration of activities on specific dates in conjunction with the use of fresh semen. In addition, the cost of the hormones to be used in the heat synchronization processes is low and ranges between COP 35.000COP and COP 50.000 for each issue. With this hormonal calendar, an effective pregnancy per month of 95% of the cows that are in heat in the month described can be ensured.

Spending on open days on the farm (they are those that elapse from the day a cow gives birth to when it starts a new pregnancy), can generate economic losses for keeping an animal that is not being productive, taking into account that the farm that has all the inputs such as the genetic material (it has the bulls, so collections can be made on the same day).

As we can see in Figure 3a, the number of cows inseminated at the beginning of the simulation does not allow us to make any conclusion since this would be the transitory stage of the simulation model. This phase is in approximately 3 months. Subsequently, it can be stated that the number of inseminated cows stabilizes at a value close to 13 and remains constant during all the months of the simulation. In the FTAI scenario, a rapid termination of the transitory state is observed, achieving the equilibrium point of animals on the farm in a shorter time.

Regarding cows returning to heat, it stabilizes at a value close to 9 in the simulation since the time it takes for cows to return to heat after unsuccessful insemination is very short.

Regarding pregnant cows, it is observed that a high value is always maintained in all simulations, reaching a maximum of almost 80 pregnant cows throughout the simulation time. This means that of the total cows, a large number will always be pregnant, which increases the maintenance and care costs. However, it ensures continuous milk production in the herd.

In terms of replacement calves, it is observed that there is an increase from the initial number obtained in the visit to the farm. The transitional period of three months is discarded and subsequently, until month 27 a sustained increase is observed until the herd maximum capacity is achieved (see Figure 3a). The cost per month to support a calf is COP$33.0000 [26].

Lactating cows have also a small adjustment at the beginning of the simulation, but it is observed that the expected maximum number of cows in milk production can be reached during the simulation time after the third year. Regarding dry cows, in the simulation, the value is low, close to 10 animals which, depending on how they perform, can be discarded from the dairy herd or treated to improve the quality in terms of milk production and effective pregnancy.

The use of systems dynamics allows us to have a holistic approach to the problem, all relevant variables are taken into consideration and later improvement policies can be carried out. The model presented in the development of the research allows us to show the base scenario and for future work is expected to evaluate different policies associated with animal management, exploitation of meat in dry cows, and continuous review policies regarding situations associated with efficiency in identifying cows in return to heat.

We can see in Figure 5, the monthly income at the beginning of the simulation has an adjustment but the investment is recovered after month 25. It means that the investment in these dairy herds is from medium to long term so that it has a return and the herd sustainability can be ensured.

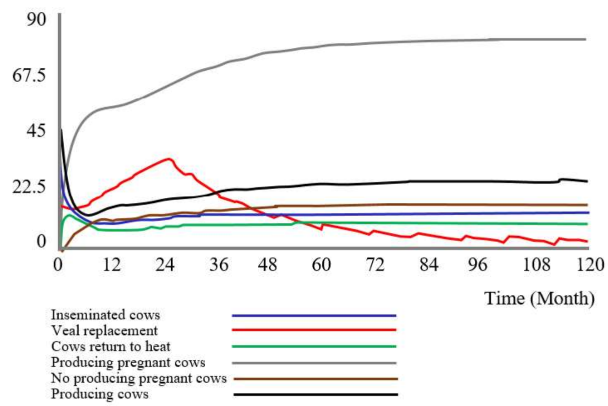
Conclusions and future work

Having a large number of cows repeating service and increasing the open period, together with the dry cow percentages, increases production costs and decreases the economic benefit, making the dairy farm unprofitable at the beginning of the simulation.

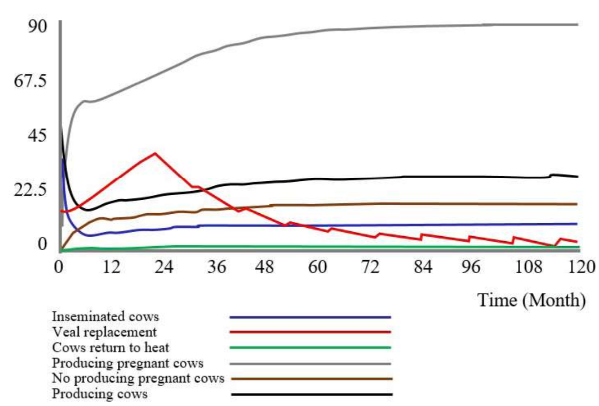
The first and perhaps the most important aspect to achieve good results is the heat detection program. If this is not developed efficiently, aspects such as the open period, birthing intervals, and the empty cows percentage will increase considerably. Another aspect is the artificial insemination program since there are a large number of repeat service cows on the farm. Therefore, there is a need for a more detailed analysis of the possible causes and factors that should be intervened.

