OSCAR ALEJANDRO OJEDA ROJAS

An agent-based simulation model to evaluate the technical, economic and financial performance of reproductive technologies in beef cattle

Pirassununga

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A Comissão de Ética no Uso de Animais da Faculdade de Medicina Veterinária e Zootecnia da Universidade de São Paulo, na reunião de 27/11/2019, **ANALISOU** e **APROVOU** o protocolo de estudo acima referenciado. A partir desta data, é dever do pesquisador:
1. Comunicar toda e qualquer alteração do protocolo.
2. Comunicar imediatamente ao Comitê qualquer evento adverso ocorrido durante o desenvolvimento do protocolo.
3. Os dados individuais de todas as etapas da pesquisa devem ser mantidos em local seguro por 5 anos para possível auditoria dos órgãos competentes.
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São Paulo, 2nd December 2019

CERTIFIED

We certify that the Research "An agent-based simulation model to evaluate the technical, economic and financial performance of reproductive technologies in beef cattle", protocol number CEUAx 8515120619 (ID 001246), under the responsibility Augusto Hauber Gameiro, agree with Ethical Principles in Animal Research adopted by Ethic Committee in the Use of Animals of School of Veterinary Medicine and Animal Science (University of São Paulo), and was approved in the meeting of day November 27, 2019.

Certificamos que o protocolo do Projeto de Pesquisa intitulado "Modelo de simulação baseado em agentes para a avaliação de tecnologias reprodutivas sobre o desempenho zootécnico e econômico de rebanhos bovinos de corte", protocolado sob o CEUAx nº 8515120619, sob a responsabilidade de Augusto Hauber Gameiro, está de acordo com os princípios éticos de experimentação animal da Comissão de Ética no Uso de Animais da Faculdade de Medicina Veterinária e Zootecnia da Universidade de São Paulo, e foi aprovado na reunião de 27 de novembro de 2019.

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I want to dedicate this thesis to my wonderful wife, Angela, and our beloved children Nina and Guiga. Life has been good to me. Sharing my days with you is a real fortune for me.

I would also like to dedicate this humble effort to the memory of my best friend, Cesar Augusto Torres Garavito "Loco Larry." I hope that my children, at some point in their lives, can find a friend as unique as the one I had, like my dear "Larry," whom I will always miss

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RESUMO

OJEDA-ROJAS, O. A. **Modelo de simulação baseado em agentes para a avaliação de tecnologias reprodutivas sobre o desempenho zootécnico e econômico de rebanhos bovinos de corte** 2020. 103 p. Tese (Doutorado em Ciências) – Faculdade de Medicina Veterinária e Zootecnia, Universidade de São Paulo, São Paulo, 2020.

O objetivo deste estudo foi criar um modelo de simulação estocástico, baseado em agentes que permita comparar o desempenho técnico e econômico de estratégias reprodutivas em uma população sintética de bovinos de corte. O modelo foi criado usando a ferramenta de simulação AnyLogic e foi parametrizado usando dados de um rebanho de gado de corte real e da literatura científica. Dez cenários foram avaliados: monta natural (NM) somente (ONM); uma inseminação artificial em tempo fixo (TAI) mais NM (1TAI+NM); dois TAI mais NM, com 24, 32 e 40 dias entre as inseminações (2TAI/24+NM, 2TAI/32+NM e 2TAI/40+NM, respectivamente); três TAI sem NM, com 24, 32 e 40 dias entre inseminações (3TAI/24, 3TAI/32 e 3TAI/40, respectivamente) e três TAI mais NM, com intervalo entre inseminações de 24 (3TAI/24+NM) e 32 dias (3TAI/32+NM). A NM iniciou-se 10 dias após a última inseminação e foi realizada até o final da estação de monta. A população inicial do modelo variou entre 400 e 415 animais, dependendo se o NM foi usado ou não. O tamanho do rebanho de fêmeas foi fixado para conter 400 indivíduos. Os resultados de cada cenário foram avaliados em 32 fazendas, usando um horizonte de 5.000 dias em intervalos de 1 dia. O cenário 3TAI/24+NM resultou em maior número de nascimentos (293 nascimentos) e bezerros desmamados (287 bezerros), enquanto o cenário ONM apresentou o menor número de nascimentos (207 nascimentos) e bezerros (203 bezerros). Os machos e fêmeas mais pesados ao desmame pertenceram a 3TAI/24, com 190,58 ± 0,77 kg para os machos e 173,67 ± 0,86 kg para as fêmeas. O cenário ONM apresentou os machos (166,59 ± 0,93 kg) e as fêmeas (151,65 ± 49 0,74 kg) mais leves. As maiores e menores taxas de prenhez foram encontradas, respectivamente, em 3TAI/24+NM (0,90 ± 0,00) e ONM (0,61 ± 0,01). O cenário 3TAI/24+NM (US$ 96.479,19 ± 709,81) resultou em receita bruta maior, enquanto que o cenário ONM (US$ 79.753,37 ± 741,87) teve a menor receita deste estudo. O cenário 3TAI/24+NM (US$ 101,720.6 ± 79.21) e o ONM (US$ 90,898.58 ± 59.17) apresentaram o maior e menor custo operacional total (TOC), respectivamente. Porém, quando TOC foi avaliado por kg de bezerro desmamado, os maiores e menores custos foram para os cenários ONM (US$ 2,8 ± 0,03/kg) e 2TAI/24+NM (US 2,17 ± 0,04/kg), respectivamente. O cenário 2TAI/24+NM (US $ -4,651.28 ± 630.72) apresentou a melhor margem liquida, enquanto que o menor resultado foi para 3TAI/40 (US$ -12,590.04 ± 746.27). O modelo de simulação baseado em agentes proposto tem todas as vantagens de um experimento físico, mas não exige gastos significativos nem altera o sistema real. Nosso modelo forneceu evidências suficientes para demonstrar que as estratégias reprodutivas que usam TAI têm melhor desempenho técnico e econômico do que aquelas sob NM. A combinação de TAI com o diagnóstico precoce da gestação resultou em melhor desempenho técnico e econômico em comparação com outros programas de TAI e com NM.

Palavras-chave: Doppler. Prenhez. Ressincronização. Inseminação artificial em tempo fixo. Simulação.

ABSTRACT

OJEDA-ROJAS, O. A.. **An agent-based simulation model to evaluate the technical, economic and financial performance of reproductive technologies in beef cattle**. 2020. 103 p. Tese (Doutorado em Ciências) – Faculdade de Medicina Veterinária e Zootecnia, Universidade de São Paulo, São Paulo, 2020.

The objective of this study was to create a stochastic, agent-based simulation model that allows to compare the technical and economic performance of reproductive strategies on a synthetic population of beef cattle. The model was created using the AnyLogic simulation tool and was parameterized using data from a real beef cattle herd and from peer-reviewed scientific literature. Ten scenarios were evaluated: natural mating (NM) only (ONM); one timed artificial insemination (TAI) plus NM (1TAI+NM); two TAI plus NM, with 24, 32, and 40 days between inseminations (2TAI/24+NM, 2TAI/32+NM, and 2TAI/40+NM, respectively); three TAI without NM, with 24, 32, and 40 days between inseminations (3TAI/24, 3TAI/32, and 3TAI/40, respectively), and three TAI plus NM, with an interval between inseminations of 24 (3TAI/24+NM) and 32 days (3TAI/32+NM). NM started 10 days after the last insemination and was performed until the end of the breeding season. The initial population of the model ranged between 400 and 415 animals, depending on whether NM was used or not. The size of the female herd was fixed to contain 400 individuals. The outcomes for each scenario were assessed on 32 farms, using a 5,000-day time horizon at 1-day time intervals and on an animal-by-animal basis. The 3TAI/24+NM scenario resulted in a greater number of births (293 births) and weaned calves (287 calves), while the ONM scenario had the lowest number of births (207 births) and calves (203 calves). The heaviest males and females at weaning belonged to 3TAI/24, with 190.58 ± 0.77 kg for males and 173.67 ± 0.86 kg for females. The ONM scenario had the lightest males (166.59 ± 0.93 kg) and females (151.65 ± 49 0.74 kg). The greatest and lowest pregnancy rates were found, respectively, in 3TAI/24+NM (0.90 ± 0.00) and ONM (0.61 ± 0.01). The 3TAI/24+NM scenario (US$ 96,479.19 ± 709.81) resulted in higher incomes, while ONM (US$ 79,753.37 ± 741.87) had the lowest incomes from this study. The 3TAI/24+NM (US$ 101.720.6 ± 79.21) and ONM (US$ 90.898.58 ± 59.17) scenario presented the highest and lowest total operating costs (TOC), respectively. However, when TOC was evaluated per kg of weaned calf, the highest and lowest costs were for ONM (US $ 2.8 ± 0.03 / kg) and 2TAI/24+NM (US $ 2.17 ± 0, 04 / kg) respectively. The 2TAI/24+NM scenario (US $ -4.551.28 ± 630.72) presented the best net margin, while the lowest result was for 3TAI/40

(US$ -12.590.04 ± 746.27). The proposed agent-based simulation model has all the advantages of a physical experiment, but it neither requires incurring significant expenses nor altering the real system. Our model provided sufficient evidence to demonstrate that reproductive strategies using TAI have better technical and economic performance than those under NM. The combination of TAI and early pregnancy diagnosis resulted in better technical and economic performance compared to other TAI and NM programs.

Keywords: Doppler. Pregnancy. Resynchronization. Timed artificial insemination. Simulation.

LISTS OF ABBREVIATIONS

1TAI+NM	One timed artificial insemination plus natural mating
2TAI/24+NM	Two timed artificial inseminations plus natural mating, with 24 days between inseminations
2TAI/32+NM	Two timed artificial inseminations plus natural mating, with 32 days between inseminations
2TAI/40+NM	Two timed artificial inseminations plus natural mating, with 40 days between inseminations
3TAI/24	Three timed artificial inseminations without natural mating, with 24 days between inseminations
3TAI/24+NM	Three timed artificial inseminations plus natural mating, with 40 days between inseminations
3TAI/32	Three timed artificial inseminations without natural mating, with 32 days between inseminations
3TAI/32+NM	Three timed artificial inseminations plus natural mating, with 32 days between inseminations
3TAI/40	Three timed artificial inseminations without natural mating, with 40 days between inseminations
AC	Age of the cows at culling
ADG	Average daily gain
AU	Animal unit
BS	Breeding season
CC	Calving counter at sale
CIDR	Controlled internal drug release
CPR	Pregnancy rate for calved cows
CPU	Central processing unit
Dopp	Doppler ultrasonography
DPR	Dry cows pregnancy rate
FC	Number of female calves weaned per year
FW	Weaning weight for females
GB	Gigabyte
HPR	Pregnancy rate for heifers

IZ	Instituto de Zootecnia, Beef Cattle Research Center, Sertãozinho, SP, Brazil
MC	Number of male calves weaned per year
MW	Weaning weight for males
NeC	Control Nelore herd line of the Instituto de Zootecnia, Beef Cattle Research Center, Sertãozinho, SP, Brazil
NeS	Selection Nelore herd line of the Instituto de Zootecnia, Beef Cattle Research Center, Sertãozinho, SP, Brazil
NeT	Traditional Nelore herd line of the Instituto de Zootecnia, Beef Cattle Research Center, Sertãozinho, SP, Brazil
NM	Natural mating
ONM	Only natural mating
PR	Pregnancy rate
TAI	Timed artificial insemination
TB	Total births
TPR	Total pregnancy rate of the herd
US	Ultrasound

LIST OF FIGURES

Figure 1 Diagram of the life cycle used for showing the states and individual transitions, purchases and sales. A = Males; B = Females. US = Ultrasound; CIDR = Controlled internal drug release; Dopp = Doppler ultrasonography.. 50

Figure 2 Reproductive management for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). 56

Figure 3 Cattle herd structure through the 6th year of simulation for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days)... 58

Figure 4 Total weaning weight of calves and total number of calves weaned per year and for each farm for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). 63

Figure 5 Calving distribution per month and proportion of born animals for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). 64

Figure 6 Survival curves for proportion of nonpregnant cows by days of breeding season for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). Survival curves without a common superscript letter differed ($P < 0.05$)... 66

Figure 7 Reproductive management for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). 79

Figure 8 Total incomes for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days) 86

Figure 9 Effective Operational Cost, Total Operating Cost and Total Cost for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). 88

Figure 10 Effective Operational Cost/kg, Total Operating Cost/kg and Total Cost/kg for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). 89

Figure 11 Gross margin, Net margin, and Profit for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days)... 91

Figure 12 Net present value for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days) 92

LIST OF TABLES

Table 1 Parameters used in the simulation model to describe the transition rates and/or the times used for the agents to move between the different states 45

Table 2 Technical results for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days)[1] 59

Table 3 Prices of the outputs used to calculate the incomes in the simulation model 81

Table 4 Prices of the inputs used to calculate the production costs in the simulation model . 82

SUMMARY

1. INTRODUCTION 22
1.1. REFERENCES 24
2. LITERATURE REVIEW 27
2.1. INTRODUCTION 27
2.2. Simulation Models 29
2.3. Types of Simulation Models 31
2.4. Use of simulation models in beef cattle 32
2.5. Final considerations 35
2.6. References. 36
3. CHAPTER 1: An agent-based simulation model to compare different reproductive strategies in beef cattle operations: Technical performance 41
3.1. ABSTRACT 41
3.2. INTRODUCTION 42
3.3. MATERIAL AND METHODS 43
3.3.1. Description of the model 43
3.3.2. Model parameterization 44
3.3.3. Structure of the population 48
3.3.4. Body weight 53
3.3.5. Culling 53
3.3.6. Replacement 54
3.3.7. Computational study 54
3.3.8. Statistical analysis 55
3.4. RESULTS 57
3.4.1. Herd structure 57
3.4.2. Effect of the scenario on productive parameters 61

3.5. DISCUSSION 66

3.6. REFERENCES 70

4. CHAPTER 1: An agent-based simulation model to compare different reproductive strategies in beef cattle operations: Economic performance 75

4.1. Abstract 75

4.2. INTRODUCTION 76

4.3. MATERIAL AND METHODS 77

4.3.1. Overview 77

4.3.2. Model description 78

4.3.3. Experimental design 78

4.3.4. Economic analysis 80

4.3.5. Statistical Methods 84

4.4. RESULTS 85

4.5. DISCUSSION 92

4.6. REFERENCES 96

5. GENERAL DISCUSSION AND CONCLUSION 100

5.1. REFERENCES 102

1. INTRODUCTION

The future of world agricultural production faces critical challenges. On the one hand, the demand for primary agricultural commodities is expected to increase significantly in the coming decades as a result of world population growth and increased urbanization and income (ALEXANDRATOS; BRUINSMA, 2012). On the other hand, non-market values, such as public acceptance of animal husbandry practices (BUSCH; GAULY; SPILLER, 2018), and substantial evidence indicating that food production is among the biggest drivers of global environmental change (WILLETT et al., 2019), has an increasing weight on consumers' decisions. Regarding beef production, although the annual growth rate of world consumption in the period 2009 - 2017 was the lowest among animal products (HANIOTIS, 2019) and production practices are more animal-friendly when compared with the other species, the beef production system is the main focus of these criticisms. Besides, the economic performance of beef cattle production has declined in the last decade due to rising production costs and the real fall in selling prices for meat (ASH et al., 2015). Historically, gains in productivity have offset this situation; now, the question is if improvements on productivity can continue to be the path to raising profitability to levels enough to ensure that the beef industry remains economically viable.

As a result, a series of innovations in production systems aimed to increase efficiency and reduce production areas are shared. As expected, in most cases, these changes require larger amounts of inputs, while local impacts intensify (STEINFELD et al., 2006). An essential part of the biotechnological and management innovations applied to beef cattle ranching is related to herd reproduction. This is mostly due to the strong relationship between the economic and reproductive results of livestock enterprises. Several authors have discussed the economic effect of reproduction on the herd. In (1977), Trenkle and Willham described that in economic terms, reproduction is five times more important than weight gain and milk production. Years later, Vishwanath (2003) explained that reproduction is one of the main factors affecting the economic efficiency of productive herds. Also, Burns, Fordyce, and Holroyd (2010), Menegassi et al. (2011), Hayes, Lewin, and Goddard (2013) and Pravia et al. (2014) reinforce the importance of reproductive performance in the financial sustainability of beef cattle enterprises.

In Brazil, according to Sartori et al. (2016), the growth in the use of reproductive biotechnologies has been significant. Regarding artificial insemination (AI), when compared to the years 2000 and 2015, the number of inseminations performed almost doubled in Brazil, from 7 million to 13 million inseminated females, respectively. Additionally, from the total of females exposed to AI, the percentage that was inseminated using the timed AI (TAI) increased significantly. From 1% to 77%, respectively, for the years 2000 and 2015. This shows that the use of TAI promoted the use of artificial insemination in Brazil.

The use of reproductive biotechnologies is known to be directly related to increases in productivity, since the use of these techniques presupposes the use of genetically superior bulls. However, its implementation presents some challenges, mainly related to economic and cultural aspects. Analysis and evaluations of the implementation of reproductive strategies go beyond investments for each of them, which in most cases, are easy to compare. As described by LeBlanc (2007), a successful or unsuccessful reproductive strategy modifies the dynamics of the herd, changing the disposal rates and the supply of replacement animals, among many other characteristics, generating losses or benefits, which in turn may be higher than the costs of implementing the technique.

Assessing the return on investments made in reproductive biotechnology is not a simple task, as these returns, in the best-case scenario, will come several months after their employment, and will come from a variety of causes. Furthermore, it is difficult to quantify the cumulative effect of genetic gains from the use of genetically superior animals that are introduced into the herd. Thus, the long-term economic benefits of using these biotechnologies are unclear.

Therefore, the redesign of agricultural systems from the focus of simulation becomes particularly relevant, since the system can be evaluated from different points of view, pointing out alternatives and sustaining the transition of change (GOUTTENOIRE; COURNUT; INGRAND, 2011). According to Law and Kelton (1991), simulation is the mathematical or logical representation of the relations that present a system, constituting a model with which one seeks to gain a better understanding of how such a system behaves, or in another case, to predict its future performance under new conditions. Thus, livestock systems must incorporate techniques that allow them to increase their efficiency, productivity, and sustainability through the planning and control of activities. This will allow to evaluate different reproductive and management strategies, with the possibility of measuring the economic and productive effect of the procedures to be established, thus contributing with tools that help the decision making by the adoption or not of the techniques.

In the present study, we propose to apply agent-based simulation (ABS), which includes discrete, dynamic, and stochastic simulation. ABS is the process of designing a model of a real system and conducting experiments with the primary purpose of understanding system behavior and evaluating possible strategies for its operation. In ABS, complex systems are represented by a collection of agents that are built to follow rules of behavior (SIEBERS et al., 2010).

Therefore, the present work aims to develop an agent-based simulation model that allows analyzing economically and financially the effects of the use of reproductive management strategies on the performance of beef cattle system. The proposal intends, in addition to deepening the knowledge in the cattle breeding system, to help producers and consultants to make decisions regarding the application and understanding of the future effects of reproductive biotechnologies on the technical and economic performance of beef herds. Additionally, the simulation model presents itself as a valuable tool for researchers and members of the veterinary pharmaceutical industry, in order to direct future research efforts and the development of new products in the bovine reproduction segment.

Thus, this Ph.D. dissertation consists of three chapters. Chapter 1, presents a literature review on simulation models with emphasis on beef cattle systems. Chapters 2 and 3 are independent manuscripts, each written in a scientific article style, and contain the following subsections: introduction, materials and methodology, results, discussion, and references. In Chapter 2, we present the agent-based simulation model using Anylogic software. In this chapter, ten scenarios are compared, and technical results are presented. In Chapter 3, the simulation model is used to evaluate the economic performance of the same scenarios analyzed in Chapter two. Additionally, a general discussion about the simulation model and the results of previous chapters, as well as some guidelines for future research are presented.

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2. LITERATURE REVIEW

2.1. INTRODUCTION

The Hindu–Arabic numeral system entered Europe between the years 1150 and 1450. Starting in Spain, which had a strong Arab influence after the Moorish invasion and spread throughout western Europe for the next four centuries (BALL, 1960). The new system increased the possibilities of calculation that Roman numbers offered at that time. Until then, the gap in knowledge of arithmetic was enormous, and only a small number of trained people could perform simple mathematical operations. Today, multiplications and divisions have become part of what we expect any child to learn in the early years of school (WILENSKY; RAND, 2015).

For Wilensky and Papert (2010), one of the most important consequences of the restructuring originated by the replacement of Roman numbers by Hindu-Arabic numbers was in the social field. The introduction of Hindu-Arabic numbers made it possible for people to solve everything from simple calculations that facilitated their every-day problems to complicated algorithms that allowed significant advances in science. From this, arithmetic was no longer exclusively for people with unique abilities, and ordinary people could now perform their own calculations, solve problems, and make decisions independently based on their results.

