R. Bras. Zootec., 53:e20230037, 2024
https://doi.org/10.37496/rbz5320230037

Animal production systems and agribusiness
Full-length research article

Revista Brasileira de Zootecnia

Brazilian Journal of Animal Science
e-ISSN 1806-9290
www.rbz.org.br

Modelling the impact of sow replacement rate on farm performance

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Received: March 28, 2023
Accepted: May 16, 2024

How to cite: Muniz, H. C. M.; Ceron, M. S.; Fraga, B. N.; Pacheco, P. S.; Gasa-Gasó, J. and Oliveira, V. 2024. Modelling the impact of sow replacement rate on farm performance. Revista Brasileira de Zootecnia 53:e20230037.
https://doi.org/10.37496/rbz5320230037

Editors:
Marcos Inácio Marcondes
Valdir Ribeiro Junior

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ABSTRACT - This study aimed to develop and assess a deterministic mathematical model for predicting the impacts of varying sow replacement rates on the performance of farms producing weaned piglets. Initially, the influence of replacement rate on herd structure was examined using two equations, which accounted for the percentage of sows replaced (55, 45, and 35%), retention rates between parities (13, 9, and 5%), and number of last parities in the herd (6, 7, and 8). The model then estimated sow development throughout the reproductive cycle, starting with an initial weight of 140 kg at first mating and adjusting for weight gains during gestation and losses during lactation, influenced by the varying number of live-born piglets across parities. Energy requirements were calculated using the factorial method, which included maintenance, protein and fat gains, and milk production. The generated data formed various scenarios to derive productive values. These scenarios were analyzed using analysis of variance with the general linear model procedure, treating each scenario as a separate treatment. Early parities (up to P3) contributed 42% in SC-35, 51% in SC-45, and 60% in SC-55. Significant differences were noted in variables such as average parity, birth weight, feed intake during gestation, and average piglet weight gain. The developed model, incorporating replacement gilt modules, gestation, and lactation, can effectively predict herd structure by parity and assess the impact of annual sow replacement rates on the productivity of farms rearing weaned piglets.

Keywords: herd composition, mathematical model, pigs, variable parity

1. Introduction

Replacement rate is defined as ratio of sows introduced into a herd to replace those culled or lost to mortality. Sow replacement is predominantly voluntary, driven by reproductive issues (such as repeated estrus without conception or abortions) and non-reproductive factors (such as weaning numbers, age, etc.). This strategy is pivotal in maintaining an optimal balance of sows in their most productive parities and substituting underperforming females (Malopolska et al., 2018).

Over recent decades, enhancements in sow productivity have led to increased replacement rates on pig farms. The chosen replacement rate significantly affects herd structure, which, in turn, influences production metrics. Typically, lower replacement rates increase the maximum parity of the herd (Lucia Jr., 2007), whereas higher rates elevate the number of younger sows (Barrales et al., 2017).

Various simulation models exist to assess the effect of replacement rates on the reproductive efficiency of a farm. These models vary in complexity and objectives, with some being straightforward to implement and calibrate (Houška, 2009) and others presenting more challenges for on-farm calibration (Hindsborg and Kristensen, 2019). Nonetheless, there appears to be a lack of mathematical models that delve into the impact of replacement rates on production performance, particularly from an energy partitioning perspective. Such an approach offers a detailed quantitative analysis, especially concerning the nutritional dynamics of the system, which significantly influences economic and environmental factors (van Milgen et al., 2008).

Hence, this study aimed to devise and assess a deterministic mathematical model to predict how varying sow replacement rates affect the productivity of farms dedicated to rearing weaned piglets.

2. Material and Methods

2.1. General description

The deterministic model utilizes a structured approach, comprising four modules—herd structure, replacement gilt, gestation, and lactation— to accurately depict a farm producing weaned piglets. The construction of the animal profile within each module involved the application of numerous equations (Table 1) and parameters (Table 2).

Energy metabolism can be characterized by understanding energy inputs and outputs. The mathematical model adopts the traditional concept of energy requirements to distribute the ingested energy (Noblet et al., 1990). It is posited that animals regulate their feed intake to fulfill their energy needs for both maintenance and production, as delineated in equation 2. Maintenance requirements, expressed as Mcal/kg$^{0.75}$.d^{-1}, are calculated using equation 2, which postulates a metabolic energy (ME) intake of 100 kcal/kg$^{0.75}$.d^{-1} across all animal categories in the model. Conversely, energy requirements for production are tailored to specific animal categories.