The discard of animals from the herd plays a fundamental role in the production profitability, considering a Difficult Cow a cow that has not had a confirmed pregnancy for more than 120 to 160 days. This leads to a considerable economic loss due to the fact that the difficult cow generates more expenses, which is why proper management must be done with animals that have fertility problems because a timely discard will bring more benefits compared to keeping a specimen for a long time trying to achieve an effective pregnancy.

Figure 3. Tendencies of the behavior of each type, a) base scenario and b) FTAI scenario.



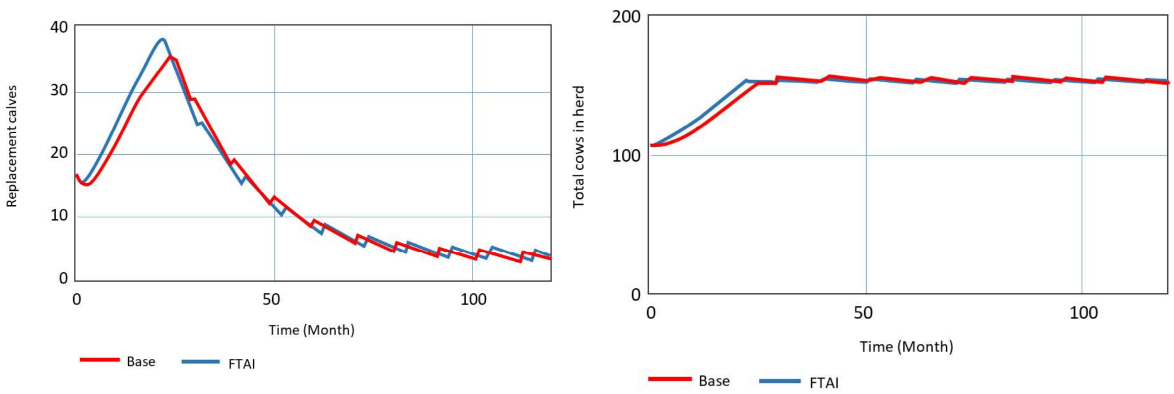
a)



b)

Source: Own elaboration

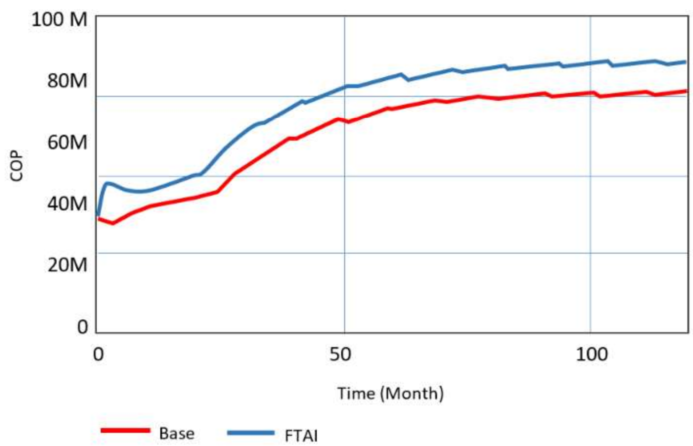
Figure 4. a) Replacement calves b) Total cows in the herd.



a) b)

Source: Own elaboration

Figure 5. Monthly income



Source: Own elaboration

Production records should be improved as this helps decision-making and the establishment of changes in the medium and long term, to improve the productivity and reproductive statistics of the herd.

It is recommended to use a reproductive biotechnologies protocol, such as heat synchronization and fixed-time artificial insemination, which are recommended tools for solving reproductive problems in dairy herds.

Finally, according to the analysis and parameters comparison reported in the literature and those obtained in the simulation, it is concluded that the farm should adopt the different improvements mentioned above to increase the dairy herd productivity.