This example allows us to draw an analogy with the problems facing our contemporary society today and to think about what would happen if they could be transformed, as with Roman numbers (WILENSKY; RAND, 2015). Today, one of the relevant problems of our society is the difficulty in understanding and managing complex systems. Complex systems are structures composed of a large number of different interacting parts, where global behavior emerges from local interactions. One of the main difficulties of complex systems is to identify and understand the relationships among the components of its own microstructure.

The newly available technologies, specifically computer simulation, can help us create a new way of representing complex systems that allow us to understand them better. Advances in the computer industry have provided more powerful, more accurate, and user-friendly equipment that has allowed specific simulation software to become available to people from the most diverse areas. Some years ago, this kind of simulation was restricted to professionals such as mathematicians and statisticians (HILLIER; LIEBERMAN, 2010).

The agricultural sector is made up of clear examples of complex production systems. Some of the causes that define this condition are the interaction between animal and plant components, the different time scales, and long production cycles (GOUTTENOIRE; COURNUT; INGRAND, 2011; HIROOKA, 2010; PETTIGREW, 2016; STYGAR; MAKULSKA, 2010). Also, food production is the focus of significant criticism from society regarding the sector's responsibility for climate change on the planet.

Livestock production historically had the vital role of providing income and food for millions of small producers worldwide as well as being a significant component of some countries' economies (GODFRAY et al., 2018). Recently, however, other challenges have emerged. On one side, the environmental impact resulting from the production systems and on the other side, the growth of the world population and the increase of the economic inflows in some parts of the world, which favor the fast increase of the demand of animal products (GOUTTENOIRE; COURNUT; INGRAND, 2011; HIROOKA, 2010; STEINFELD et al., 2006). As a result, a series of innovations in production systems aimed to increase efficiency and to reduce the production area. As expected, in most cases, these changes require more massive amounts of inputs, while local impacts intensify (STEINFELD; GERBER; WASSENAAR; CASTEL *et al.*, 2006).

An essential part of the biotechnological and management innovations applied to beef cattle ranching is related to animal reproduction. This is mainly due to the strong relationship between the reproduction and economic results of livestock enterprises (BARUSELLI; FERREIRA; SA; BO, 2018). However, finding the best reproductive strategy is not a simple task. There are many alternatives available in the market, some of them with significant resource mobilization and high return on invested capital.

Testing different reproductive alternatives combined with variability in the market and financial scenarios is complicated, requires a large number of resources, and it takes time to show results, so determining the best strategy through conventional field experiments will be practically impossible (MAYER; BELWARD; BURRAGE, 1998). Simulation models are an efficient tool to overcome these obstacles. A model is defined as a simplified representation of a system that seeks to detect quantitative relationships between variables, identify knowledge gaps, predict system evolution, and assist decision-making (GOUTTENOIRE; COURNUT; INGRAND, 2011; JALVINGH, 1992; STYGAR; MAKULSKA, 2010). Therefore, the redesign of agricultural systems from the focus of simulation becomes particularly relevant, since the system can be evaluated from different points of view, pointing out alternatives and sustaining the change transition (GOUTTENOIRE; COURNUT; INGRAND, 2011).

This literature review, therefore, addresses aspects related to simulation models in livestock systems, with emphasis on those that approached beef cattle operations.

2.2. SIMULATION MODELS

One of the basic cognitive processes of human behavior in decision making. In this process, an option or a series of options is chosen from a set of alternatives, considering personal references and any restrictions of a legal, economic or physical nature (WANG; RUHE, 2007). In the human mind, data stored in memory is revised and sorted according to its importance. Subsequently, alternatives are identified and ordered according to the level of relevance; risks and consequences are considered; and decisions are finally made (JALVINGH, 1992; PEART; SHOUP, 2018).

For Stygar (2010), making the right decisions implies knowing the current state of the system; know the interrelationships of the factors used; and the effects resulting from these interactions. In beef cattle production systems, some analyzes, such as economic ones, have been limited by the inability to describe the interrelationships of the system entirely. This inability makes the correct measurement of inputs and outputs impossible; consequently, on several occasions, the analyzes of these systems are mere conjectures and the resulting conclusions questionable.

Studying a beef cattle production system through traditionally designed experiments may be impractical or simply impossible. However, it is theoretically possible to construct models that allow us to predict outcomes of potential system interventions (BLACK; DAVIES; FLEMING, 1993; GOUTTENOIRE; COURNUT; INGRAND, 2011; JALVINGH, 1992; PETTIGREW, 2016; STYGAR; MAKULSKA, 2010). According to Machline (1975) and Lachtermacher (2004) Operational Research (OR) is a discipline that makes use of mathematics, statistics, and computer science to find optimal, or almost optimal, solutions to complex problems between a series of conflicting and competing alternatives that interact, making the decision-making process difficult. In general, OR is subdivided into: i) Linear Programming, which involves optimization models based on linear equations; ii) Nonlinear Programming, which presents the theory of optimization in nonlinear problems; and iii) Probabilistic Models, which incorporate random variables within their models. Simulation is immersed in this last classification.

According to Banks (1998), simulation is the imitation of a real-world process or system over time, or as described by Peart and Robert (2018), computer simulation is an imitation of what is a complicated way happens in the human mind. For this, an artificial history of this process needs to be generated, and in this way, it is possible to infer the operational characteristics of the studied system. Simulation models require the quantitative description, in terms of mathematical equations, of each step of a process within the studied system, largely avoiding subjectivity in the analyses performed (BLACK, 2014). For Law and Kelton (1991), simulation is the mathematical or logical representation of the relations that are present in a system, constituting a model with which one seeks to gain a greater understanding of how that system behaves, or in another case, to predict its future and performance under new conditions.

Simulation is a tool that enables numerous advantages such as: i). Managing time, increasing or decreasing the speed with which one wants to study a given phenomenon. ii). Be a conceptual framework that allows exploring new possibilities such as policies, methods, or procedures and can stimulate the emergence of new ideas and experimental approaches without incurring significant expenses or disturbances to the real system. iii). Identification of bottlenecks and assist in planning with the possibility of observing the process operation from various angles and levels; iv) provide a means for research data to be used by producers in a practical and user-friendly manner; and vi) stimulate multidisciplinary research projects, among others (BANKS, 1998; HIROOKA, 2010; NITU; BURLACU; DAVID, 2010).

Goldsman (2010) succinctly divided the history of simulation into three periods:

i) The pre-computer age (1777 - 1945). The idea of using randomness in a decisive way to solve problems initiated in this period. In 1777, the French scientist Georges Louis LeClerc Comte de Buffon developed several studies using randomized methods. One of the most notable was the "Buffon's needle," in which needles were repeatedly dropped randomly onto a plane with equally spaced parallel lines to calculate the π value. Many consider that this kind of experiments gave rise to the Monte Carlo method. Several years later, William Sealy Gosset, who developed the Student Statistical Significance Test, used simulation techniques to verify his conjectures about the exact shape of the probability density function for Student's t-distribution. Undoubtedly a striking example of the synergy of simulation-based experimentation and analytical techniques in finding solutions.

ii) The formative period (1945 - 1970). In the formative period, the rapid growth of the simulation field took place. Two significant developments contributed to this: the completion of the construction of the first general-purpose electronic computer, the ENIAC, and the hydrogen bomb design that brought problems that were only solved using methods such as Monte Carlo (GOLDSMAN; NANCE; WILSON, 2010). After ENIAC, the availability of computers increased, which allowed a proliferation of techniques and their application in other disciplines. Subsequently, researchers from various parts of the world provided simulation tools as well as simulation texts that contributed to research and teaching.

iii) The period of expansion (1970 - 1982). During the expansion period, different simulation languages were developed, and important enhancements, extensions, and additions throughout the art and science of teaching, research, and simulation practice were conducted (GOLDSMAN; NANCE; WILSON, 2010).

2.3. TYPES OF SIMULATION MODELS

Simulation can be classified into two major types:

i) According to the role that time plays within the simulation, whether dynamic or static. Generally, in dynamic models, time is a relevant variable, and they present themselves as a group of differential equations (HIROOKA, 2010; STYGAR; MAKULSKA, 2010). How time is handled within dynamic models may vary depending on whether time progresses in fixed units or whether time passes from the point at which an event occurred to the beginning of the next event (JALVINGH, 1992). Dynamic models are most useful to show the cumulative effects of some factor or, for example, the sequence of management decisions during an animal's life (PETTIGREW, 2016). In static models, time is not included as a variable, so it is impossible to simulate a system over time. This characteristic of static models makes them of little use in the simulation of agricultural systems (HIROOKA, 2010; STYGAR; MAKULSKA, 2010).

ii) According to the random or non-random nature of the input data, simulation could be stochastic or deterministic. In a stochastic simulation, probability distributions (Random Elements) represent the variation of parameters and variables. Including random elements in the model implies the need to perform repeated model executions to obtain information about the potential variation of the result (JALVINGH, 1992). For Spreen et al. (2019), a stochastic model is one in which one or more random variables are incorporated. As a result, the results of successive simulations vary even though the input data remain constant. The results of repeated simulations can be statistically tested in the same way as with experimental replicates.

iii) On the other hand, the deterministic simulation predicts results based on fixed variables and parameters, without associated probability distributions. In other words, it is assumed that the simulated system does not have a random variation. According to the nature of agricultural production, in which parameters are associated with plants and animals, the stochastic approach is more appropriate (HIROOKA, 2010; STYGAR; MAKULSKA, 2010). However, most agricultural system simulation models are deterministic (PETTIGREW, 2016).

2.4. USE OF SIMULATION MODELS IN BEEF CATTLE

Since the early twentieth century, agricultural researchers have been using information and databases to improve the management of their systems. Initially, mere observations of data behavior were made, focusing on unusual occurrences. Later, with more technological tools, data interrelationships were determined and studied (PEART; SHOUP, 2018). From 1950 onwards, due to the remarkable advances of the computer industry, which allowed the use of mathematical techniques that were previously impossible to use, there was an increase of interest by professionals close to the agricultural and mathematical sciences in modeling biological systems (SPREEN; LAUGHLIN; DOREN; WALKER, 2019). Subsequently, the work of Arcus (1963) introduced the use of simulation as a research technique in agriculture.

Between 1960 and 1980, the concept of Dynamic Systems emerged and formalized, contributing to time-related representations (PEART; SHOUP, 2018). Also, during this same period, due to the increasing interest in agricultural modeling, specific journals in the area were formed, such as the Journal of Agricultural Systems (SPREEN; LAUGHLIN; DOREN; WALKER, 2019). Subsequently, Wilton et al. (1974) described the use of Linear Programming in beef cattle production in order to find the ideal combination of agriculture, nutrition, and reproduction programs. Similarly, at the end of this period, as reported by Sanders and Cartwright (1979a; b), Texas A&M University developed the Texas A&M Cattle Production Systems Model. This was a deterministic model that aimed to simulate livestock production under a wide range of conditions, under a determined genetic potential and forage. In 1980, advances in computer programming techniques, model verification, validation, and evaluation took place (PEART; SHOUP, 2018). At this point, simulation of agricultural systems has become an essential part of the development of science in this area of knowledge.

Congleton and Goodwill (1980) developed a deterministic simulation model that determined the influence of different natural planes on herd age and, consequently, their productivity. Also, Loewer et al. (1980) described the relevant contribution of the University of Kentucky to the development of the BEEF model (an acronym for Beef Energy and Economic evaluator for Farms). This model was built to simulate plant development, growth, and animal reproduction as a function of as well as to calculate the energy use, cash flow, and net worth of a farm. Subsequently, some authors performed new studies based on modifications of the model presented by Sanders and Cartwright (1979a; b). Among these, Kahn and Spedding (1983) developed a new model in which animal performance was evaluated individually, and variables such as calf conception, mortality, and sex were treated stochastically, additionally new supplementation and discarding routines were included. Another study that used and modified the Texas A&M model was Bourdon and Brinks (1987). The modifications had to do with the effects of growth, milk production, and management system on the biological and economic efficiency of beef production. Still, between 1980 and 1990, issues related to the nutrition of beef cattle were treated using simulation models, among them Loewer et al. (1983), Fox and Black (1984), and Fox et al. (1988).

Years later, Werth (1991) used two simulation models to determine the effect of reproductive performance on the net income of a cow-calf operation. In this case, a stochastic model was used to simulate the reproductive performance of cows. The results of the stochastic model served as inputs to a deterministic model that calculated the net ingress of a 365-day production cycle. In the same year, using life-cycle evaluation, Green (1991) compared the biological performance of a herd of F1 cows crossed with bulls of 3 different breeds. The following year, Lamb et al. (1992) determined the biological and economic performance of three breeding systems using a deterministic simulation model. In turn, Koots and Gibson (1998) used a deterministic model of beef cattle production to estimate the economic effects of genetic traits. In 1999 Canadian researchers developed the Alberta Beef Production Simulation System (ABPSS), a dynamic and deterministic simulation model that aimed to predict the nutritional needs of cows and calves and to evaluate the effects of production characteristics and management strategies on economic efficiency. of the system (PANG; MAKARECHIAN; BASARAB; BERG, 1999).

Tess and Kolstad (2000) developed a model that evaluated the effect of forage quality and management strategies on different genetic types and reproductive performance of cow-calf operations. In the model, reproductive characteristics were managed stochastically, while growth and body composition were deterministic. In the United Kingdom, Roughsedge et al. (2003) constructed a deterministic simulation model to evaluate the effects of changes in breeds and mating systems on the technical and economic performance of beef cattle. With similar objectives, but in central Europe, Wolfová et al. (2005) developed a bioeconomic model that, under the deterministic approach, allowed the evaluation of traits in a wide variety of breeds and production systems in a wide range of management and marketing circumstances. Miller et al. (2004) evaluated 12 estrus synchronization protocols, including natural breeding, on the economic performance of beef cattle in the United States.

On the other hand, also in North America, Reisenauer et. (2007) used the model previously developed by Tess and Kolstad (2000) to evaluate alternative birth seasons and different calf marketing strategies and their effect on herd profitability. Later, Johnson and Jones (2008) developed a stochastic simulation model to compare the costs of different reproductive systems, which included estrus synchronization and natural breeding. In Australia, Ash et al. (2015) developed the Northern Australia Beef Systems Analyzer (NABSA), a dynamic simulation model that aimed to test, technically and economically, technological interventions related to genetics and nutrition.

2.5. FINAL CONSIDERATIONS

According to Pettigrew (2016), the current use of simulation models in animal research can be classified into three categories:

1) Those that are directly used in the decision-making process within the production system. These types of models are infrequent due to the required high standards of accuracy, which in turn require very accurate inputs, which are scarce.

2) Simulation models that were used indirectly in production system decision making and highlighted the magnitude of the benefits of some practice such as nutrition and management.

3) Finally, the third classification groups models that guide future research. The description of the system interrelationships and the parameterization during the modeling process help to identify knowledge gaps that would not be detected otherwise. These gaps become opportunities for further research.

The simulation model that will be the subject of this Ph.D. dissertation falls into the second and third categories of this classification. In this dissertation, an agent-based simulation (ABS) model was created. This kind of model includes discrete, dynamic, and stochastic simulation. The ABS is the process of design a model of a real system and carry out experiments with the primary objective of understanding the behavior of the system and evaluate possible strategies for its operation. In ABS, complex systems are represented by a collection of agents that are built to follow rules of behavior (SIEBERS; MACAL; GARNETT; BUXTON *et al.*, 2010).

Agents are the primary and most important unit of an agent-based model (CHEN, 2012). They are entities designed to mimic the behavior of something in the real world and constitute a system. Agents have their own set of goals and behaviors, which makes their behavior autonomous and interactive, being able to make autonomous decisions (taking actions according to the interaction with the environment), consequently being heterogeneous. The ABS is based on a bottom-up approach that begins by considering explicitly the components of a system, its agents, and tries to understand how the system properties emerge from interactions between these components (MCLANE; SEMENIUK; MCDERMID; MARCEAU, 2011).

According to Macal and North (2005), the SBA applies to a wide variety of fields, because of their ability to describe complex systems, they include business and organizations, economy, infrastructure, society and culture, terrorism, military, and biology.

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3. CHAPTER 1: An agent-based simulation model to compare different reproductive strategies in beef cattle operations: Technical performance[1]

3.1. ABSTRACT

The objective of this study was to create a stochastic, agent-based simulation model that allows to compare the technical performance of reproductive strategies on a synthetic population of beef cattle. The model was created using the AnyLogic simulation tool and was parameterized using data from a real beef cattle herd and from peer-reviewed scientific literature. Ten scenarios were evaluated: natural mating (NM) only (ONM); one timed artificial insemination (TAI) plus NM (1TAI+NM); two TAI plus NM, with 24, 32, and 40 days between inseminations (2TAI/24+NM, 2TAI/32+NM, and 2TAI/40+NM, respectively); three TAI without NM, with 24, 32, and 40 days between inseminations (3TAI/24, 3TAI/32, and 3TAI/40, respectively), and three TAI plus NM, with an interval between inseminations of 24 (3TAI/24+NM) and 32 days (3TAI/32+NM). NM started 10 days after the last insemination and was performed until the end of the breeding season. The initial population of the model ranged between 400 and 415 animals, depending on whether NM was used or not. The size of the female herd was fixed to contain 400 individuals. The outcomes for each scenario were assessed on 32 farms, using a 5,000-day time horizon at 1-day time intervals and on an animal-by-animal basis. The 3TAI/24+NM scenario resulted in a greater number of births (293 births) and weaned calves (287 calves), while the ONM scenario had the lowest number of births (207 births) and calves (203 calves). The heaviest males and females at weaning belonged to 3TAI/24, with 190.58 ± 0.77 kg for males and 173.67 ± 0.86 kg for females. The ONM scenario had the lightest males (166.59 ± 0.93 kg) and females (151.65 ± 0.74 kg). The greatest and lowest pregnancy rates were found, respectively, in 3TAI/24+NM (0.90 ± 0.00) and ONM (0.61 ± 0.01). The ONM scenario required 52.5 days more than scenarios that included TAI to reach 50% of pregnancy. The greatest ages of culling for cows were found in 3TAI/24+NM (3348.45 days) and 3TAI/32+NM (3,272.52 days). In contrast, the lowest age of culling was found in

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ONM (2,655.75 days). The proposed model represents the main interactions of a real beef cattle herd. It has all the advantages of a physical experiment, but it neither requires incurring significant expenses nor altering the real system. This study offers evidence that the scenarios that present the best reproductive performance and produce more and heavier calves are those that use reproductive technologies.

Key words: beef cow, doppler, pregnancy, resynchronization, timed artificial insemination

3.2. INTRODUCTION

Reproductive efficiency is one of the critical factors that influence productivity and ensure the economic sustainability of cow-calf enterprises (VISHWANATH, 2003; BURNS et al., 2010; BÓ et al., 2007; LIMA et al., 2010; RODGERS et al., 2012; HAYES et al., 2013; PRAVIA et al., 2014; LAMB; MERCADANTE, 2016; BARUSELLI et al., 2018;). The intensification of reproductive programs that use natural mating (NM), by combining it with reproductive biotechnologies such as artificial insemination (AI) and timed artificial insemination (TAI), are a way to improve the technical and economic results of farms (SÁ FILHO et al., 2013; BARUSELLI et al., 2018).

Artificial insemination has many advantages in cattle production (LIMA et al., 2010), but is also limited by postpartum anestrus, estrus detection (especially when there are many animals per paddock in the beef cattle herd), and the labor costs resulting from this task. Due to such inconveniences, many producers still use NM because they believe it is an easy and cheaper strategy (LIMA et al., 2010). To avoid the problems associated with the detection of estrus, to take advantage of AI, and to increase its use, essential efforts have been made to develop hormonal treatments, allowing TAI (AI without the need of estrus detection) independently of the day of the cycle of the cow (at the moment of starting the hormonal protocol) (LAMB et al., 2001; BÓ et al., 2013; BÓ et al., 2016; BARUSELLI et al., 2017).

Advances of research in this field have allowed dairy and beef cattle producers to have a range of possibilities related to the number of TAI, the time interval between two TAI (using resynchronization protocols) (COLAZO et al., 2006; CAVALIERI et al., 2007; PUGLIESI et al., 2019), and different techniques for early pregnancy diagnosis (GREEN et al., 2010;

PUGLIESI et al., 2014). Nonetheless, as in all decision-making processes, some trade-offs need a particular analysis. Although a significant number of studies have evaluated the technical performance of different reproductive strategies (LAMB et al., 2001; WILLIAMS et al., 2002; SÁ FILHO et al., 2013; PUGLIESI et al., 2019), most of these studies are limited to only comparing two or three strategies, mainly because of the limited availability of time, farms, animals, and labor, as well as the high cost of such trials.