Table 1 - Equations used to describe energy requirements of gestation and lactation sows as well herd dynamics

Item	Equation	Number
Feed intake[1] (FI; kg)	Energy requeriments ÷ Energy diet	1
Energy for maintenance[2] (Mcal)	$100 \times BW^{0.75}$	2
Empty body weight (kg)	$BW \times 0.96$	3
Weight of fluids and membranes[3] (g)	$BW_{fetal} \times 48.677e^{(0.00146 \times d)}$	4
Weight of placentas[4] (g)	$e^{(7.02746 - 0.95164 \times e^{(-0.06879 \times (d - 45))} + 0.000085 \times f \times d + 0.09335 \times n)}$	5
Metabolizable energy in conceptus[5] (Mcal.d^{-1})	$((Ln\,(11.72 - 8.62 \times EXP(-0.0138 \times d) + 0.0932 \times LS)) \div Kc) \div 4.184$	6
BW_{fetal}		
BW 0-45 days post mating[3] (g)	$0.474 \times d$	7
BW 45-115 days post mating[3] (g)	$-62.922 + 0.00108 \times d^3$	8
Metabolizable energy for milk production[5] (Mcal.d^{-1})	Milk energy output ÷ 0.70	9
Milk energy output[5] (Mcal.d^{-1})	4.92 × mean litter gain (g.day^{-1}) − 90 × LS	10
Birth weight of piglets[6] (BWP; kg)	B − 0.035 × LS	11
Non-productive days[7]	365 − ((LP + GP) ÷ PSY)	12
Replacement rate[7] (%)	PSY × First parity (%)	13
First parity[7] (%)	$100 \div \sum_{k=0}^{np} (1 - RBP)^{n-1}$	14

BW - body weight; d - days of gestation; f - energy intake during gestation (MJ ME/d); Ln - neperian logarithm; n - number of fetuses; PD - protein deposition; LD - lipid deposition; LS - litter size; P - parities; LP - lactation period; GP - gestation period; PSY - parity sow year; RBP - retention between parity; np - maximum number parity.
[1] Noblet et al. (1990).
[2] Dourmad et al. (2008).
[3] Hansen et al. (2014).
[4] Bergsma et al. (2009).
[5] NRC (2012).
[6] Thomas et al. (2018).
[7] Authors.

Table 2 - Input parameters used for gestation and lactation module

Item	Parameter		Number
Maternal weight gain in gestation[1] (g.d^{-1})			1
P1	439		
P2	175		
P3-4	132		
P5-6-7-8	88		
Number piglets born alive[2]	Average	SD	2
P1	12.40	3.03	
P2	13.33	3.37	
P3	14.09	3.42	
P4	14.28	3.50	
P5	14.19	3.55	
P6	14.04	3.56	
P7	13.68	3.52	
P8	13.30	3.45	
Average piglets daily gain per parity[3] (g)			3
P1	180		
P2-3-4	200		
P5-6-7-8	190		
Average daily gain per BWP at birth[3] (g)			4
<0.6	150		
0.6-0.8 kg	150		
0.8-1.0 kg	170		
1.0-1.2 kg	180		
1.2-1.4 kg	190		
1.4-1.6 kg	190		
1.6-1.8 kg	200		
>1.8 kg	210		
Mortality rates[3] (%)			5
<0.6	50.0		
0.6-0.8 kg	28.6		
0.8-1.0 kg	17.0		
1.0-1.2 kg	8.9		
1.2-1.4 kg	8.1		
1.4-1.6 kg	5.6		
1.6-1.8 kg	5.2		
>1.8 kg	4.6		
Weight loss by involution of mammary gland[1] (kg)			6
P1-2	22.5		
P3-4	17.5		
P5-6-7-8	12.5		

P - parities; SD - standard deviation; BWP - body weight of piglets.
[1] van der Peet-Schwering and Bikker (2019).
[2] Sell-Kubiak et al. (2019).
[3] Zotti et al. (2017).

2.2. Modules description

2.2.1. Herd structure

Reproductive parameters and characteristics defining each animal category must be specified to accurately compute a herd structure. This module supplies vital information, including numbers and proportion of animals, along with their age and weight ranges, and body composition, segregated by category.

2.2.2. Replacement gilt

A replacement rate module focuses on females from their arrival at the farm to the onset of their first gestation. Within this framework, the model calculates the daily energy and protein maintenance requirements. These calculations are based on a predetermined daily empty body weight gain (655 $g.d^{-1}$) and the specific body composition of the replacement gilts.

2.2.3. Gestation

The model calculates energy and protein requirements during gestation by accounting for the energy utilized in developing reproductive tissues, conceptus growth, and the sow's body weight gain. Throughout gestation, development of maternal tissues occurs with specific allometric changes, necessitating the inclusion of time as a variable in the calculations (Hansen et al., 2014). The model uses equation 4 to estimate the increase in fluids and equation 5 for reproductive membranes and placenta growth during gestation. These calculated values are then integrated into the sow's weight to determine daily maintenance requirements. The model assumes an energy utilization efficiency of 0.5 for placental growth (Hansen et al., 2014) and employs equation 6 to estimate daily energy expenditure based on the number of conceptuses.