References

1. Herrero, M., Thornton, P.K., 2013. Livestock and global change: emerging issues for sustainable food systems. Proc. Natl. Acad. Sci. U. S. A. 110, 20878–20881. https://doi.org/10.1073/pnas.1321844111
2. Dianne Mayberry, Andrew Ash, Di Prestwidge, Cécile M. Godde, Ben Henderson, Alan Duncan, Michael Blummel, Y. Ramana Reddy, Mario Herrero, Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India, Agricultural Systems, Volume 155, 2017, Pages 43-51, ISSN 0308-521X, https://doi.org/10.1016/j.agsy.2017.04.007.
3. Salinas-Martínez, J. A., Posadas-Domínguez, R. R., Morales-Díaz, L. D., Rebollar-Rebollar, S., & Rojo-Rubio, R. (2020). Cost analysis and economic optimization of small-scale dairy production systems in Mexico. Livestock Science, 104028. https://doi.org/10.1016/j.livsci.2020.104028.
4. Anderson, W., Johansen, C., & Siddique, K. H. M. (2016). Addressing the yield gap in rainfed crops: a review. Agronomy for Sustainable Development, 36(1). doi:10.1007/s13593-015-0341-y.
5. Diwakar Vyas, Corwin D. Nelson, John J. Bromfield, Pradeep Liyanamana, Matthew Krause, Geoffrey E. Dahl, MILK Symposium review: Identifying constraints, opportunities, and best practices for improving milk production in market-oriented dairy farms in Sri Lanka. Symposium: Improving Milk Production, Quality, and Safety in Developing Countries at the ADSA Annual Meeting, Cincinnati, Ohio, June 2019., Journal of Dairy Science, Volume 103, Issue 11, 2020, Pages 9774-9790, https://doi.org/10.3168/jds.2020-18305.
6. Rivera, F., C. Narciso, R. Oliveira, R. L. A. Cerri, A. Correa-Calderón, R. C. Chebel, and J. E. P. Santos. 2010. Effect of bovine somatotropin (500 mg) administered at ten-day intervals on ovulatory responses, expression of estrus, and fertility in dairy cows. J. Dairy Sci. 93:1500–1510. https://doi.org/10.3168/jds.2009-2489.
7. Britt, J. H., R. G. Scott, J. D. Armstrong, and M. D. Whitacre. 1986. Determinants of estrous behavior in lactating Holstein cows. J. Dairy Sci. 69:2195–2202. https://doi.org/10.3168/jds.S0022 -0302(86)80653-1.
8. Burnett, T. A., L. Polsky, M. Kaur, and R. L. A. Cerri. 2018. Effect of estrous expression on timing and failure of ovulation of Holstein dairy cows using automated activity monitors. J. Dairy Sci. 101:11310–11320. https://doi.org/10.3168/jds.2018-15151.
9. Bombardelli, G. D., H. F. Soares, and R. C. Chebel. 2016. Time of insemination relative to reaching activity threshold is associated with pregnancy risk when using sex-sorted semen for lactating Jersey cows. Theriogenology 85:533–539. https://doi.org/10.1016/ j.theriogenology.2015.09.042.
10. Borchardt, S., L. Schüller, L. Wolf, C. Wesenauer, and W. Heuwieser. 2018. Comparison of pregnancy outcomes using either an Ovsynch or a Cosynch protocol for the first timed AI with liquid or frozen semen in lactating dairy cows. Theriogenology 107:21–26. https:// doi.org/10.1016/j.theriogenology.2017.10.026.
11. M. F. Perdomo Calderón, L. F. Peña Bosa, J. D. Carvajal Yasnó, and L. Y. Murillo Saldaña, “Relación nutrición-fertilidad en hembras bovinas en clima tropical,” *Rev. Electron*. Vet., vol. 18, no. 9, 2017.
12. Alcaldia de Medellin, “Límites del Municipio de Medellín, sus corregimientos y Veredas,” Planeación, 2003. https://www.medellin.gov.co/irj/go/km/docs/wpccontent/Sites/Subportal del Ciudadano/Planeación Municipal/Secciones/Indicadores y Estadísticas/Documentos/LIBRO_PLANEACION.pdf (accessed Aug. 31, 2020).

13. J. F. Vásquez, D. Barrios, and M. Olivera, “Análisis del desempeño técnico económico de un hato lechero en Colombia: estudio de caso,” Vet. y Zootec., vol. 9, no. 1, pp. 16–26, 2015, https:// doi.org/10.17151/vetzo.2015.9.1.7.