Given the complexity of the beef cattle production system and the numerous variables that affect reproductive performance, simulation models are presented as a valuable tool that allows modeling a herd and conducting *in silico* experiments in order to understand the system and to evaluate several strategies for its operation (GOUTTENOIRE et al., 2011). Agent-based simulation models can provide a methodological framework that allows studying a system in-depth, allowing new strategies to be tested and evaluated without incurring the cost of implementing experiments in real farms (SIEBERS et al., 2010). In this context, the objective of this study is to create and describe a stochastic, agent-based simulation model that allows the comparison of the technical performance of reproductive programs that use NM only, TAI only, or different combinations of TAI + NM. The effect of the number of TAI (one, two, or three TAI) and the interval between TAI (24, 32, and 40 days) is also evaluated.

3.3. MATERIAL AND METHODS

3.3.1. Description of the model

The purpose of this study was to develop a model that represents the behavior and estimates the technical performance of a synthetic population of beef cattle (*in silico*). The model was implemented as an agent-based stochastic simulation model. In the model, agents are males and females, and each has 21 attributes that remain constant throughout the animal's life (e.g., name). Also, each animal has four attributes that change daily (e.g., age) or that change every time there is a change of status (e.g., average daily gain). The model is stochastic because the value of some attributes and the occurrence of some events are decided based on random variables taken from probability distributions. The input information was chosen to represent a Nelore cattle herd in São Paulo state, Brazil, in the year 2018.

3.3.2. Model parameterization

The model was parameterized using a combination of field data collected at the Instituto de Zootecnia, Beef Cattle Research Center (IZ), Sertãozinho, SP, Brazil, and data available from specialized scientific literature. The IZ is located in the north of the state of São Paulo, Brazil (21° 10 'S, 47° 57' W). From the year 1980, the Nelore herd of the IZ has been partitioned into three lines: Control (NeC), Selection (NeS), and Traditional (NeT). In NeS and NeT, males and females with greater adjusted yearling weight were selected to continue in the herd, while males and females with a selection differential for yearling weight around zero were selected to continue in the NeC. Reproduction in the herd occurs in the 90-day breeding season (BS; from 15 November to 15 February) using only NM. A more comprehensive and detailed description of the characteristics and management of the herd is provided elsewhere (Mercadante et al., 2003).

This study considers a historical database containing all zootechnical information of the IZ herd as a reference for animal performance. This database contains records of 9,781 animals born in the IZ between 1981 and 2016 from the NeC, NeT, and NeS line groups. After analyzing the entire period and observing the effect of the genetic selection of the IZ on the herd and, consequently, the substantial variability of the data, it was decided to use an intermediate period, from 1995 to 2005, and only NeT and NeS records, which are expected to more accurately represent the reality of the Brazilian commercial production. The data includes gender, date of birth, parental information, birth weight, weight at 120 days, and weaning weight. Also, we considered weight records of females aged between the weaning age and 2 years, approximately, and reproductive performance data records.

The detailed description of the parameters of the model is presented in Table 1. No seasonal effects were considered in order to maintain the simplicity of the model. Mortality rates (age-specific) were general parameters shared by the entire herd, regardless of the sex.

Table 1 Parameters used in the simulation model to describe the transition rates and/or the times used for the agents to move between the different states

Parameter	Value	Distribution	Reference
mortalityRateUpTo3DaysOld	2.66%	-	(Schmidek *et al*., 2013)
mortalityRateFrom3To30Days	2.62%	-	(Schmidek *et al*., 2013)
mortalityRateFrom30DaysOldToWeaning	2.71%	-	(Schmidek *et al*., 2013)
adultMortalityRate	1.00%	-	IZ Database
sexProbability	50%	-	Assumption
serviceRateToTAI	100%	-	Assumption
semenFertilityRate	95%	-	Assumption
ageOfBoughtHeifers	-	Normal (truncated) (Min. 711 months, Max. 826 months, Mean 780 months, Standard deviation 23.1706 months)	IZ Database
liveWeightOfBoughtHeifers	-	Uniform (300 kg, 400 kg)	-
femaleBirthWeight	-	Normal (truncated) (Min. 16.0 kg, Max. 45.0 kg, Mean 29.5209 kg, Standard deviation 4.3644 kg)	IZ Database
avgDGPreWeaningFemale	-	Normal (truncated) (Min. 0.210 kg, Max. 1.025 kg, Mean 0.7360369 kg, Standard deviation 0.112999 kg)	IZ Database
avgDGWeaningToHeifer	-	Normal (truncated) (Min. 0. 09148 kg, Max. 0.80541 kg, Mean 0.44720 kg, Standard deviation 0,11381 kg)	IZ Database

Source: Ojeda-Rojas (2020)

Table 1 Parameters used in the simulation model to describe the transition rates and/or the times used for the agents to move between the different states (Continued)

Parameter	Value	Distribution	Reference
avgDGPreReproSeason	-	Normal (truncated) (Min. -0.13736 kg, Max. 0.18375 kg, Mean 0.03557 kg, 0.04617)	IZ Database
avgDGInPreReproSeason	-	Normal (truncated) (Min. -0.2333 kg, Max. 1.4222 kg, Mean 0.737 kg, 0.2877)	IZ Database
maximumAgeForBreeding	4000 days	-	Assumption
pregnancyLoss	0.0145% per day	-	(Aono *et al.*, 2013)
gestationLength	-	Normal (truncated) (Min. 273 days, Max. 314 days, Mean 296.6 days, Standard deviation 5.9 days)	(Chud *et al.*, 2014)
voluntaryWaitPeriod	45 days	-	Assumption
cowsFertilityRate	60%	-	Assumption
ageOfBoughtBulls	-	Normal (truncated) (Min. 711 months, Max. 826 months, Mean 780 months, Standard deviation 23.1706 months)	IZ Database
liveWeightOfBoughtBulls	-	Uniform (450 Kg, 650 Kg)	-
MaleBirthWeight	-	Normal (truncated) (Min. 19.0 kg, Max. 48.0 kg, Mean 32.4905 kg, Standard deviation 4.4650 kg)	IZ Database

Source: Ojeda-Rojas (2020)

Table 1 Parameters used in the simulation model to describe the transition rates and/or the times used for the agents to move between the different states (Continued)

Parameter	Value	Distribution	Reference
avgDGPreWeaningMale	-	Normal (truncated) (Min. 0.258 kg, Max. 1.143 kg, Mean 0.8104624 kg, Standard deviation 0.1226086 kg)	IZ Database
bullsFertilityRate	50%	-	Assumption
bullMaxTimeInReproduction	1095 days	-	Assumption
dayOfTheCycle	-	Uniform (1 day, 26 days)	Assumption

Source: Ojeda-Rojas (2020)

3.3.3. Structure of the population

The initial population of the model was approximately 400 agents. This number of animals was in agreement with the size (500 ha) and the stocking rate (0.8 animal unit [AU] [450 kg BW]/ha) of the simulated farm. An open population was modeled, with inputs (i.e., births and purchases) and outputs (i.e., deaths and sales). The behavior of each agent was defined using life cycle states. Figure 1 describes the male and female life cycles.

3.3.3.1. Heifers

The initial herd was composed of 400 heifers. The age of the initial heifer population, *ageOfBoughtHeifers*, was described by a truncated normal distribution (Table 1). A uniform distribution was selected to describe the initial weight of heifers, *liveWeightOfBoughtHeifers*. The BS starts on November 15, but only females weighing more than 350 kg have the possibility of joining. The BS is composed of three states: “noPregnant”, “serviced”, and “pregnant”. The first one, which consists of empty females, is where the heifers are available to be served, either by NM or TAI. The transition from this state to the female-served state will depend on the type of service. In the case of NM, this transition is conditioned by the number of females available at that time.

Regarding the number of females available for NM, it was established that 70% of the heifers would be cycling at the beginning of the BS (Dias et al., 2009). The remaining percentage will be available only 30 days later. Also, as naturally happens in cyclic females, on a given day, the females will be in a different phase of the estrous cycle; therefore, they will only be served when they are on estrus. This scheme was outlined employing the *dayOfTheCycle* parameter that followed a uniform distribution between 1 and 26 days, which determines the time remaining for the next estrus. Thus, a female that enters the "noPregnant" state and has a value of 10 in the *dayOfTheCycle* parameter will only be available to be served by the bulls 10 days later. In the case of TAI, this transition is dependent on the service rate of the TAI, *serviceRateToTAI* (Table 1), and the number of females available at that time, which in this case will be 100% of the females. The transition to the “pregnant” state, the last one of the BS, is also dependent on the reproductive strategy employed. For NM, this transition will depend on the product between the fertility rate of the cow, *cowsFertilityRate* (Table 1), times the fertility rate of the bull, *bullsFertilityRate* (Table 1). For TAI, this transition will depend on the fertility rate of the cow times the fertility rate of the semen, *semenFertilityRate*. Finally, there are two options to leave the state of pregnant females. The first case is the delivery and birth of the calf after completing the gestation time, *gestationLength* (Table 1), which follows a truncated normal distribution. The second case is pregnancy loss, *pregnancyLoss* (Table 1). The BS ends on February 15. On this day, females that did not achieve a gestation pass to the "openHeifer" state. There are two ways to leave the "openHeifer" state. The first one is to wait until the next BS and, consequently, to start a new cycle. The second one occurs when a female accumulates two consecutive years without achieving a gestation. In such a case, it will be culled.

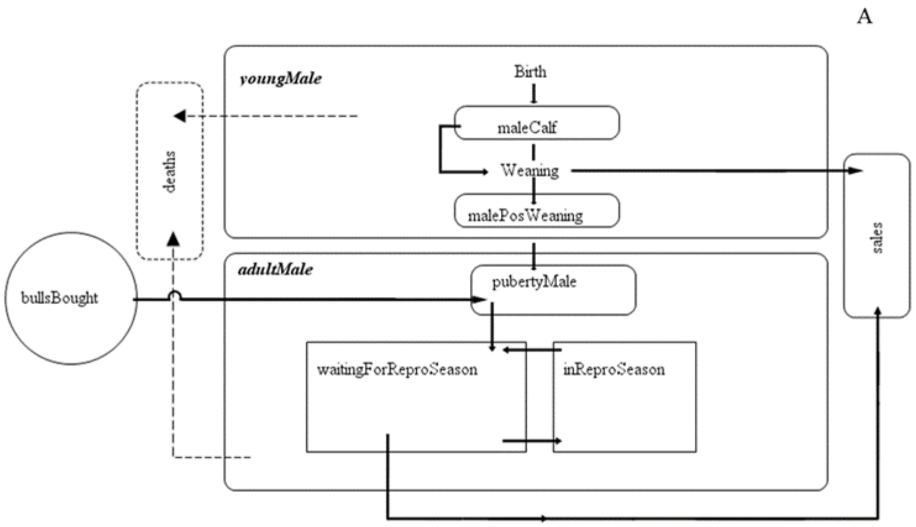
3.3.3.2. Calved cows

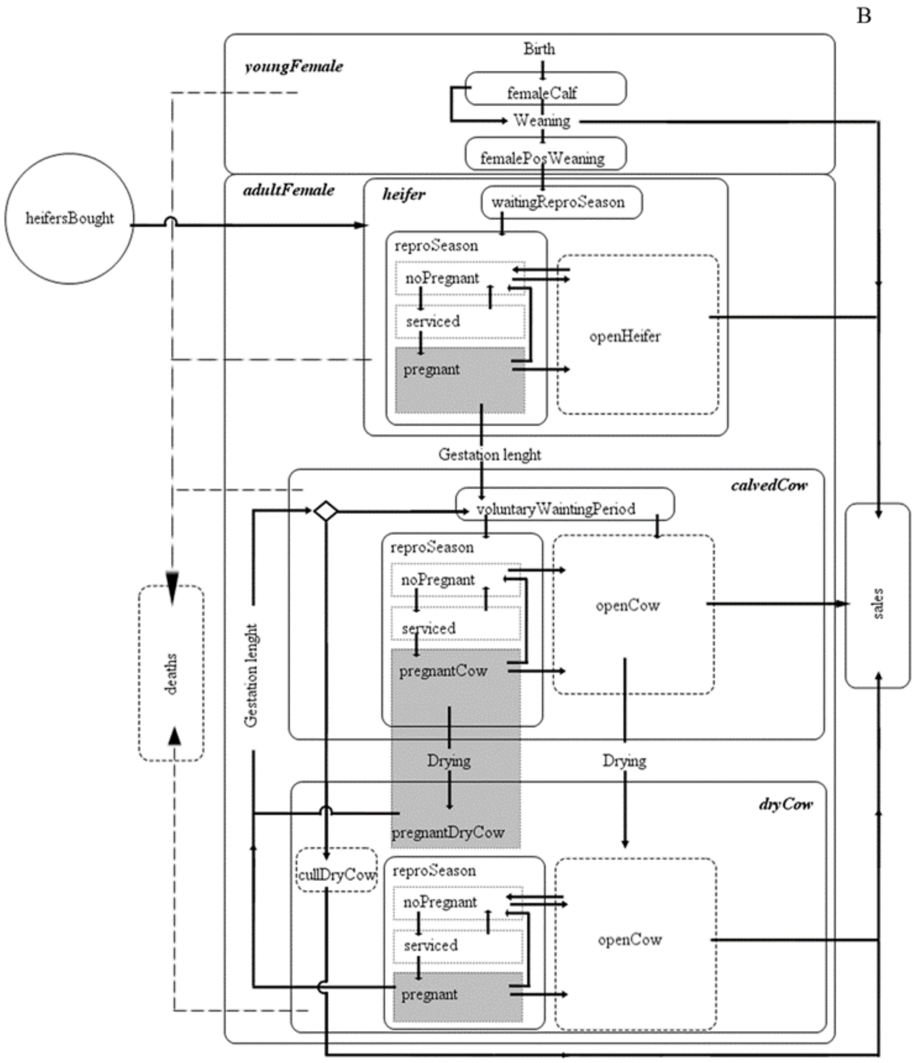
The calved cows are divided into two sets, the primiparous and multiparous cows. In the primiparous ones, after completing the gestational time, the heifer gives birth and becomes a primiparous calved cow. At the same time, the voluntary waiting period starts. To advance to the next state, the "noPregnant" state of calved cows, two conditions must be fulfilled. First, the voluntary waiting period must be completed, *voluntaryWaitPeriod* (Table 1). Second, the BS should be started (November 15 - February 15). Both conditions are necessary for the transition to occur.

Additionally, as with the heifers, this transition is related to the type of service. Multiparous cows follow the same pattern as primiparous cows, with the difference that for NM, the availability of cyclic cows after the voluntary waiting period will be 50% for multiparous and 10% primiparous cows (Stevenson et al., 2000; Lucy et al., 2001). From the moment a cow enters into the BS ("reproSeason" state), it follows the same pattern followed by the heifers.

Another essential feature of the female agent in the "calvedCow" state is the relationship with its calf, because the permanence of the cow in this state is strictly conditioned to the survival of its calf. Therefore, if the calf dies, the cow will simultaneously become a dry cow, changing its state.

Figure 1 Diagram of the life cycle used for showing the states and individual transitions, purchases and sales. A = Males; B = Females. US = Ultrasound; CIDR = Controlled internal drug release; Dopp = Doppler ultrasonography.





Source: Ojeda-Rojas (2020)

3.3.3.3. Dry cows

In the model, weaning was scheduled to occur on April 15. That day, the cows, whether pregnant or not, are transferred to the dry cow category. Depending on their gestational status, dry cows could take two paths. The first option consists of finishing the pregnancy and going to a new BS as a calved cow. The second option represents the case when a dry cow is open. The cows will wait for the beginning of the next BS to perform the same reproductive process performed by heifers and calved cows. The only difference will be that we considered that 100% of the empty dry cows will be cycling and, therefore, available for NM.

As with heifers, dry cows that accumulate 2 years in a row without becoming pregnant will be discarded from the farm and eliminated from the herd by sale.

During the state transition from “dryCow to “calvedCow", the condition called “maximum age for reproduction” will continuously be evaluated, *maximumAgeForBreeding* (Table 1). This condition checks whether the age of a given cow exceeds the maximum age for reproduction (4,000 days). If so, the cow will not enter the breeding season. It will continue in the herd, but it will be discarded soon after weaning, being eliminated from the system as a sale.

3.3.3.4. Female calf

After calving, a new agent is created. The sex of the agent depends on the probability *sexProbability* (Table 1), which controls the ratio of males to females. After females are born, they are assigned some parameters that will remain unchanged throughout their life, including a female fertility rate, *cowsFertilityRate* (Table 1), and a birth weight, *femaleBirthWeight* (Table 1).

The “femaleCalf" state is subdivided into two states by age. The calves stay in the first state until their age is ≤ 30 days. After that, they enter the second state and remain there until weaning (April 15 of each year). This division takes place due to mortality rates directly related to age. For calves, three possible outflows due to mortality are considered. 1st, animals aged between their birthday and three days of age, *mortalityRateUpTo3DaysOld* (Table 1); 2nd, animals aged between 3 and 30 days, *mortalityRateFrom3To30Days* (Table 1); and 3rd, animals aged between 30 days and the next weaning date, *mortalityRateFrom30DaysOldToWeaning* (Table 1). They are all sold at weaning time.

Furthermore, as with calved cows, the permanence of calves in this state depends on the survival of their mother. Therefore, if the mother of this calf dies, it will be weaned prematurely and will be sold.

3.3.3.5. Young bulls

The initial number of young bulls varies according to the scenario and can be 0, 7, or 15. This condition will be explained afterward. The parameters that indicate the initial weight, *liveWeightOfBoughtBulls*, and age, *ageOfBoughtBulls*, at the purchase of bulls are presented in Table 1. After the purchase, the young bulls enter the "pubertyMale” state, and in the sequence, they pass to the state in which they will wait for the BS to begin, the "waitingForReproSeason” state.

3.3.3.6. Bulls

In the “adultMale” state, bulls are affected by three conditions. First, they are affected by the mortality rate of adult males, *adultMortalityRate* (Table 1); second, they are also affected by the maximum time allowed for reproduction, *bullMaxTimeInReproduction* (Table 1); and finally, the third condition affecting bulls is the start date of the BS. At this moment, the bull moves to the "inReproSeason” state and remains in this state until the end of the BS, when it returns to the “waitingForReproSeason” state.

3.3.3.7. Male calves

As female calves, when male calves are born, they are assigned a set of parameters that will be fixed throughout their lives (Table 1). Male calves follow the same path as female calves.

3.3.4. Body weight

The variable body weight is calculated daily as a function of birth weight and a specific weight gain rate associated with the state in which the animal is at every moment. For females, the average daily gain (ADG) values before weaning, from weaning to heifer, before the breeding season, and during the breeding season are given, respectively, by the parameters *avgDGPreWeaningFemale*, *avgDGWeaningToHeifer*, *avgDGPreReproSeason*, and *avgDGInPreReproSeason*. For males, the ADG value before weaning is greater than that of females and is given by *avgDGPreWeaningMale*. This increase in body weight will only take place until the agent enters the first “reproSeason” state in the case of females and the “pubertyMale" state in the case of males. After that, the weight will remain constant.

3.3.5. Culling

Females are discarded and sold when they accumulate two consecutive years without having parturition and when their age exceeds 4,000 days.

Bulls are discarded depending on the bull/cow ratio established in the herd (see experimental design) and their time of service. In the first case, annually on August 1, the availability of bulls with respect to the total number of breeding adult females (heifers, calved cows, and dry cows) is evaluated, and bulls will be bought or sold according to need. For the case of service time, a maximum time of service for bulls is given by the parameter *bullMaxTimeInReproduction* (Table 1). Annually, on March 1, the model evaluates the time the bull has remained in service, and if it is greater than the value of the parameter, the bull is culled.

3.3.6. Replacement

To keep the number of breeding adult females constant, each year on May 15, the model calculates the number of females that have died or have been sold during the last 365 days. Afterward, on August 1, for each dead or sold female, a heifer is purchased to keep the herd size constant.

3.3.7. Computational study

3.3.7.1. Implementation.

The agent-based simulation model was implemented using the AnyLogic® simulation tool, University Edition 7.1.2 (XJ Technologies). The experiments were conducted on the University of Florida's HiPerGator supercomputer. An average of 96 hours was required to run the simulations for each scenario, using a CPU with 16 cores and 32 GB of memory.

3.3.7.2. Experimental design.

Three factors and some interactions between them were considered to structure a total of 10 scenarios. The following factors were considered: two breeding methods used independently or in combination (NM or TAI), the number of inseminations performed (1, 2 or 3 TAI), and the time interval between inseminations (24, 32, or 40 days). The following scenarios were generated: a scenario using only NM (**ONM**); a scenario using one TAI plus NM (**1TAI+NM**); three scenarios using two TAI plus NM, with an interval between inseminations of 24 (**2TAI/24+NM**), 32 (**2TAI/32+NM**), and 40 days (**2TAI/40+NM**); three scenarios using three TAI without NM, with an interval between inseminations of 24 (**3TAI/24**), 32 (**3TAI/32**), and 40 days (**3TAI/40**); and two scenarios with three TAI plus NM, with an interval between inseminations of 24 (**3TAI/24+NM**) and 32 days (**3TAI/32+NM**) (Figure 2).

For all scenarios with NM, bulls were introduced to breed adult females 10 days after the last insemination and remained there until the end of the BS. In the ONM and 1TAI+NM scenarios, the initial number of bulls was 15, and the bull/cow ratio was one bull for 30 cows. For 2TAI/40+NM, 2TAI/32+NM, 2TAI/24+NM, 3TAI/32+NM, and 3TAI/24+NM, the initial number of bulls was set to seven, and the bull/cow ratio was equal to one bull for 60 cows.

In the scenarios with a 24-day inter-insemination interval, non-pregnant animals were diagnosed through regression of corpus luteum, using color Doppler ultrasonography on day 22 after TAI (Pugliesi et al., 2014; Pugliesi et al., 2019). For all scenarios, the BS began on November 15 and continued for 90 days until February 15.

The primary response variables considered were the total of births per year, the number of weaned calves, and the average weaning weight of calves (females, males, and total), aggregated per year. Likewise, the reproductive indicators considered were pregnancy rate (PR) (for heifers, calved cows, dry cows, and total) and the calving counter at the time of sale. The latter is defined as the number of births that a culled cow had when it is sold. Finally, the average age of the cows at culling was also analyzed.

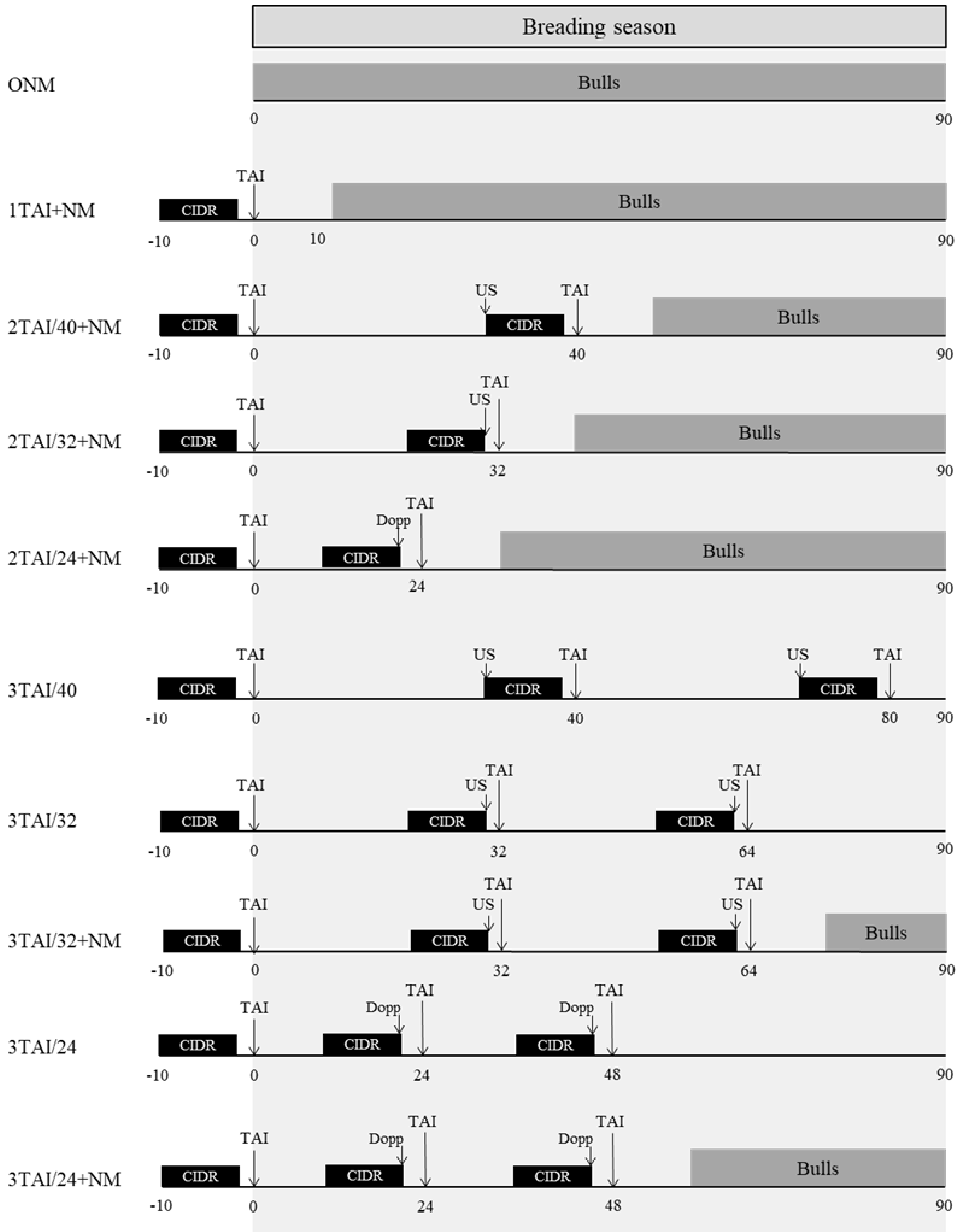
To analyze the moment when each cow was pregnant among the considered scenarios, the date of the pregnancy during the 10th year was collected to generate a survival plot.

3.3.8. Statistical analysis

Each scenario was replicated 32 times (32 iterations), and each replica consisted of a farm with 400 cows, with data collection represented by 1-day time intervals that spanned over a time horizon of 5,000 days. The data generated by the AnyLogic model were exported to a Microsoft Office Excel spreadsheet (Version 2010) for data organization.

The collected data were checked for normality and homogeneity of variance using the Shapiro–Wilk test and Bartlett and Levene's test, respectively. Transformations were used when the data were not normally distributed. In those cases, the transformed data were used to calculate *P*-values, and the corresponding mean ± standard deviation (S.D.) of the non-transformed data are presented in the results for clarity. Data were analyzed using ANOVA and post hoc Tukey HSD tests. All analyses were carried out using the R programming language version 3.6.1 (R Core Team, 2019). Values of $P < 0.05$ were considered statistically significant.

Figure 2 Reproductive management for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).



Source: Ojeda-Rojas (2020)

To compare the differences among scenarios for the time to pregnancy, SURVFIT and SURVDIFF functions, implemented in R, were used. The graphics were developed using the Tableau® software (Version 10.5) and R.

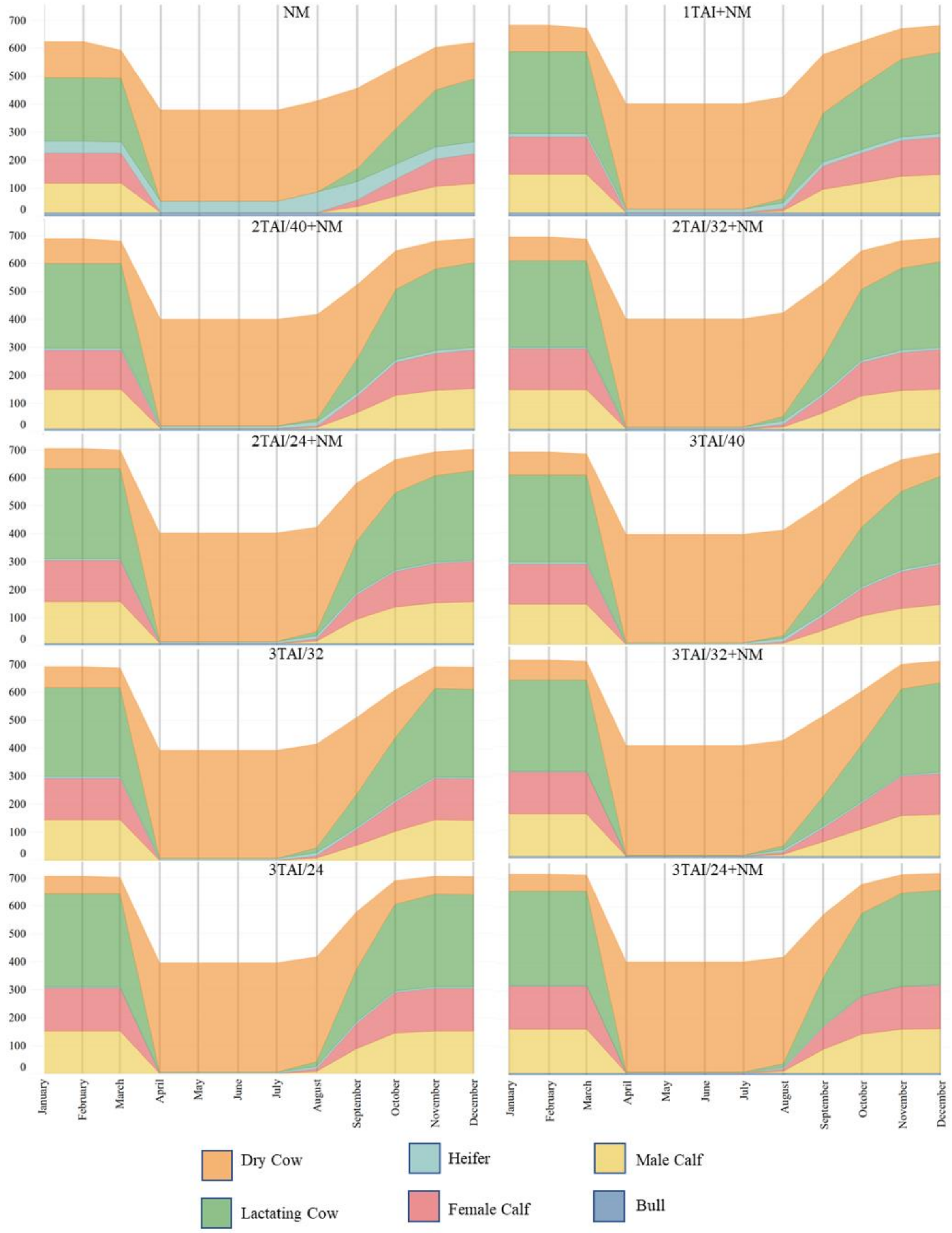
3.4. RESULTS

3.4.1. Herd structure

The herd structure for each scenario over the sixth year of simulation (Figure 3) shows how animals pass from one category to another as time passes and how the different scenarios affect the population dynamics of the herd. For example, in February/2024, it is notable how the relationship between calved cows and the total number of breeding adult females was different among scenarios. There were four scenarios (2TAI/24+NM, 3TAI/32+NM, 3TAI/24, and 3TAI/24+NM) in which 80% of the breeding adult females correspond to calved cows. The 3TAI/24+NM scenario had the greatest value (84.30% of calved cows), while the ONM scenario had the lowest value (57.00% of calved cows). On March/2024, 1 month before weaning, substantial differences in the total number of calves between the different scenarios were observed. While the ONM scenario had 212 calves, the 3TAI/24+NM scenario had 309 animals in the same category.

Starting on April/2024 and for the following 2 months, the herd was partitioned into dry cows and heifers. At this point, the number of heifers for each scenario also had a relevant difference. As the reproductive program became more intense, the number of heifers decreased as a consequence of the low demand for replacement heifers, which, in turn, was derived from the reduction of the culling of females due to reproductive problems. Then, on August/2024, the calving season started, and gradually, the females passed to the calved cow category.

Figure 3 Cattle herd structure through the 6th year of simulation for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).



Source: Ojeda-Rojas (2020)

Table 2 Technical results for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days)[1]

	Scenario[2]									
Item[3]	ONM	1TAI+NM	2TAI/40+NM	2TAI/32+NM	2TAI/24+NM	3TAI/40	3TAI/32	3TAI/32+NM	3TAI/24	3TAI/24+NM
TB	207.74 (2.22) ^{h}	259.96 (2.12) ^{g}	268.44 (1.73) ^{f}	271.85 (2.13) ^{e}	279.90 (2.16) ^{c}	275.38 (2.61) ^{d}	278.89 (1.55) ^{c}	284.81 (2.06) ^{b}	286.06 (2.16) ^{b}	293.90 (2.12) ^{a}
MC	102.10 (2.53) ^{g}	126.76 (2.46) ^{f}	130.65 (3.72) ^{e}	132.58 (2.07) ^{de}	137.39 (2.79) ^{c}	133.51 (3.19) ^{d}	134.47 (2.65) ^{d}	138.35 (3.59) ^{bc}	139.88 (2.92) ^{b}	143.91 (2.61) ^{a}
MW	166.59 (0.93) ^{i}	186.52 (0.81) ^{d}	182.28 (1.09) ^{f}	184.78 (0.85) ^{e}	188.94 (0.87) ^{b}	176.52 (1.16) ^{h}	182.83 (0.78) ^{f}	179.90 (1.24) ^{g}	190.58 (0.77) ^{a}	187.41 (0.83) ^{c}
FC	101.79 (2.25) ^{g}	127.04 (2.48) ^{f}	131.07 (3.98) ^{e}	132.45 (1.92) ^{de}	136.52 (3.21) ^{c}	134.43 (2.71) ^{cd}	135.91 (2.84) ^{c}	139.08 (3.00) ^{b}	140.20 (1.90) ^{b}	143.31 (2.88) ^{a}
FW	151.65 (0.74) ^{h}	170.22 (0.95) ^{c}	166.03 (0.70) ^{e}	168.19 (1.11) ^{d}	172.37 (1.02) ^{b}	160.95 (1.02) ^{g}	166.54 (0.94) ^{e}	163.80 (0.86) ^{f}	173.67 (0.86) ^{a}	170.59 (0.66) ^{c}
HPR	0.72 (0.02) ^{e}	0.90 (0.03) ^{d}	0.91 (0.03) ^{cd}	0.91 (0.03) ^{cd}	0.93 (0.02) ^{bc}	0.92 (0.03) ^{cd}	0.92 (0.04) ^{cd}	0.95 (0.03) ^{ab}	0.92 (0.04) ^{cd}	0.97 (0.03) ^{a}
CPR	0.49 (0.01) ^{i}	0.72 (0.01) ^{h}	0.76 (0.01) ^{g}	0.78 (0.01) ^{f}	0.82 (0.01) ^{d}	0.79 (0.01) ^{e}	0.80 (0.02) ^{e}	0.83 (0.01) ^{c}	0.85 (0.01) ^{b}	0.88 (0.01) ^{a}
DPR	0.77 (0.01) ^{f}	0.89 (0.01) ^{e}	0.90 (0.01) ^{d}	0.92 (0.01) ^{c}	0.93 (0.01) ^{b}	0.92 (0.01) ^{bc}	0.92 (0.01) ^{bc}	0.95 (0.01) ^{a}	0.93 (0.01) ^{bc}	0.96 (0.01) ^{a}

Source: Ojeda-Rojas (2020)

Table 2 Technical results for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days)[1] (Continued)

	Scenario[2]									
Item[3]	ONM	1TAI+NM	2TAI/40+NM	2TAI/32+NM	2TAI/24+NM	3TAI/40	3TAI/32	3TAI/32+NM	3TAI/24	3TAI/24+NM
TPR	0.61	0.79	0.82	0.83	0.86	0.84	0.85	0.87	0.88	0.90
	(0.01) ^{i}	(0.01) ^{h}	(0.01) ^{g}	(0.01) ^{f}	(0.00) ^{c}	(0.01) ^{e}	(0.01) ^{d}	(0.01) ^{b}	(0.01) ^{b}	(0.00) ^{a}
CC	2.31	3.84	4.09	4.18	4.29	4.26	4.33	4.57	4.42	4.70
	(0.15) ^{h}	(0.14) ^{g}	(0.11) ^{f}	(0.14) ^{ef}	(0.17) ^{d}	(0.13) ^{de}	(0.12) ^{cd}	(0.13) ^{b}	(0.13) ^{c}	(0.15) ^{a}
AC	2655.74	3168.92	3222.72	3253.23	3257.77	3260.53	3275.17	3333.69	3275.55	3348.45
	(41.67) ^{e}	(49.65) ^{d}	(43.13) ^{c}	(58.35) ^{bc}	(68.67) ^{bc}	(49.01) ^{bc}	(54.16) ^{b}	(54.70) ^{a}	(52.18) ^{b}	(56.08) ^{a}
DO	212.53	158.38	147.29	143.99	131.96	138.14	136.66	128.21	123.82	115.26
	(31.71) ^{i}	(32.04) ^{h}	(31.64) ^{g}	(32.62) ^{f}	(30.95) ^{d}	(31.91) ^{e}	(33.20) ^{e}	(31.52) ^{c}	(32.99) ^{b}	(32.18) ^{a}

Source: Ojeda-Rojas (2020)

[2] ONM = Natural mating; 1TAI+NM = one TAI plus NM; 2TAI/40+NM = two TAI, with 40 days of interval between TAI plus NM; 2TAI/32+NM = two TAI, with 32 days of interval between TAI plus NM; 2TAI/24+NM = two TAI, with 24 days of interval between TAI plus NM; 3TAI/40 = three TAI, with 40 days of interval between TAI; 3TAI/32 = three TAI, with 32 days of interval between TAI; 3TAI/32+NM = three TAI, with 32 days of interval between TAI plus NM; 3TAI/24 = three TAI, with 24 days of interval between TAI; 3TAI/24+NM = three TAI, with 24 days of interval between TAI plus NM. NM started 10 days after the last TAI until the end of the breeding season.
[3] TB = Total births; MC = Number of male calves weaned per year; MW = Weaning weight for males; FC = Number of female calves weaned per year; FW = Weaning weight for females; HPR = Pregnancy rate for heifers; CPR = Pregnancy rate for calved cows; DPR = Pregnancy rate for dry cows; TPR = Total pregnancy rate of the herd; and CC = Calving counter at sale; and AC = Age of the cows at culling in days.
$^{(a,b,c,d,e,f,g,h,i)}$ Means in the same row with different lowercase superscript letters are significantly different ($P < 0.05$).

3.4.2. Effect of the scenario on productive parameters

The scenario with the lowest ($P < 0.05$) amount of births was ONM (Table 2). There was no difference in the total births per year between the scenarios 3TAI/32+NM and 3TAI/24. Both scenarios had a smaller ($P < 0.05$) number of calves born than the 3TAI/24+NM scenario, which, in turn, was the scenario with the greatest number of births in this simulation. Also, no difference was observed between the 2TAI/24+NM and 3TAI/32 scenarios. Nonetheless, the number of calves born in these last two scenarios was lower than that in the 3TAI/32+NM scenario.

Similarly, the scenario that weaned a greater ($P < 0.05$) amount of male calves per year was the 3TAI/24+NM. There was no difference in the number of male calves weaned produced by 3TAI/24 and 3TAI/32+NM. The latter was no different from 2TAI/24+NM. Also, the number of male weaned calves produced by 3TAI/32, 3TAI/40, and 2TAI/32+NM was not statistically different; however, the number of male calves weaned produced by the 2TAI/40+NM scenario was not different from 2TAI32+NM, but it was inferior to those of the 3TAI/40 and 3TAI/32 scenarios. Finally, the 1TAI+NM and ONM scenarios produced the lower number of male calves weaned, with statistical differences between them. When analyzing the average weaning weight of the males, all scenarios were statistically different ($P < 0.05$), except the 3TAI/32 and 2TAI/40+NM scenarios, which had a similar performance. The heaviest and lightest males at weaning belonged to the 3TAI/24 and the ONM scenarios (Table 2).