14. K. Quiróz, C. Carmona, and J. Echeverri, “Parámetros genéticos para algunas características productivas y reproductivas en un hato Holstein del oriente antioqueño, Colombia,” Rev. la Fac. Ciencias Agropecu. la Univ. Nac. Colomb., vol. 64, no. 2, pp. 6199–6206, 2011, [Online]. Available: http://www.scielo.org.co/pdf/rfnam/v64n2/v64n2a16.pdf.

15. J. Aracil and F. Gordillo, Dinamica de sistemas. Alianza Editorial Madrid, 1997.

16. J. D. J. D. Sterman, Business dynamics: Systems thinking and modeling for a complex world with CD-ROM, vol. 53. Irwin/McGraw-Hill, 2000.

17. S. Jaén, “Ayudas para la elaboración de diagramas causales,” Aprende en Línea, Universidad de Antioquia, 2017. .

18. S. Calsamiglia, G. Espinosa, G. Vera, A. Ferret, and L. Castillejos, “A virtual dairy herd as a tool to teach dairy production and management,” J. Dairy Sci., vol. 103, no. 3, pp. 2896–2905, 2020, Parámetros genéticos para algunas características productivas y reproductivas en un hato Holstein del oriente antioqueño, Colombia https://doi.org/10.3168/jds.2019-16714.

19. D. González and A. Quintero, “Manejo de las novillas de reemplazo,” in Manejo de la ganadería de doble propósito, 2005, p. 436.

20. M. Severich, “Evaluación de comportamiento lechero de ganado,” Universidad Autonoma “Gabriel Rene Moreno,” 2007.

21. C. Aguilar, R. Cañas, F. García, R. Quiroz, and M. Ruiz, “Simulación de sistemas: aplicaciones en producción animal,” Ponencias, Result. y Recom. Eventos Técnicos A1/SC, pp. 185–284, 1992, Accessed: Oct. 21, 2011. [Online]. Available: http://orton.catie.ac.cr/cgi-bin/wxis.exe/?IsisScript=IICARD.xis&method=post&formato=2&cantidad=1&expresion=mfn=000256.

22. M. C. Wiltbank, “How information of hormonal regulation of the ovary has improved understanding of timed breeding programs", in Proceeding of the Annual Meeting of the Society for theriogenology, 1997, pp. 83–97.

23. F. Gonzalez, F. Bas, N. Rahaussen, and E. Caceres, “Efecto de la sincronización con prostaglandina, en el postparto temprano, sobre el comportamiento reproductivo en vacas lecheras de alta producción,” Cien. Inv. Agr, vol. 1, no. 28, pp. 15–22, 2001.

24. A. Correa-Orozco, L. Uribe-Velásquez, and E. Pulgarín-Velásquez, “Factores que afectan la preñez en vacas Brahman sometidas a inseminación artificial a tiempo fijo,” Rev. MVZ Córdoba, vol. 18, no. 1, pp. 3317–3326, 2013, doi: 10.21897/rmvz.194.

25. R. F. G. Peres, I. C. Júnior, O. G. S. Filho, G. P. Nogueira, and J. L. M. Vasconcelos, “Strategies to improve fertility in Bos indicus postpubertal heifers and nonlactating cows submitted to fixed-time artificial insemination,” Theriogenology, vol. 72, no. 5, pp. 681–689, 2009, https://doi.org/10.1016/j.theriogenology.2009.04.026.

26. E. J. De la Hoz Domínguez, T. J. Fontalvo Herrera, y A. A. Mendoza Mendoza, "Aprendizaje automático y PYMES: Oportunidades para el mejoramiento del proceso de toma de decisiones", Investigación e Innovación en Ingenierías, vol. 8, n.º 1, pp. 21-36, 2020. DOI: https://doi.org/10.17081/invinno.8.1.3506

27. C. J. Obando Gamboa, "Influencia del agua en el desempeño de los pavimentos: lluvia ácida", Investigación e Innovación en Ingenierías, vol. 5, n.º 2, pp. 190-206, 2017. DOI: https://doi.org/10.17081/invinno.5.2.2761

28. J. A. Elizondo-Salazar and A. M. Vargas-Ramírez, “Determinación del costo de la crianza de terneras desde el nacimiento hasta el destete en una lechería comercial especializada,” Nutr. Anim. Trop., vol. 9, no. 2, p. 1, 2015, https://doi.org/10.15517/nat.v9i2.20989