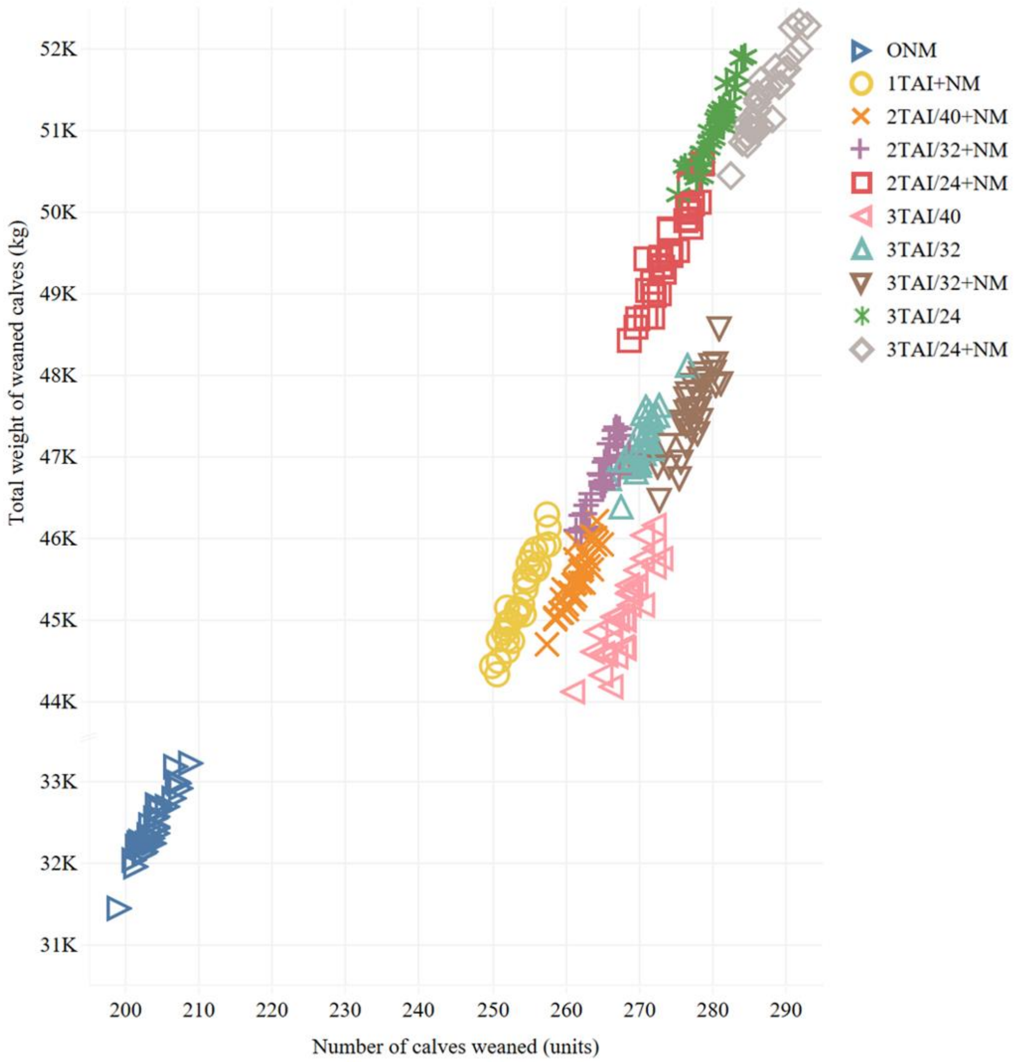
A greater number ($P < 0.05$) of females was weaned in the 3TAI/24+NM scenario. There were no differences between the 3TAI/24 and 3TAI/32+NM scenarios. The number of female weaned calves produced by 2TAI/24+NM, 3TAI/32, and 3TAI/40 was not statistically different. The latter had a performance similar to that of 2TAI/32+NM, but inferior to the performances of 2TAI/24+NM and 3TAI/32. In the same way, 2TAI/40+NM was not statistically different from 2TAI/32+NM (Table 2). The 1TAI+NM scenario weaned less ($P < 0.05$) females than the 2TAI/40+NM scenario. Finally, with only 101.79 ± 2.25 female calves weaned on average per year, the ONM scenario had the lowest ($P < 0.05$) production.

Regarding the weaning weight of females, the 3TAI/24 scenario had the heaviest ($P < 0.05$) females, followed by 2TAI/24+NM. The 3TAI/24+NM and 1TAI+NM scenarios were not different, but both produced lighter female calves than 2TAI/24+NM (*P* < 0.05). The weaning weight of the females produced by 2TAI/32+NM was lower (*P* < 0.05) than that of 1TAI+NM, but greater (*P* < 0.05) than those of 3TAI/32 and 2TAI/40+NM. The latter two had a superior performance than 3TAI/32+NM; at the same time, 3TAI/32+NM produced heavier female calves than 3TAI/40. The females produced in the ONM scenario had a lower (*P* < 0.05) performance (Table 2).

Regarding the total weaning weight, the farms were divided into three groups of high, medium, and low production. The high production group (> 48,500 kg per year) was conformed by scenarios that include early pregnancy diagnosis and, thus, 24 days of interval between TAI (3TAI/24+NM, 3TAI/24, and 2TAI/24+NM). The second group contained farms with productions between 44,000 and 48,500 kg per year. The scenarios allocated in this intermediate group were 3TAI/32+NM, 3TAI/32, 2TAI/32+NM, 3TAI/40, 2TAI/40+NM, and 1TAI+NM. The last group, with productions between 31,000 and 44,000 kg, only contained the 32 farms (replicas) of the ONM scenario (Figure 4). Regarding the total number of weaned animals, the different farms could be partitioned into two main groups. All farms of the ONM scenario could be allocated to the first group, with less than 210 calves produced per year. On the other hand, the farms of the other nine scenarios, which used TAI, could be allocated to a second group producing 250 to 295 calves per year, with the farms of the 1TAI+NM scenario at the lower level and those of the 3TAI/24+NM scenario at the upper level.

The reproductive strategy influenced the calving distribution and the monthly proportion of the total calves born for each scenario (Figure 5). In the model, the BS started on November 15; therefore, the first births occurred in August, and the calving season finished in December. It is remarkable that in all the scenarios when TAI was included in the reproductive program, more than 40% of the births occurred during the first 45 days of the calving season, while in the ONM scenario, only 20% of the births happened during the same time-lapse. Additionally, in the scenarios that included early pregnancy diagnosis, with an interval of 24 days between TAI, more than 55% of the births happened in the first 45 days. Also, it is interesting to note that two scenarios (3TAI/24 and 3TAI/32) did not present any births in December.

Figure 4 Total weaning weight of calves and total number of calves weaned per year and for each farm for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).

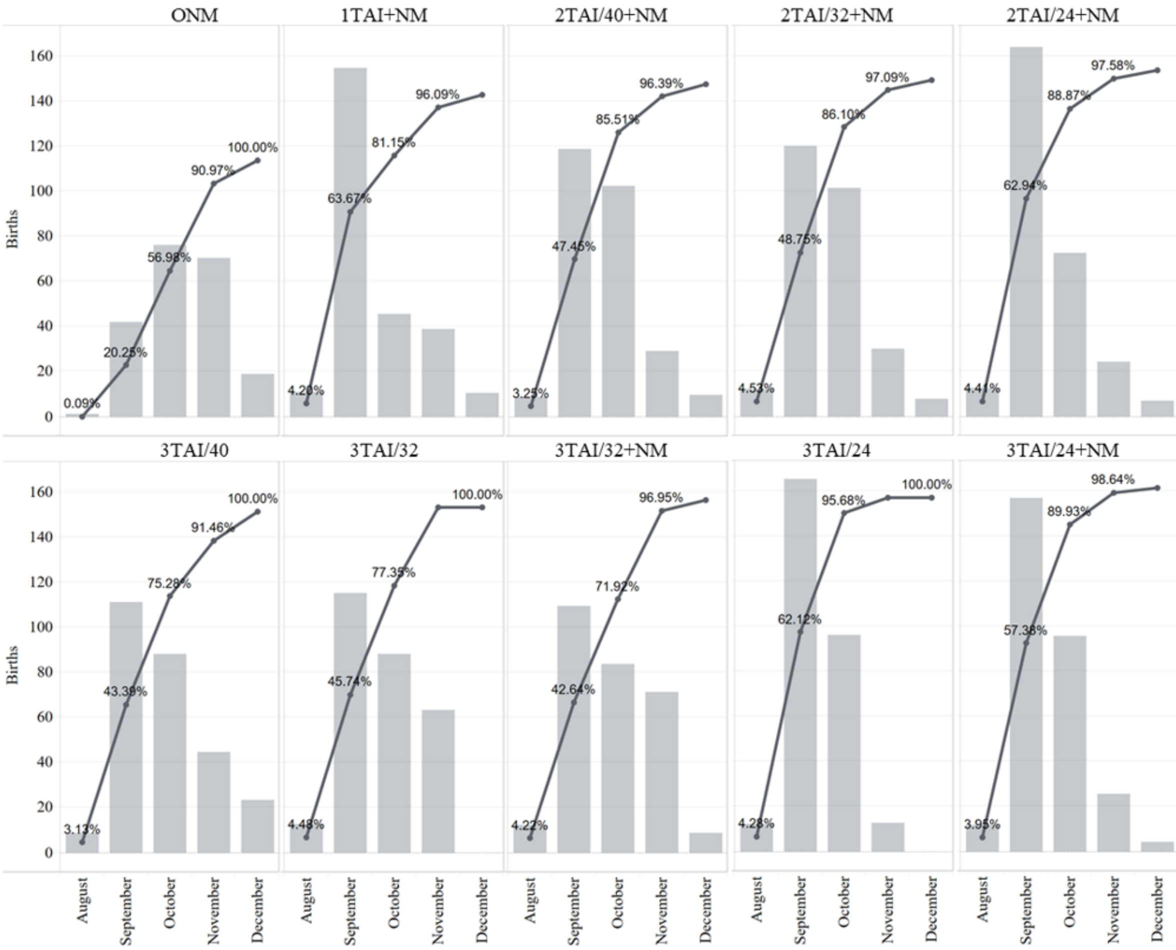


Source: Ojeda-Rojas (2020)

The scenarios with the greatest PR at the end of the BS of the heifers (HPR – Table 2) were 3TAI/24+NM and 3TAI/32+NM. The latter was not different when compared to 2TAI/24+NM, and this scenario was also not different when compared to 3TAI/24, 3TAI/32, 3TAI/40, 2TAI/32+NM, and 2TAI/40+NM. At the same time, 1TAI+NM was similar to the three scenarios using three TAI without NM and to the 2TAI/32+NM and 2TAI/40+NM scenarios, but had a greater PR for the heifers than the ONM scenario. The PR in calved cows (CPR – Table 2) was different ($P < 0.05$) in all scenarios, except for 3TAI/32 and 3TAI/40. The scenarios with the best and worst PR values were 3TAI/24+NM and ONM, respectively. In the dry cow category, the best PR value (DPR – Table 2) was founded for the 3TAI/24+NM and

3TAI/32+NM scenarios. Further, there was no difference between scenarios 2TAI/24+NM, 3TAI/24, 3TAI/32, and 3TAI/40; the latter three had a similar PR than the 2TAI/32+NM scenario. Finally, the inferior values of PR for dry cows were found for 2TAI/40+NM, 1TAI+NM, and ONM, which were statistically different.

Figure 5 Calving distribution per month and proportion of born animals for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).



Source: Ojeda-Rojas (2020)

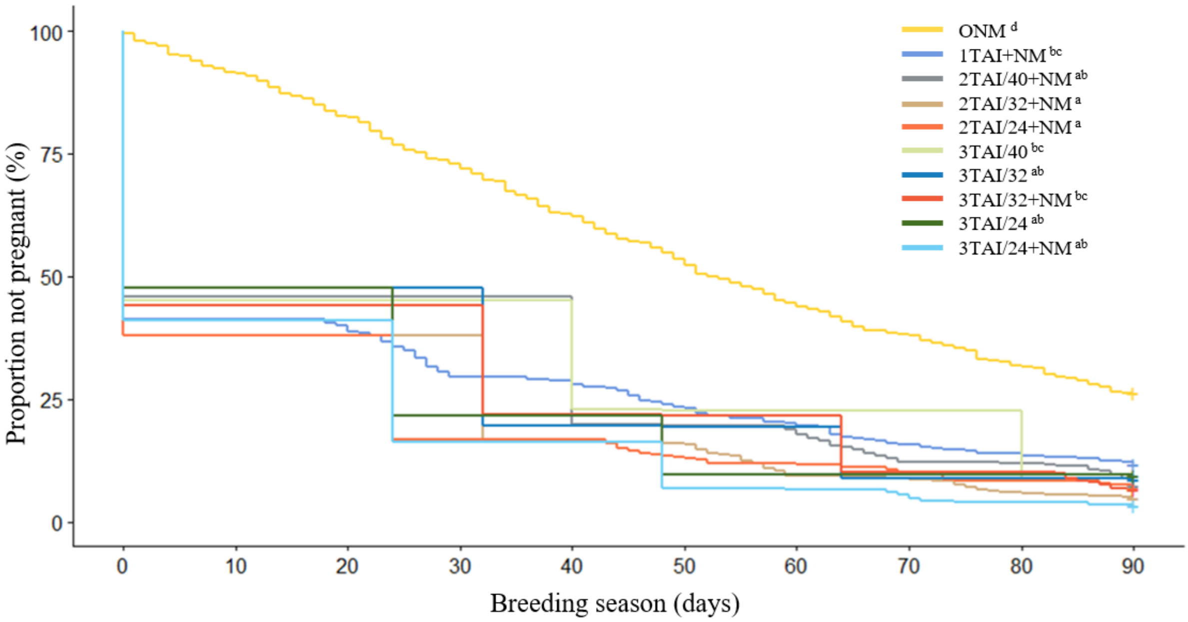
The total PR (TPR – Table 2) was different ($P < 0.05$) for all the scenarios analyzed, except for 3TAI/24 and 3TAI/32+NM. The scenario that had the best total PR was 3TAI/24+NM, while the lowest total PR was found for the ONM scenario.

The time to pregnancy was affected ($P < 0.05$) by scenario (Figure 6). The ONM scenario delayed ($P < 0.05$) the time to pregnancy compared to the other scenarios. The time to pregnancy was hastened in 2TAI/24+NM, 2TAI/32+NM, 3TAI/32, 3TAI/24, 3TAI/24+NM, and 2TAI/40+NM; the latter four scenarios were not statistically different from 1TAI+NM, 3TAI/40, and 3TAI/32+NM. The median time to pregnancy (median days to reach 50% of pregnancy) was 52.5 days shorter ($P < 0.05$) in cows belonging to the scenarios that included TAI within their reproductive strategy when compared to the ONM scenario. Most likely, this is because in all the scenarios that included TAI, the first AI happened on day zero of the BS. When analyzing the average open days (Table 2), our results showed that all the scenarios were statistically different ($P < 0.05$), except 3TAI/32 and 3TAI/40. The scenario with the lowest number of open days was 3TAI24/NM, while that with the greatest number was ONM.

The calving counter (CC - Table 2) was defined as the number of births that a cull cow had when it was sold. The scenarios where cows were sold with a greater number of births were 3TAI/24+NM, 3TAI/32+NM, and 3TAI/24, which were statistically different from each other (Table 2). The latter was not different when compared to 3TAI/32, which, in turn, presented similar results than 2TAI/24+NM and 3TAI/40. Again, 3TAI/40 was not different from 2TAI/32+NM, but it was superior to 2TAI/40+NM. However, the number of births when cows were sold did not differ between 2TAI/32+NM and 2TAI/40+NM. Finally, the lowest numbers of births when cows were sold were registered for the scenarios 1TAI+NM and ONM, which, at the same time, were statistically different ($P < 0.05$; Table 2).

Finally, the average age of the cows at culling (AC – Table 2) showed that programs with three TAI presented the older cows at culling, followed by scenarios that included two TAI and one TAI. In this way, 3TAI/24+NM and 3TAI/32+NM presented better results. Next, 3TAI/24, 3TAI/32, 3TAI/40, 2TAI/24+NM, and 2TAI/32+NM presented similar ages at culling; the latter three were not different from 2TAI/40+NM. Cows were culled younger in the 1TAI+NM and ONM, which were statistically different from each other.

Figure 6 Survival curves for proportion of nonpregnant cows by days of breeding season for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days). Survival curves without a common superscript letter differed (P < 0.05).



Source: Ojeda-Rojas (2020)

3.5. DISCUSSION

An agent-based simulation model was created to compare the technical performance of different reproductive strategies in a beef cattle operation. Stochastic models can better represent the risk and uncertainty associated with a decision-making process than deterministic approaches (Shafer et al., 2007). In addition, agent-based models are a suitable and natural approach to describe a system composed of "behavioral" agents (Bazghandi, 2012). Expressly, in agent-based simulation models, a collection of agents, programmed to follow rules of behavior, represents a complex system. Agents are designed to mimic the behavior of something in the real world; in our case, the agents were cows and bulls that interacted among each other and, throughout their lives, moved to different states. Because of the complexity of our simulation, which combined agent-based simulation and stochastic and deterministic parameters, we used the AnyLogic software.

The results of the experiments conducted in the present study allow us to obtain important insights on how the dynamics of the herd drastically changed depending on the reproductive technology that was used. The use of insemination increases the number of calves produced per year and their weaning weight. The present study showed that scenarios that used TAI protocols produced more and heavier calves when compared to the ONM scenario. This result is in accordance with several *in vivo* experiments that show that TAI increases the productivity of the herd (Baruselli et al., 2018; Pessoa et al., 2018). This fact is mainly mediated by three factors: 1) TAI allows to use semen from better bulls. 2) The use of a hormonal protocol allows cows that are not cycling at the beginning of the breeding season to be served at day zero of the BS, so the service rate is 100% when TAI was used. 3) The scenarios using TAI result in a concentration of the pregnancies in the first 30 days of the BS and, subsequently, the concentrations of the births in the first 30 days of the calving season. Moreover, we highlight that in the present study, we did not take into consideration the genetic gain due to the use of AI, which means that the birth weight and the average daily gain were the same in calves originated by NM or AI in our study. In this sense, the genetic gain from AI could have increased the average weight of calves at weaning in a dependent manner according to the use of one TAI or two or three TAI, although the model shows that only the concentrations of the births at the beginning of the calving season have a tremendous impact on the productivity of the farm.

The use of TAI increased the number of calves and, as more TAI were used, the number of calves produced gradually increased. Thus, scenarios with one TAI, two TAI, and three TAI produced, on average, 50, 65, and 75 more calves per year than the ONM scenario. Dill et al. (2015), using a multivariate analysis, evaluated the adoption of different types of technologies and their impacts on weaning weight in cattle operations. To this aim, the farms were classified into high, intermediate, and low weaning weights. Subsequently, the adoption of 48 technologies (including forages, feed supplementation, reproductive technologies, genetics, and health) was evaluated. The authors showed that the use of TAI is one of the seven technologies that most differ among the farms and that the use of TAI improves the weaning rate.

In the same way, the use of TAI increased the weaning weights. In the present study, scenarios that involved the use of TAI produced, on average, calves weighing 17 kg more than the ONM scenario, ranging from 9 to 23 kg for 3TAI/40 and 3TAI/24, respectively. Similar results are presented by Rodgers et al. (2012), who conducted a study in several herds in the United States comparing the use of TAI with NM. Their study showed that the distribution of births was affected by the treatment, because animals submitted to TAI had a shorter calving season. Consequently, weaning weights of calves originated from TAI treatments were greater (193.4 kg) when compared to calves from NM (175.9 kg). Also, Cutaia et al. (2003), after analyzing 1,935 births, showed that calves from TAI weighted ~34.5 kg more than the ones originating from NM. Funston et al. (2012) conducted a retrospective analysis to evaluate the calving distribution (n = 1,019 calves) and its effect on herd performance. They divided the calving season into three periods of 21 days each and showed that calves born in the first period were ~ 6 kg heavier than those born in the second period and ~ 22 kg heavier than those born in the third and last period.

Scenarios that involved the use of TAI showed a better reproductive performance than the ONM scenario. This scenario resulted in 61% of PR, a result that may seem low; however, similar results have been presented in other *in vivo* studies. For example, Pessoa et al. (2018) found 45.1% of PR in suckled cows and Ferreira et al. (2018) 61% in first-calf heifers. This shows that, in the NM programs performed in beef herds and in extensive systems under native or poor-quality forage in Brazil, do not have an excellent reproductive performance. For this reason, the use of programs involving TAI, which helps to restore postpartum cyclicity, allows greater service rates and, consequently, a better reproductive performance. Also, in the present simulation, the use of one TAI or two and three TAI increased the average total PR to 78.78, 83.47, and 86.82%, respectively. Pessoa et al. (2018) reported PR values of 71.0% for one TAI and 83.7 and 81.5% for two TAI with 40 and 32 days between AIs, respectively. Also, in Nelore suckled cows, Sa Filho et al. (2013) reported PR values of 83.2 and 92.7% for NM and one TAI and subsequent NM. Likewise, Crepaldi et al. (2017) evaluated the final PR after using resynchronization programs with 32 days between TAI. They reported values of 77.1, 87.7, and 87.8% for one TAI with NM, two TAI with NM, and three TAI, respectively. Similarly, Arantes et al. (2019) obtained a PR of 80.92% after submitting Nelore cows and heifers to three TAI in 48 days. In this case, the results for the first, second, and third TAI were 51.03, 40.69, and 43.45%, respectively.

The present simulation model proves the importance of using clean-up bulls after the TAI protocols. In the scenarios that included three TAI + NM when compared to those that only used three TAI, the number of weaned calves, weaning weights, total PRs, calving counters at sale, and the age of the cows at culling were greater. This indicates that females that were not pregnant by the three TAI services could have the chance to be pregnant by the bulls, and this has an impact on the productivity of the herd. However, the model does not calculate the cost of the bulls, and therefore, a new study that compares the economic performance of the scenarios evaluated here will be essential in order to support the decision-making process. Also, the length of the BS can be reduced when three TAI without clean-up bulls are used.

The present simulation model compares the use of three resynchronization strategies, with 24, 32, and 40 days between TAI. Again, the use of 24 days was the most productive program when evaluating the number of calves produced and the weaning weight. When using shorter TAI intervals, the time to pregnancy was diminished. In the present study, the proportion of pregnant cows in the first 30 days of the BS for the three programs that involved early pregnancy diagnosis was ~80%. In contrast, in programs that used intervals of 32 or 40 days, the proportion of pregnant cows in the first 30 days of the BS was ~55%. Similar results have been presented by Pugliesi et al. (2019), who compared the efficiency of two resynchronization protocols using two TAI with an interval of 22 days. The cumulative PR at 30 days of gestation in that study was 74.65%. Also, Penteado et al. (2016) reported cumulative PR values of 75 and 77% for programs using 24 and 32 days of interval between AI, respectively. In summary, the use of early pregnancy diagnosis increased the proportion of pregnant cows in the first 30 days of the BS. However, this is performed by using Doppler imaging around 20 to 22 days after the first TAI, and in this study, we did not estimate the cost of using this technology. For this reason, new studies that evaluate the involved trade-offs are required.

In summary, the present study demonstrates the utility of agent-based simulation models within the scope of cow-calf production systems. Because it is a virtual environment, it was possible to simulate 10 different scenarios, something which would be almost impossible in real life, considering the large number of animals needed and the high costs involved. Enabling the study and the analysis of different technological combinations without altering the real world is one of the most significant contributions of the simulation models. Regarding the experiment conducted, we conclude that, as the use of technology increases, the productivity of the herd also increases. Thus, scenarios where novel and more advanced technologies were used (two or three TAI, early diagnosis of pregnancy) seem to be those that presented better reproductive performance and produced more and heavier calves. A new study is necessary to evaluate not only the technical performance of the herd, but also the economic and financial viability of each of the scenarios evaluated.

Conflict of interest statement. No conflicting or professional interests exist for these authors.

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4. CHAPTER 1: An agent-based simulation model to compare different reproductive strategies in beef cattle operations: Economic performance

4.1. ABSTRACT

The development of a stochastic, agent-based simulation model of cow-calf production was described in a companion paper. The present study aimed at assessing the economic outcome of 10 different reproductive management. The scenarios evaluated were natural mating (NM) only (ONM); one timed artificial insemination (TAI) plus NM (1TAI+NM); two TAI plus NM, with 24, 32, and 40 days between inseminations (2TAI/24+NM, 2TAI/32+NM, and 2TAI/40+NM, respectively); three TAI without NM, with 24, 32, and 40 days between inseminations (3TAI/24, 3TAI/32, and 3TAI/40, respectively), and three TAI plus NM, with an interval between inseminations of 24 (3TAI/24+NM) and 32 days (3TAI/32+NM). Each scenario was composed of 32 farms (replicas), analyzed daily that spanned over a time horizon of 5000 days. Model outcomes suggested that the 3TAI/24+NM scenario (US$ 96,479.19 ± 709.81) resulted in higher incomes, while ONM (US$ 79,753.37 ± 741.87) had the lowest incomes from this study. The 3TAI/24+NM (US$ 101.720.6 ± 79.21) and ONM (US$ 90.898.58 ± 59.17) scenario presented the highest and lowest total operating costs (TOC), respectively. The scenario with the highest total cost (TC) was 3TAI/24+NM (US$176,946.8 ± 81.65) and the ONM scenario had the lowest value within this cost item, with US$ 166,358.6 ± 57.35. However, when TOC was evaluated per kg of weaned calf, the highest and lowest costs were for ONM (US$ 2.8 ± 0.03/kg) and 2TAI/24+NM (US$ 2.17 ± 0, 04/kg), respectively. Regarding to TC/kg, ONM (US$ 5.12 ± 0.06) had the highest cost; the lowest value was for 2TAI/24+NM (US$ 3.82 ± 0.07) that had no statistical deference with 3TAI/32+NM, 3TAI/24, and 3TAI/24+NM. The 2TAI/24+NM (US$ -4,651.28 ± 630.72) scenario presented the best net margin, while the lowest result was for 3TAI/40 (US$ -12,590.04 ± 746.27). About profit, the 2TAI/24+NM scenario obtained the best result with US$ -79,867.17 ± 631.13, and the lowest profit was to 3TAI/40, with a value of US$ -87,239.1 ± 744.33. Our model suggests that reproductive strategies that use TAI have better economic performance than those under NM. However, when three TAI were performed with an interval of 40 days, the benefit was lower, and even for some analyzes, it was worse than the ONM. Combining TAI with early pregnancy diagnosis resulted in better economic performance compared to other TAI programs and with

NM. The 2TAI/24+NM scenario outperformed the others because of the contrast between its high income with moderate costs.

4.2. INTRODUCTION

Pasture-based tropical beef cattle operations are generally characterized as low-productivity enterprises and when compared to other agricultural activities has significant limitations, such as lack of well-defined production plan, a more significant mobilization of resources, and more extended periods for the return of invested capital (CORSI; MARTHA JR; NASCIMENTO JR; BALSALOBRE, 2001). All of these restrict the diffusion and adoption of technologies in the cow-calf operations, jeopardizing the survival of the farms, and discouraging the new investors (DILL et al., 2015). The above can be argued for the inefficiency of many parts of the production system, including reproduction, nutrition, health, and management (DILL et al., 2015).

Of these four potential causes of inefficiency, reproduction has received significant attention in cow-calf enterprises partly due to its role in the number of calves produced, the distribution of births throughout the year, and the age and weight at weaning of calves. Reproductive strategies within farm management are a way to improve the economic performance of the farm (BARUSELLI et al., 2018). Among these strategies, artificial insemination (AI) has the potential to accelerate genetic gain, improve farm planning, and reduce the risks associated with natural mating (NM) (LIMA et al., 2010; VISHWANATH, 2003). Furthermore, AI allows the use of breeds (especially *Bos taurus* breeds) that otherwise would not be possible to use due to the climatic and sanitary conditions in tropical countries like Brazil (BÓ et al., 2007). However, mainly due to the challenges arising from estrus detection, in some important countries of the global beef industry, such as the United States, Argentina, and Brazil the percentage of females that are artificially inseminated is very low (~ 5% to 12%) (BARUSELLI et al., 2018; VISHWANATH, 2003).

Advances of research in reproduction physiology allowed to avoid the estrus detection, to take advantage of AI and to increase its use through hormonal treatments, commonly called timed artificial insemination (TAI) (BARUSELLI et al., 2017; BÓ; BARUSELLI; MAPLETOFT, 2013; BÓ et al., 2016; LAMB et al., 2001). Today the producers have a wide range of possibilities related to the number of TAI, the time interval between them (resynchronization) (CAVALIERI et al., 2007; COLAZO et al., 2006), and different techniques for the early diagnosis of pregnancy (GREEN et al., 2010; PUGLIESI et al., 2014). Nonetheless, as in all decision-making processes, the implementation of a TAI program presents some trade-offs, mainly related to economic and cultural aspects, and this needs a particular analysis.

Implementation analysis of any reproductive strategy go beyond the investments. As described by Leblanc (2007), a reproductive strategy, whether successful or not, modifies the dynamics of the herd, altering the culling and replacement rates, among many other characteristics, generating losses or benefits, which may be higher than the costs of implementing the technique.

No research to date has evaluated the economic effects of reproductive programs that use NM only, TAI only, early pregnancy diagnosis, or different combinations of those. This a significant gap that contributes to the difficulty of the decision-making process. Therefore, the aim of this study was evaluating the effect of using NM only, TAI only, or different combinations of both TAI+NM, including the number of TAI (one, two, or three TAI) and the time interval between them (24, 32, and 40 days) on the economic performance of Cow-calf operations.

4.3. MATERIAL AND METHODS

4.3.1. Overview

The companion study (Ojeda-Rojas et al., 2019) describes an agent-based simulation model that analyses the effects on the technical performance of the implementation of reproductive strategies that include NM, TAI, and early pregnancy diagnosis. For details in the description of the model, model implementation, and technical results, please see Ojeda et al. 2019.

4.3.2. Model description

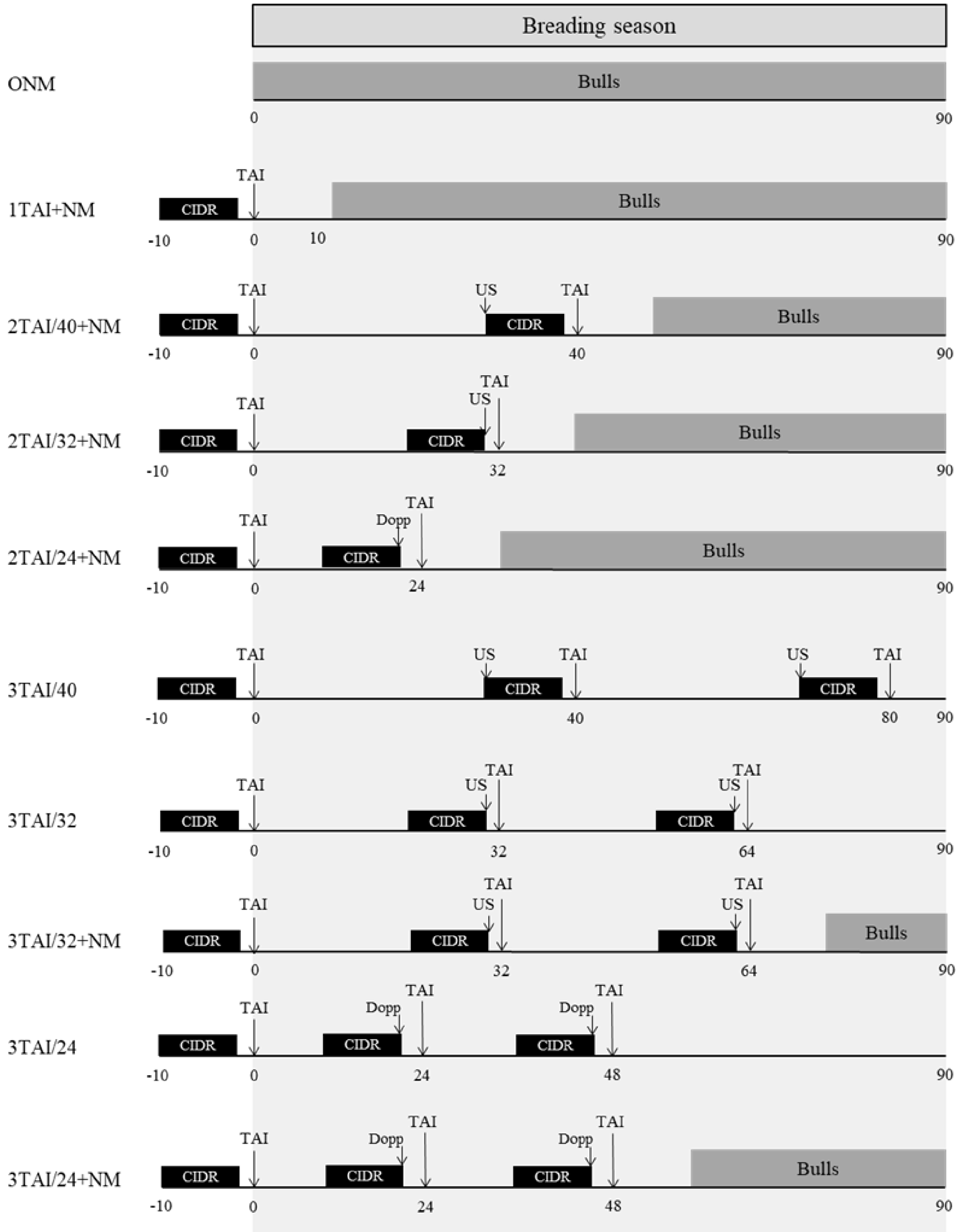
The agent-based stochastic simulation model was the same described in the first paper of this series. Briefly, the model was constructed using AnyLogic simulation software, University 7.1.2 (XJ Technologies). It was considered stochastic since the occurrence of some events were decided based on random variables taken from probability distributions. These distributions were generated from the database of the Instituto de Zootecnia, Beef Cattle Research Center (IZ), Sertãozinho, SP, Brazil, and data available from the specialized scientific literature. Full details about parameterization, population structure, culling, and replacement have been presented by Ojeda-Rojas et al., 2019. In the model, the initial population consisted of 400 heifers and 0, 7, or 15 bulls, depending on the proposed scenario. Therefore, the initial population of the model was in a range between 400 and 415 agents. This number of animals was in agreement with the size (500 ha) and the stocking rate (0.8 animal unit [AU] [450 kg BW]/ha) of the simulated farm because some calculations are tied to the size of the farm. An open population was modeled, having inputs (i.e., births and purchases) and outputs (i.e., deaths and sales).

4.3.3. Experimental design

In the present study, the simulation model was used to generate an experiment to evaluate the effect of 10 different reproductive management programs (scenarios) with two breeding methods used independently or in combination (NM or TAI), the number of inseminations performed (1, 2 or 3 TAI), and the time interval between inseminations (24, 32 or 40 days) on the economic performance of the beef herds.

The scenarios generated were: A scenario using only NM (**ONM**); a scenario using one TAI plus NM (**1TAI+NM**); three scenarios using two TAI plus NM, with an interval between inseminations of 24 (**2TAI/24+NM**), 32 (**2TAI/32+NM**), and 40 days (**2TAI/40+NM**); three scenarios using three TAI without NM, with an interval between inseminations of 24 (**3TAI/24**), 32 (**3TAI/32**), and 40 days (**3TAI/40**); Lastly, two scenarios with three TAI plus NM, with an interval between inseminations of 24 (**3TAI/24+NM**) and 32 days (**3TAI/32+NM**) (Figure 7).

Figure 7 Reproductive management for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).



Source: Ojeda-Rojas (2020)

The results of each scenario were replicated 32 times. Each replica consisted of a farm with 400 cows with data collection represented by one-day time intervals that spanned over a time horizon of 5000 days. The data generated by the AnyLogic model were exported to a

Microsoft® Office Excel® spreadsheet (Version 2010) for data organization. The experiment was conducted using the graphical user interface (GUI) of the University of Florida's HiPerGator supercomputer. An average of 96 hours was required to run the simulations for each combination using a CPU with 16 cores and 32GB of memory.

4.3.4. Economic analysis

All the input and outputs prices, except price per kg of male calves, were average prices corresponding for the year 2018, deflated according to the General Price Index "Internal Availability" (IGP-DI), calculated by the Getúlio Vargas Foundation (FGV) and adjusted for the effect of inflation for June 2019. The description of the items was summarized in Table 3. These values were kept constant over time.

The American dollar (US$) was considered as the monetary unit, and for 2018 period, the average exchange rate was US$ 1.00 = R$ 3.66 (Brazilian Reais; source: Central Bank of Brazil).

4.3.4.1. Incomes

This item was calculated annually. The primary source of income came from the sale of females and males at weaning. The value of the income was calculated by multiplying calves' body weight (kg) at the time of sale (weaning) by the price per kg. The price per kg was different for females and males. For females, $ 1.50 per kg was considered. For males, $ 1.64 per kg. The latter was calculated from the daily time series of the Live Cattle Indicator Bovespa/BM&F (CEPEA/USP, 2018), 2019), from January 2, 2004, to June 4, 2019. The nominal prices were deflated by the General Price Index - Internal Availability (IGP-DI), of Fundação Getulio Vargas, and converted into real values to June 2019 (FGV, 2019).

On the other hand, adult animals sold were marketed per animal (unit). Thus, heifers culled by reproductive performance, cows culled by age, cows culled by reproductive problems, and bulls culled were also considered as income.

4.3.4.2. Costs

Based on the description reported by Matsunaga et al. (1976), the annual production costs were structured and divided into items that allowed to calculate the Effective operating cost (EOC), Total operating cost (TOC), and Total Cost (TC).

Table 3 Prices of the outputs used to calculate the incomes in the simulation model

Item	Value	Unit
Weaned male	1.64	US$/kg
Weaned female	1.50	US$/kg
Heifer	377.50	US$/Animal
Old cow culled	339.21	US$/Animal
Open cow culled	701.94	US$/Animal
Bull culled	797.41	US$/Animal

Source: Ojeda-Rojas (2020)

The EOC consists of all variable expenses plus some fixed costs, such as labor, assumed by the farm annually, and represents a cash outlay. The EOC involves all cost components generated by the relationship between the amount of supplies or services used and their prices, such as farm animal health plan (vaccines and anthelmintics), mineral supplementation, bull breeding soundness evaluation, semen and hormonal protocols for TAI, technical assistance, labor, forage maintenance, livestock pharmacy, machine maintenance, and utilities.

The animal health plan activities considered in the model were: Both male and female calves receive one mL of Ivermectin at birth. Then, at three months of age, males and females' calves are vaccinated and revaccinated, 21 days later, against diseases caused by Clostridium bacteria. Additionally, between 3 and 8 months, the females receive the vaccine to prevent brucellosis. All calves, male and female, receive a dose of vermifuge, 7 mL of Levamisole, on the day of weaning. Pregnant females receive a dose of vaccine against Clostridiosis before delivery. At the time of delivery, each cow receives a vermifuge (10 mL of Levamisole). Similarly, bulls receive a vermifuge, 10 mL of Levamisole, at the end of the breeding season. Finally, on two occasions a year (November and May), all animals older than one month receive a vaccine to prevent Foot-and-mouth disease. Prices of the products used in the animal health plan are presented in Table 4.

The consumption of mineral supplement was established as 0.03 kg of supplement for each 100 kg of live weight. The amount consumed was modeled daily to be in function of the bodyweight of the animals, given in kg. The total mineral supplement consumption was calculated by the sum of individual consumption. The price per kg of the mineral supplement is presented in Table 4.

Table 4 Prices of the inputs used to calculate the production costs in the simulation model

Item	Value	Unit
Brucella abortus vaccines	0.34	US$/Dose
Clostridial vaccine	0.15	US$/Dose
Foot and Mouth disease vaccine	0.66	US$/Dose
Anthelmintic Levamisole	0.03	US$/ml
Anthelmintic ivermectin	0.09	US$/ml
Mineral supplement	0.61	US$/kg
Semen and synchronization program	16.41	US$/Unit

In the scenarios with NM, every year before starting the breeding season, all bulls were subjected to bull breeding soundness evaluation, each evaluation had a cost of $ 27.36. In the scenarios that include TAI within their reproductive strategy, the cost of semen and synchronization (protocol and services) per cow was estimated at $ 16.41. This value includes assistance in the execution of the protocol as well as the necessary inputs for this.

The cost for technical assistance per year was calculated based on a global basis for all scenarios of US$ 820.66. Additionally, increases related to reproductive management were made according to the level of technology used. Thus, the scenarios with NM only and TAI plus NM had an increment to the technical assistance cost of US$ 273.01. The scenarios with two TAI plus NM with an interval between 40 and 32 days had an additional cost of US$ 546.01. The technical assistance had a rising cost of US$ 819.02 in scenarios that made three

TAI with intervals of 40 and 32 days. The scenario with two TAI with a 24-day interval (early pregnancy diagnosis) had an additional cost of US$ 1,365.03. Finally, scenarios with three TAI with a 24-day interval (early pregnancy diagnosis) had an additional cost of US$ 2,457.05. The basis for the calculation of these values was the costs of the pregnancy diagnosis by conventional ultrasonography or by Doppler ultrasonography, which respectively were US$ 273 (to diagnose up to 800 cows per day) and US$ 546 (to diagnose up to 200 cows per day). These values were obtained through interviews with experienced field technicians of Brazil.

Concerning labor, the herd was managed by a farm manager and a worker. The total annual labor cost was US$ 19,554.13, at US$ 11,923.25 and US$ 7,630.88 for the farm manager and the worker, respectively. Finally, were established annual costs for pasture maintenance (US$ 18,808.68), livestock pharmacy (US$ 1,875.48), machine maintenance (US$ 483,09), and utilities (US$ 1,504.54).

The value of depreciation (improvements, machinery, implements, and working animals) was estimated at US$ 15,489.36, and wage compensation (for corporate officers) set in US$ 16,413.17 was added to the EOC to calculate TOC.

Finally, the TC was calculated by adding to the TOC the value of the remuneration on invested capital, the opportunity cost of the land, and animals, using a Long-Term Rate of 5.56% per year; the choice of this discount rate was arbitrary, but in accordance with the Brazilian macroeconomic reality. The remuneration of invested capital and opportunity cost of the land were fixed values for all scenarios and were calculated at US$ 16,486.50 and US$ 45,628.62, respectively. On the other hand, the opportunity cost of the animals was calculated independently for each scenario. Thus, annually in August, the animal inventory was valued, and in this way, the opportunity cost was calculated.

Further, EOC, TOC, and TC were calculated per kg of live weight produced. For this, the cost item is divided by the total weight (male and female) at the time of weaning.

All input prices were average prices corresponding for the year 2018 and were deflated following the same process described above. The values are presented in Table 3. These values were kept constant over time.

Additionally, some indicators, such as the Gross Margin (GM), Liquid Margin (LM), and Profit, were calculated. GM is the result of the subtraction between incomes and EOC. LM is the result of the subtraction between incomes and TOC. Finally, Profit is the subtraction between incomes and TC.

4.3.4.3. Financial Analysis

The investment analysis was evaluated using the cash flow method. Thus, every year the cash flow was evaluated considering a time horizon of 13 years. The cash flow was composed of initial investment (Cash outflow in time 0); the operating cash flows, which are the operating income of the company (revenues less costs); and (in the final period) the value of animals and all other initial investments made in the farm, at their depreciated value (BORDEUX-RÊGO; PAULO; SPRITZER; ZOTES, 2008). The discount rate used was 6% per year for all scenarios

To compare the cash flows of the proposed scenarios and to choose, in an objective way, the best option, the Net Present Value (NPV), was calculated. NPV allows bringing to the present the sum of all the estimated cash flows for each period, using for this, the best available rate in the market. It is given by equation 1:

$$NPV = -I + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{1}$$

Where:
I = Initial investment;
CF_t= Net cash flow at time t; and
r = Cost of the capital defined by the company.

4.3.5. Statistical Methods

The present study evaluates the effect of 10 different reproductive managements (scenarios) on the economic performance of a cattle herd. The experimental unit was the farm and each scenario had 32 farms (replicas). During the simulation, the data was exported, from the AnyLogic software to a Microsoft Office Excel spreadsheet, in which they were organized.

All data were tested for normality and homoscedasticity using the Shapiro-Wilk and Bartlett and Levene's test, respectively. Data were analyzed using ANOVA and post hoc Tukey HSD tests. All analyses were carried out using the R programming language version 3.6.1 (R Core Team, 2019). Values of $P < 0.05$ were considered statistically significant. All results are presented as the mean ± standard deviation.

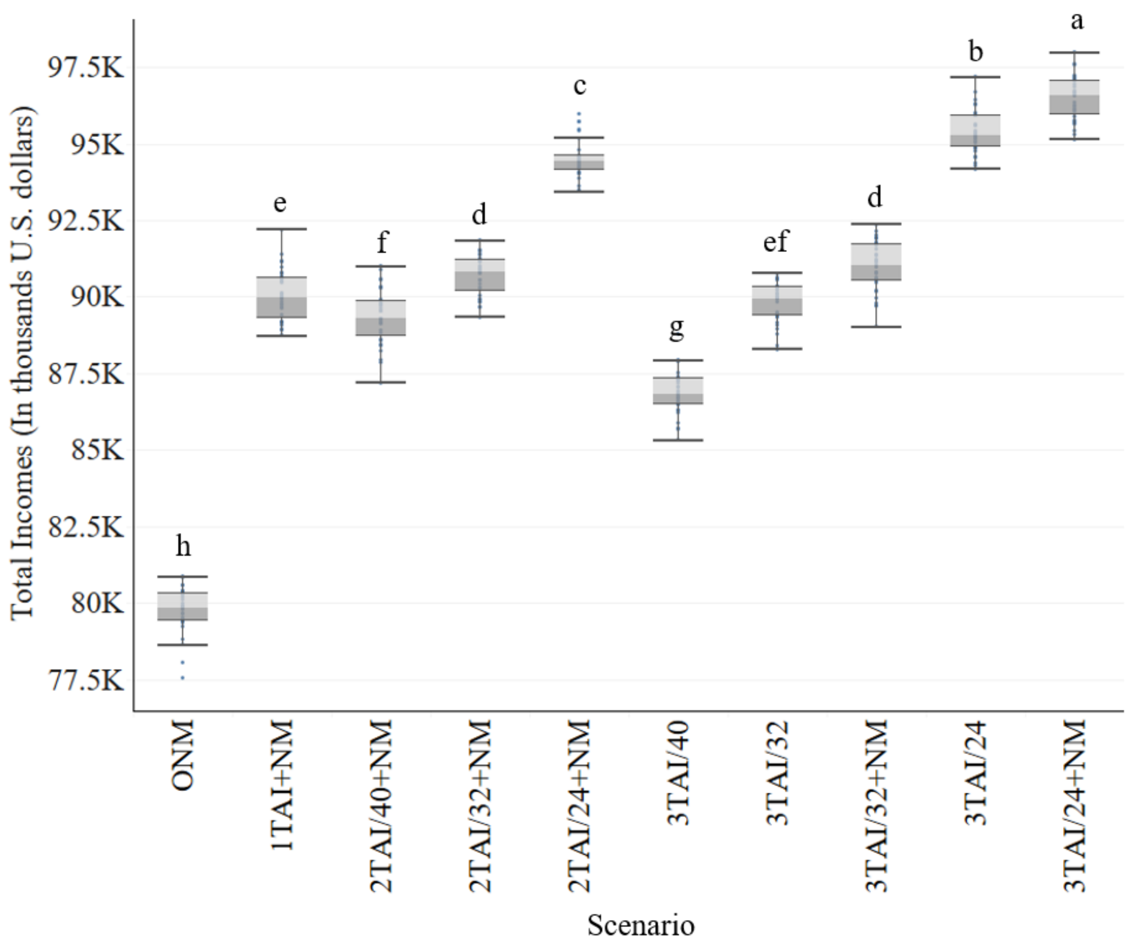
4.4. RESULTS

This stochastic, agent-based simulation model evaluated the technical (accompanying paper OJEDA-ROJAS et al. 2019) and economic performance of reproductive programs that used NM and TAI, only or in different combinations, considering one, two, or three TAI and 24, 32, and 40 days of interval between TAI.

The scenario had a significant effect ($P < 0.05$) on the total income of the herd (Figure 8). The 3TAI/24+NM (US$ 96,479.19 ± 709.81) scenario resulted in higher incomes when compared to other scenarios. Additionally, 3TAI/32+NM (US$ 90,967.97 ± 827.52) and 2TAI/32+NM(US$ 90,686.96 ± 655.13) did not differ statistically between them. Also, these last two scenarios were higher than 1TAI+NM ($ 90,036.09 ± 845.98) and 3TAI/32 (US$ 89,772.96 ± 642.13) which in turn did not differ from each other. The 2TAI/40+NM (US$ 89,341.55 ±) was equal to 3TAI/32 but less than 1TAI+NM. The ONM (US$ 79,753.37 ± 741.87) scenario had the lowest income of the 10 reproductive programs compared (Figure 8). These differences in income are mainly due to differences in the total production of kg of weaned calves.

Costs (EOC, COT, and CT) for the 10 reproductive programs are shown in Figure 9. The EOC was statistically different ($P < 0.05$) for all the scenarios analyzed (Figure 9), except between 2TAI/40+NM (US$ 66,159.57 ± 70.3) and 2TAI/32+NM ($ 66,129.39 ± 82.81) Figure 9. The 3TAI/24+NM scenario had the highest EOC (US$ 69,818.05 ± 79.21). On the other hand, ONM had the lowest value at US$ 58,996.05 ± 59.17. As expected, the scenarios that used three TAI (3TAI/40, 3TAI/32, 3TAI/32+NM, 3TAI/24, and 3TAI/24+NM) were more expensive, and within them, those that used early pregnancy diagnosis (3TAI/24 and 3TAI/24+NM) had the highest EOC. In the same way, when two TAI was performed, a higher EOC was observed for the lower interval between TAI (2TAI/24+NM with US$67,256.89 ± 85.97).

Figure 8 Total incomes for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days)



Source: Ojeda-Rojas (2020)

Because the difference between EOC and TOC, which corresponds to the value of depreciation and wage compensation, is constant for all scenarios (US$ 31,902.54), the TOC had an equal behavior to the EOC where significant statistical difference (P < 0.05) was observed, with the 3TAI/24+NM (US$ 101,720.6 ± 79.21) and ONM (US$ 90,898.58 ± 59.17) scenarios being the ones with the highest and lowest TOC, respectively.

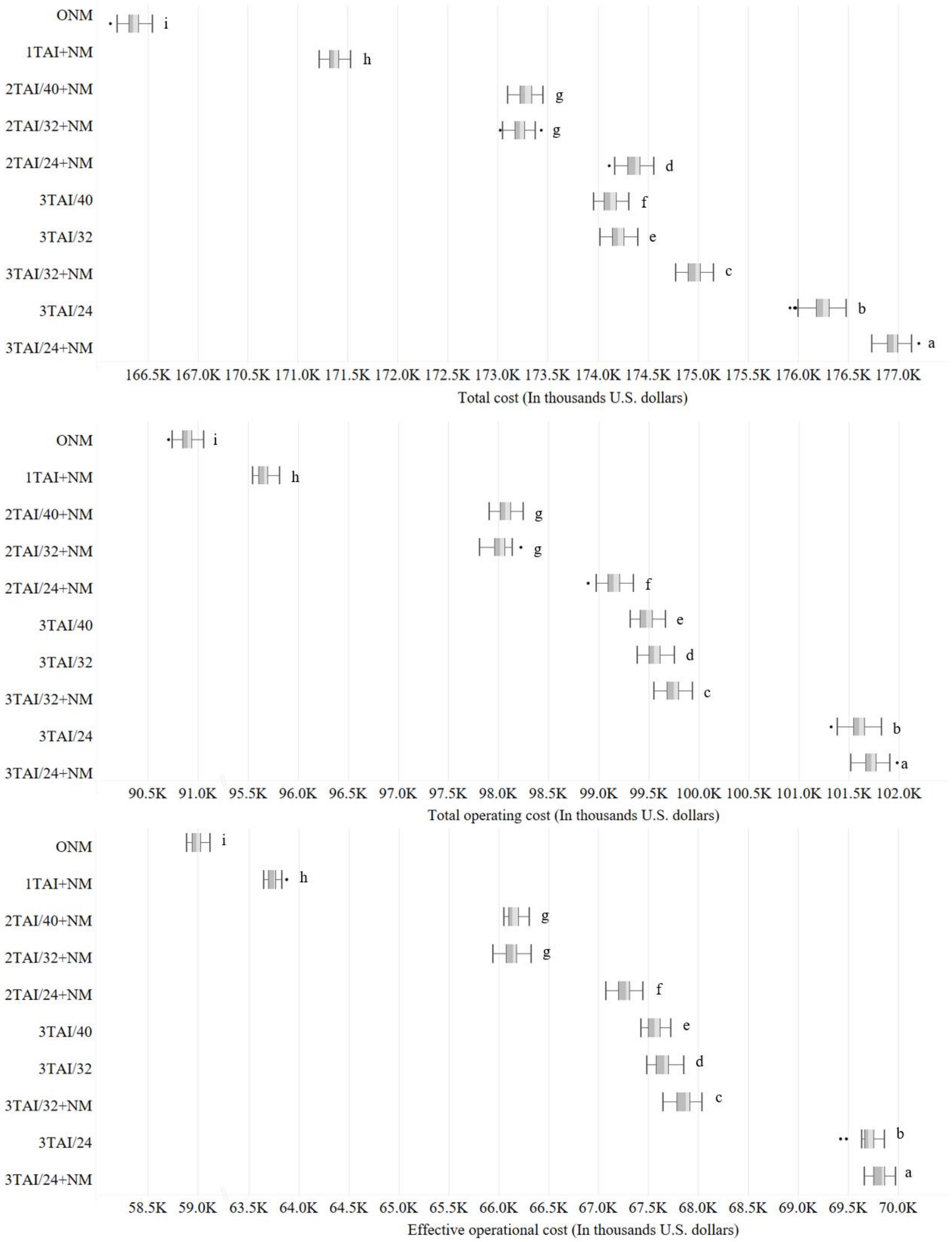
Regarding the TC, all scenarios were statistically different(P < 0.05), except 2TAI/32+NM (US$ 173,238.9 ± 86.67) and 2TAI/40+NM (US$ 173,266.2 ± 70.7). The scenario with the highest TC was 3TAI/24+NM ($176,946.8 ± 81.65). Again, the ONM scenario had the lowest value within this cost item, with $ 166,358.6 ± 57.35. Because the TC considers the cost of capital immobilized in animals, the order that had been observed in the previous cost items (EOC and TOC) changed slightly. Now the scenario 2TAI/24+NM (US$ 174,375.3 ± 85.78) happened to have a higher cost than 3TAI/32 (US$ 174,200 ± 99.47) and 3TAI/40 (US$ 174,116.8 ± 82.62). The ONM (US$ 166,358.6 ± 57.35) scenario had the lowest TC of all the scenarios evaluated.

Related to TOC/kg, higher costs were found in the ONM (US$ 2.8 ± 0.03/kg of weaned calf), 3TAI/40 (US$ 2.26 ± 0.02/kg of weaned calf), and 2TAI/40+NM (US$ 2.23 ± 0.03/kg of weaned calf) scenarios, which were different ($P < 0.05$) from each other. The 3TAI/24 (US$ 2.2 ± 0.03/kg of weaned calf), 3TAI/32+NM (US$ 2.2 ± 0.03/kg of weaned calf), and 3TAI/24+NM (US$ 2.19 ± 0.05/kg of weaned calf) scenarios were similar to 3TAI/32 (US$ 2.21 ± 0.02/kg of weaned calf), 1TAI+NM (US$ 2.21 ± 0.03/kg of weaned calf), and 2TAI/32+NM (US$ 2.21 ± 0.03/kg of weaned calf), however less than 2TAI/40+NM. The lowest COT/kg was obtained from 2TAI/24+NM with US$ 2.17 ± 0.04/kg of weaned calf.

In the case of TC/kg, ONM (US$ 5.12 ± 0.06) had the highest ($P < 0.05$) cost. The following scenarios with higher TC/kg were 3TAI/40 (US$ 3.96 ± 0.05/kg of weaned calf), 1TAI+NM (US$ 3.95 ± 0.05/kg of weaned calf), and 2TAI/40+NM (US$ 3.94 ± 0.06/kg of weaned calf), among which there was no statistical difference. The 2TAI/32+NM, with US$ 3.9 ± 0.05/kg of weaned calf, had a cost similar to 2TAI/40+NM, but lower than 1TAI+NM. Similarly, 3TAI/32+NM (US$ 3.85 ± 0.05) had a CT/kg of weaned calf similar to that found in 3TAI/32 (US$ 3.87 ± 0.04), but less than 2TAI/32+NM. No significant statistical difference was observed between the 3TAI/32+NM, 2TAI/24+NM (US$ 3.82 ± 0.07), 3TAI/24 (US$ 3.82 ± 0.08), and 3TAI/24+NM (US$ 3.82 ± 0.09) scenarios, which in turn had the lowest TC/kg of weaned calf.

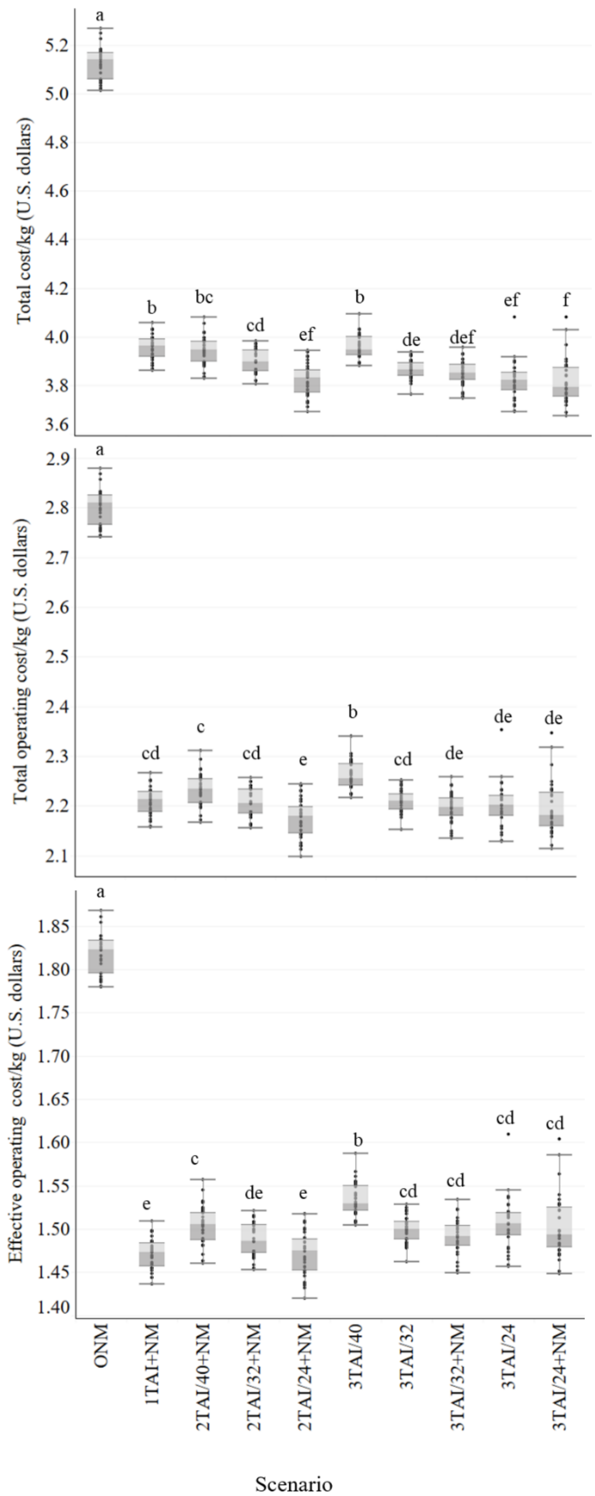
When the gross margin was evaluated (Figure 11), a significant ($P < 0.05$) effect of the scenario was observed. The 2TAI/24+NM (US$ 27,251.26 ± 630.72) and 3TAI/24+NM (US$ 26,661.13 ± 707.75) scenarios resulted in higher gross margins when compared to others. The 1TAI+NM (US$ 26,289.95 ± 830.61) scenario had a performance similar to 3TAI/24+NM, however less than 2TAI/24+NM. Similarly, no difference was observed between 2TAI/40+NM (US$ 23,181.98 ± 876.75) and 3TAI/32+NM (US$ 23,111.9 ± 847.01). The 3TAI/40 (US$ 19,312.5 ± 746.27) scenario had the lowest gross margin of this study.

Figure 9 Effective Operational Cost, Total Operating Cost and Total Cost for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).



Source: Ojeda-Rojas (2020)

Figure 10 Effective Operational Cost/kg, Total Operating Cost/kg and Total Cost/kg for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).



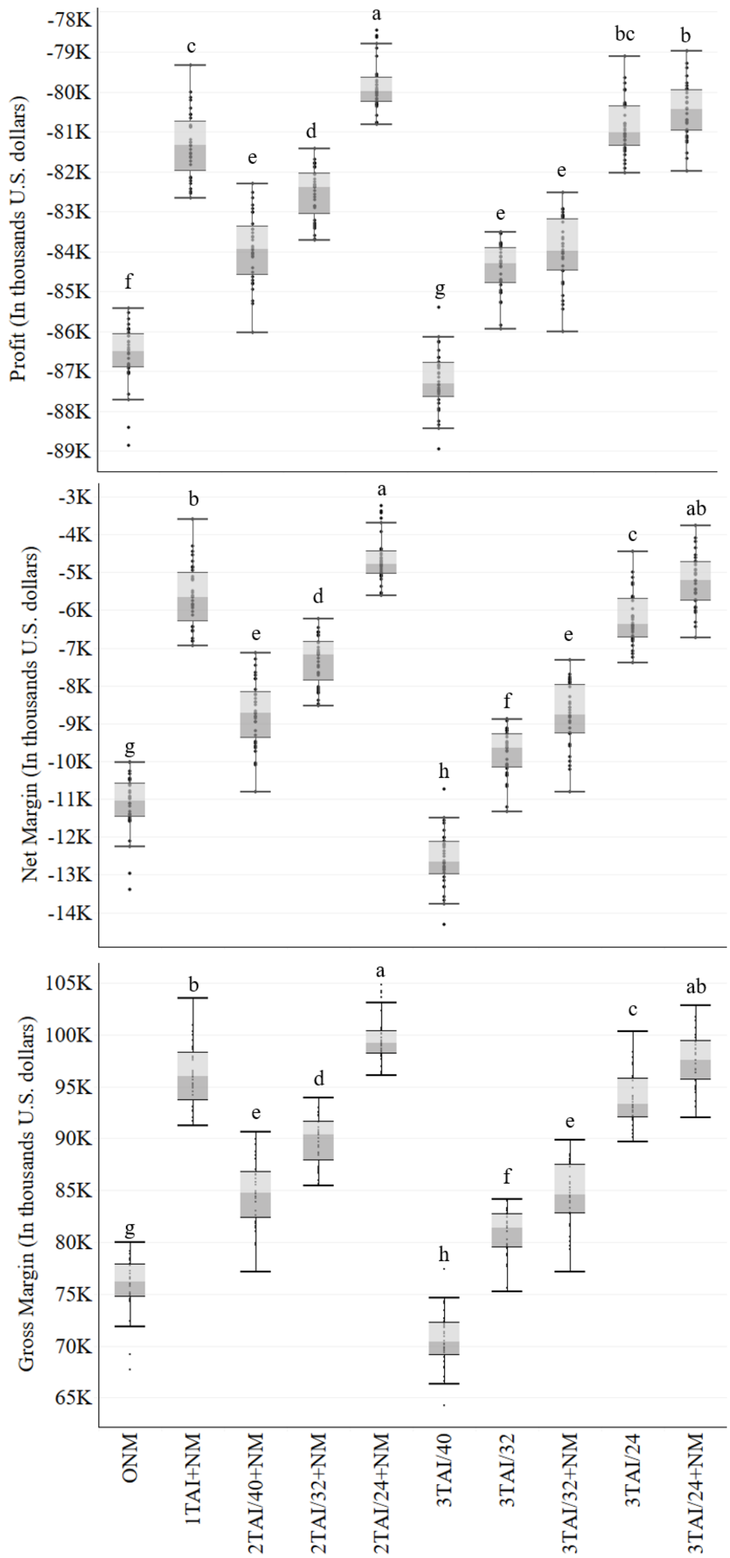
Source: Ojeda-Rojas (2020)

Also, when evaluating the net margin (Figure 11), a significant effect (*P* < 0.05) of the scenario was observed. The net margin followed the same behavior as the gross margin, with the difference that all its values were negative. The 2TAI/24+NM and 3TAI/24+NM scenarios had the best performances with US$ -4,651.28 ± 630.72 and US$ -5,241.4 ± 707.75, respectively. The 1TAI+NM (US$ -5,612.59 ± 830.61) scenario behaved similarly (*P* > 0.05) to 3TAI/24+NM (US$ -6,226.98 ± 692.36), but less than 3TAI/24+NM. Similar (*P* > 0.05) behaviors were observed in scenarios 2TAI/40+NM, 3TAI/32+NM, and 3TAI/32 with -8720.56 ± 876.75 and -8790.64 ± 847.01, and US$ -9,782.99 ± 631.63, respectively. The worst result was for 3TAI/40 with US$ -12,590.04 ± 746.27.

Regarding profit, no scenario had a positive result (Figure 11) because partly to the high value of the investments that a cow-calf enterprise requires. Additionally, a significant effect (*P* < 0.05) of the scenario was observed. The 2TAI/24+NM scenario obtained the best result with US$ -79,867.17 ± 631.13. 1TAI+NM (US$ -81,320.33 ± 828.9) had a performance similar to 3TAI/24 (US$ -8,0878.58 ± 692.31), however less than 3TAI/24+NM (US$ -80,467.63 ± 707.9). Finally, the scenario with the lowest profit was 3TAI/40, with a value of US$ -87,239.1 ± 744.33.

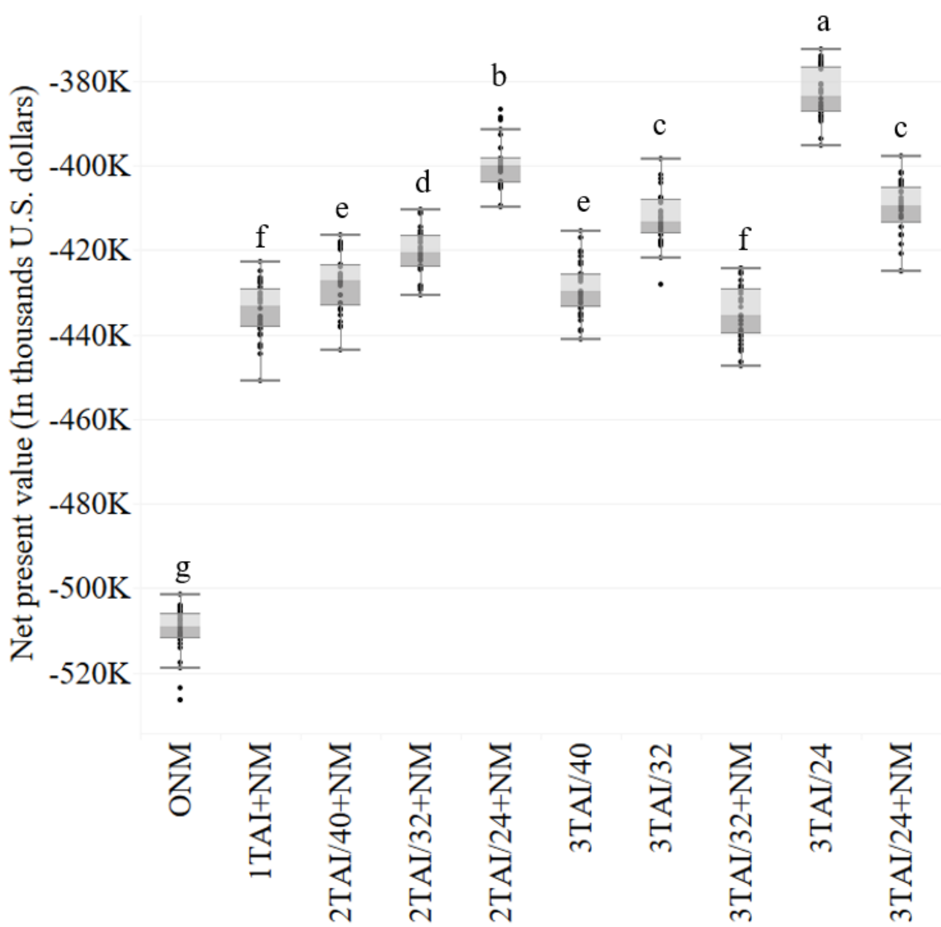
In relation to the NPV (Figure 12), negative results were observed for all scenarios. This is because the project has high costs and its present value exceeded the present value of the income (assuming a discount rate of 6%). Additionally, there was significant effect (*P* < 0.05) of the scenario. The 3TAI/24 scenario had the best NPV value with US$ -383,040.9 ± 5,902.15. Also, no significant statistical differences (*P* > 0.05) were observed between 3TAI/24+NM (US$ -410,150.8 ± 6,541.3) and 3TAI/32 (US$ -412,526.5 ± 6,049.22). Nonetheless, the VPN in these last two scenarios was lower than that in the 2TAI/24+NM scenario. Similarly, 2TAI/40+NM (US$ -427,883.7 ± 6844.75) and 3TAI/40 (US$ -429,064.3 ± 6,414.11) were similar (P> 0.05). These last two were less than 2TAI/32+NM (US$ -420,530.3 ± 5,326.69). Finally, 1TAI+NM (US$ -434,141.3 ± 6,302.17) did not differ from 3TAI/32+NM (US$ -434,907.8 ± 6,583.34), but both were superior to the ONM (US$ -510,496.1 ± 6,150.6) scenario, which in turn resulted in the worst NPV result.

Figure 11 Gross margin, Net margin, and Profit for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days).



Source: Ojeda-Rojas (2020)

Figure 12 Net present value for two breeding methods that used natural mating (NM) and timed artificial insemination (TAI) independently or in combination, with different number of TAI performed (1TAI, 2TAI or 3TAI), and different time interval between TAI (24, 32 or 40 days)



Source: Ojeda-Rojas (2020)

4.5. DISCUSSION

In this study, a stochastic agent-based simulation model, previously developed in the complementary study (OJEDA-ROJAS et al., 2019), was used to evaluate the effect of different reproductive strategies on the economic performance of cow-calf operations. Our purpose was to assess whether higher investments in reproductive technology would bring increases in technical efficiency, sufficient to cover the costs of implementing the technique. The peculiarities of the beef cattle production system, such as high initial investments, long production cycles, and the high number of variables in the system, among others, hinder the economic evaluation of the activity. Accounting for resources for the purchase of inputs, as well as the costs of implementing a reproductive program is a simple task. However, calculating the return on these investments and additionally identifying the sources from which these resources come is somewhat more complicated (JOHNSON; JONES, 2008; LEBLANC, 2007). Simulation models can be useful to understand this complexity, because they allow us to work with a large number of variables, with the possibility of advancing rapidly over time and even better to evacuate several scenarios simultaneously. This is the first time that a stochastic agent-based model is used to evaluate the economic effect of reproductive strategies, including early pregnancy diagnosis in beef cattle.

Data allowed to determine which scenarios with more technology involved (early pregnancy diagnosis) had a higher income level because the anticipation of births results in calves older and, therefore, heavier at weaning. Similar behavior was also reported by Rodgers et al. (2012) using suckled beef cows undergoing two treatments that included NM or one TAI plus NM. In this study, weaning weights of exposed cows to TAI plus NM treatment were 17.5 kg heavier than cows bred exclusively with NM. This weight gain in the North American study increased income per exposed cow of US$ 47.09. In our simulation model, the cows belonging to the 1TAI+NM scenario had an income per cow exposed increase of US$ 25.96 when compared to the ONM scenario. The variation observed in this item between these two studies can be partly explained by the higher selling price considered in Rogers' study (US$ 2.66/kg), while our simulation considered US$ 1.64/kg.

In this context, the results of our study show that, based on the ONM scenario, adding one TAI to the reproductive strategy increased incomes per year by US$ 10,282.72. Also, the fact of performing two TAI, with early pregnancy diagnosis followed by natural mating, increased incomes by US$ 14,754.78 per year. In the same way, performing three TAI with early pregnancy diagnosis followed by natural mating or not, increased income per year by US$ 16,725.82 and US$ 15,625.03, respectively.

Additionally, in Brazilian conditions, this concentration of births at the beginning of the season brings with it other advantages such as a period with less rainfall at the beginning of the birth station, consequently dry environment for calves' birth, and better nutritional conditions for the mother after the first month of the calf's life. These aspects were outside the context of this study, but they are of the utmost importance. All of the above contributes to the scenarios that used early pregnancy diagnosis in order to reduce the interval between inseminations, increase the amount of kg of calves weaned per year.

In the present study, it was evident that the cost of production increased as more technology was used in the reproductive program. Thus, the ONM scenario had the lowest production costs of the experiment. Our findings corroborate with the observations by Cutaia (2006) in Argentina, where costs were increased by US$ 6,450 if TAI was combined with NM, when compared to a program based only on NM, for a herd of 400 cows. In our simulation model, the 1TAI+NM scenario had an increase in the EOC of US$ 4,750.09, when compared to the ONM scenario. The EOC item includes all the costs effectively paid in a year. The differences in cost between the two studies are based on the fact that the Argentine study considered a high price for semen. Similarly, Rodgers et al. (2012), reported a cost increase of US$ 33.18/cow exposed (labor and supplies) to a TAI plus NM program, when compared to a 100% natural mating program. There is an essential difference between the cost values reported by Rodgers and those considered in our simulation model, which are mainly due to differences in the synchronization protocol used and labor costs.

Concerning the TOC, an item that takes into consideration depreciation and wage compensation, scenarios that included early pregnancy diagnosis were more expensive. Thus, the 2TAI/24+NM scenario had an increase of US$ 8,260.85 over the annual TOC of the ONM scenario. Likewise, when the 3TAI/24+NM was performed, the difference in the ONM scenario increased to US$ 10,822.01.

In any commercial activity, analyze costs or income separately does not allow substantial conclusions. The activity with the lowest cost or the one with the highest income is not necessarily the best, from an economic point of view. Therefore, it is necessary to evaluate the relationships between them, and thus determine if the productive activity is economically viable.

The gross margin for all simulated scenarios was positive. This indicates that in all cases, the activity pays its cost and, at least in the short term, will continue. The worst gross margin result was for the 3TAI/40 scenario. In this case, the high interval between inseminations did not allow us to take advantage of the effect of TAI on the anticipation of births. In addition to that, the investment made in the 3TAI/40 scenario was one of the highest. On the other hand, the scenarios that included early pregnancy diagnosis and NM, whether with two TAI or three TAI, had the best gross margin value. Here, despite the high investment of the reproductive program, inseminations concentrated the gestations at the beginning of the reproductive season, and the NM decreased the open cows at the end of the reproductive season resulting in a higher amount of calves that in turn were heavier.

Interestingly, no statistical difference was observed for the gross margin in the 2TAI/24+NM and 3TAI/24+NM scenarios. This reinforces the importance of not analyzing costs and revenues independently. The scenario with three inseminations was, in fact, the one with the highest income; however, its costs were also proportionally higher. So, we can think that carrying out a less intense protocol such as 2TAI/24+NM, with less investment, less management, and less risk, can lead to similar economic results.

The 1TAI+NM scenario had proper behavior, taking into account its low investment. This scenario did not show a statistical difference with 3TAI/24+NM; however, it was less than 2TAI/24+NM. This finding is contrary to what was reported by Miller et al. (2004), who using a stochastic simulation model obtained better net return results for NM than for TAI using a CIDR (Controlled inter-vaginal drug release) based protocol. This variation may be due to differences in labor and supplie's prices. Additionally, Miller's model only considered costs related to the reproductive program, while our simulation model considers all costs

The scenarios behaved similarly in the net margin and profit; however, for all scenarios analyzed, the values were negatives. The negative net margin indicates that the activity is in a decapitalization process because costs with the depreciation and the remuneration of the producer are not being covered. Referring to profit, negative values indicate that the producer, by using his capital in the livestock activity, is no longer earning. In this case, alternative activities would generate higher income.

About NPV, in all scenarios, the calculated value was negative. varying from US$ -383,040.90 to US$ -510,496.10, for 3TAI/24 and ONM, respectively. In other words, this means that under the proposed scenarios, the farms are not able to produce enough resources so that it is possible to recover the investment. The scenarios that anticipate the diagnosis of pregnancy through Doppler had better NPV values; this is in line with what was previously reported by Diaz-Rodriguez et al. (2020). In this study, the effect of nutritional management and gestation diagnosis technique was evaluated on NPV of farms dedicated to calf production, and the early pregnancy diagnosis technique had a higher NPV when compared to the traditional diagnosis with conventional ultrasound.

Because of the complexity of the beef cattle production system and the extensive range of reproductive strategies available, taking an objective and correct decision about the technique to be used would be practically impossible using intuition or even conventional tools such as spreadsheets. Simulation models and new techniques such as agent-based simulation are tools of great utility when making decisions that will imply a significant mobilization of resources, such as the choice of the strategy for the next reproductive season

Considering the simulated particular conditions of a commercial farm in Sao Paulo, Brazil, the agent-based simulation model used in this study, provided sufficient evidence to demonstrate that reproductive strategies that use TAI have better economic performance than those under NM. However, when three TAI were performed with an interval of 40 days, the benefit was lower, and even for some analyzes, it was worse than the ONM. Combining TAI with early pregnancy diagnosis resulted in better economic performance compared to other TAI programs and with NM. Among the scenarios that used early pregnancy diagnosis, the 2TAI/24+NM scenario outperformed the others because of the contrast between its high income with moderate costs. This model does not consider genetic improvement within the analyzes, and this could potentially improve the results of some scenarios. Therefore, a new study that incorporates the effect of genetic improvement into the existing agent-based simulation model will be extremely relevant.

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5. GENERAL DISCUSSION AND CONCLUSION

Livestock producers are part of a small portion of the total population of developed countries; nevertheless, their decisions, the management practices they host, the technologies they incorporate and the treatment they give their animals and soils have significant implications in the rest of the population (DAVIDSON; ROLLINS; LEFSRUD; ANDERS *et al.*, 2018). At the same time, the market chains of the livestock sector employ at least 1.3 billion people worldwide and contribute to the livelihood of 600 million small farmers (THORNTON, 2010). Some of the main concerns, such as the use of global land, greenhouse-gas emissions, and the use of freshwater by agriculture could be reduced by improving the efficiency of agricultural production (ESHEL; SHEPON; SHAKET; COTLER *et al.*, 2018). Historically, increases in productivity of the livestock sector have been driven by technological developments in animal health, nutrition, and reproduction (THORNTON, 2010).

Regarding reproduction, several studies reinforce the idea of the close relationship between advances in reproductive techniques and increases in productivity and consequently in economic results (DE VRIES, 2007; GALVAO; FEDERICO; DE VRIES; SCHUENEMANN, 2013; RODGERS; BIRD; LARSON; DILORENZO *et al.*, 2012; TRENKLE; WILLHAM, 1977). Reproductive efficiency plays a fundamental role in the performance of cow-calf operations. A wide variety of reproductive programs are available to increase farm productivity. However, characteristics of the beef cattle production system such as long production cycles, large farms, and many animals per farm hinder the analysis of technical and economic results after the adoption of new technologies. Simulation models are an efficient tool to deal with this complexity; through this, it is possible to predict the results of potential interventions in the system. The main objective of this Thesis was to develop a simulation model, under the agent-based approach, that would allow investigating the effect of different reproductive management programs on the technical and economic performance of beef cattle herds.

The present study used stochastic variables and agent-based simulation to create a model that simulates a beef cow operation considering the Brazilian reality. In the deterministic simulation, the parameter values are a constant while, in stochastic simulation, variables can assume any values within ranges defined by probability distributions. This means that stochastic models incorporate the risk and probability associated with the decision, which does not occur in deterministic models where every time the model is run, without changing the input data, the same output data will be obtained. The present study also used agent-based simulation. This methodology is most potent and natural for describing a system composed of "behavioral" entities (BAZGHANDI, 2012). Expressly, in agent-based simulation models, a collection of agents, programmed to follow rules of behavior, represent a complex system. Agents are designed to mimic the behavior of something in the real world; in the simulation model presented in this Ph.D. dissertation, the agents were cows and bulls that, throughout their life, they moved to different categories. Because of the complexity of this simulation, which combines agent-based simulation and stochastic and deterministic parameters, AnyLogic software was used. Software commercially available for Agent-based simulation are still relatively few and, most of them were created for academic research purposes. Hence, building models in them involves writing code, which represents a critical limitation for researchers outside the area of computer sciences. AnyLogic is a software that allows, in addition to agent-based simulation, discrete events simulation, and system dynamics methods. Because this software uses a graphical interface, the user can drag-and-drop icons on the screen and use dialog boxes to enter model parameters, making this task much user-friendly (BRAILSFORD; ELDABI; KUNC; MUSTAFEE *et al.*, 2019).

In Chapter 1 of this Ph.D. dissertation, an agent-based simulation model was created to compare the technical performance of 10 reproductive scenarios applied to a cow-calf operation. The performance was monitored daily for ten years in a total of 320 *in silico* farms, each one with 400 breeding adult females. The study showed that scenarios that used TAI protocols produced more and heavier calves when compared to the ONM scenario. When using shorter TAI intervals (due to the incorporation of early pregnancy diagnosis), the proportion of pregnant cows in the first 30 days of the breeding season (BS) was ~80%. Thus, scenarios, where novel and more advanced technologies were used (two or three TAI, early diagnosis of pregnancy), seem to be those that presented better reproductive and productive performance. However, this study did not perform economic analysis.

In Chapter 2, the previously developed model was used to evaluate whether higher investments in reproductive technology would bring increases in technical efficiency, sufficient to cover the costs of implementing the technique. It was determined that the scenarios with early pregnancy diagnosis followed by natural mating, increased incomes when compared to the scenario where only natural mating was employed. The latter also presented the lowest costs, but also the lowest incomes. When the net margin was evaluated (total operational cost-income), the scenario that carried out two inseminations, using early pregnancy diagnosis, had the best performance. Other scenarios where reproductive technologies were involved, also presented significative increases in productivity and income values, when compared to only natural mating scenarios. All this together indicates that, when investing in the implementation of TAI and early pregnancy diagnosis, the results could pay the investments.

As a summary, the present Ph.D. dissertation shows that stochastic agent-based simulation is an excellent tool to evaluate the implementation of different technologies in a commercial cow-calf operation. The model could be improved for future applications, for example, adding a new value of the calves according to their genetic merit. Also, because of the model is now working, could be adjusted to simulate new scenarios such as different breed of animals, different states or countries, different types of production (i.e., pure breed operations), adoption of different technologies (i.e., embryo transfer, new diets, management, or sanitary plans). Also, the experiments conducted here allow us to conclude that farms that include TAI in their reproductive management have better economic and technical performance than those under NM only. However, when three TAI were performed with an interval of 40 days, the benefit was lower, and even for some analyzes, it was worse than the ONM. Combining TAI with early pregnancy diagnosis resulted in better performance compared to other TAI programs and with NM only. Among the scenarios that used early pregnancy diagnosis, the 2TAI/24+NM scenario outperformed the others because of the contrast between its high income with moderated costs.

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