Conceptus growth follows the patterns described by Hansen et al. (2014), utilizing data from McPherson et al. (2004). This growth is modeled as linear for the first 45 days of gestation (equation 7) and then transitions to a curvilinear pattern until farrowing (equation 8). The model adjusts daily sow growth during gestation based on parameters provided by van der Peet-Schwering and Bikker (2019) (Parameter 1).

2.2.4. Lactation

During the lactation phase, which commences post-farrowing, a sow's maintenance and milk production requirements are prioritized (Dourmad et al., 2008). If a sow experiences negative energy balance, it will mobilize its body energy reserves, primarily from adipose tissue. The energy needs of lactating sows (equations 9 and 10) are calculated based on milk production, which correlates with litter size and piglet weight gain (NRC, 2012).

Piglet birth weight is estimated using an equation from Thomas et al. (2018) (equation 11), with intercepts of 1.78 for primiparous and 1.90 for multiparous sows. The model accounts for average daily piglet gain and mortality rates during lactation, drawing on birth weight categories and sow parities (Zotti et al., 2017). Sow weight loss during lactation is determined by the difference between consumed energy and the energy expended for maintenance and milk production (Dourmad et al., 2008).

The energy required for milk production is derived from the average weight gain of the litter (Parameters 3 and 4). Due to the high-energy demands of milk production and potentially insufficient intake, sows may experience a negative energy balance during lactation. The model posits that primiparous and multiparous sows fulfill 75 and 83%, respectively, of their nutritional energy needs through feed (Dourmad et al., 2008). The calculation includes average daily feed intake and body energy mobilization. Each 129 g of fat is considered to have an energy value of 9.3 kcal, with an efficiency rate of 0.80. The weight loss attributed to mammary gland involution for each parity is sourced from van der Peet-Schwering and Bikker (2019) (Parameter 6), standardizing values for sows at parities 6, 7, and 8.

2.3. Scenario description

To assess the impact of annual sow replacement rates on the productivity of farms producing weaned piglets, a simulation study was conducted using various scenarios. The herd structure comprised 250 sows and adhered to specific values for replacement rates, retention between parities, and the last parity in the herd: SC-35 (35% replacement; 5% retention; last parity 8), SC-45 (45% replacement; 9% retention; last parity 7), and SC-55 (55% replacement; 13% retention; last parity 6). Consistent across all scenarios were the gestation period (115 days), weaning-to-estrus interval (7.8 days), sow parities per year (2.4), and age at weaning (25 days). Equation 12 was employed to determine the non-productive days, adding the days gilts were fed until their first insemination.

2.4. Statistical analysis

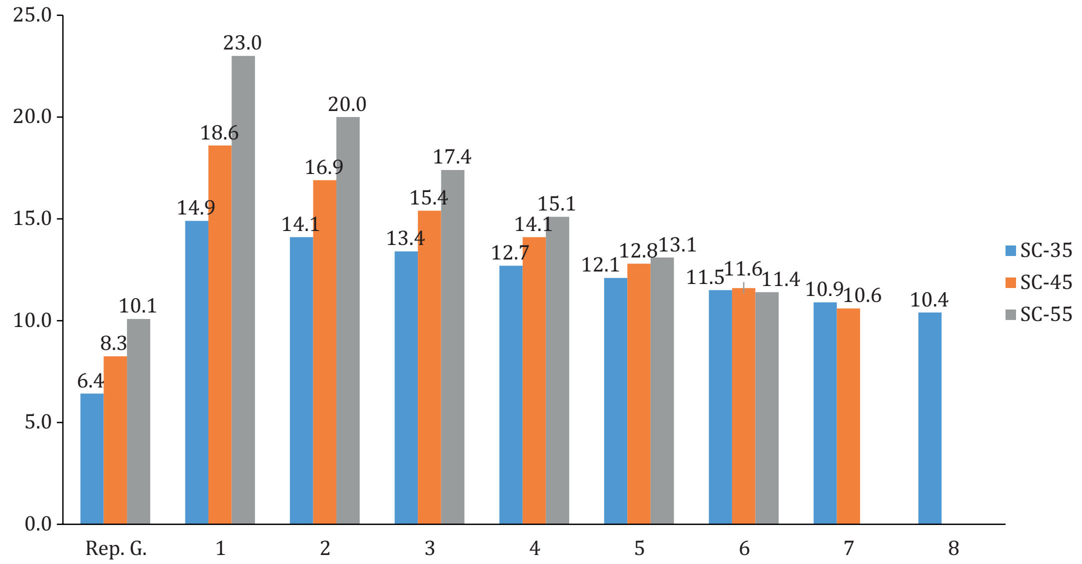
A simulation study was conducted to assess production variables on pig farms with varying sow replacement rates (35, 45, and 55%). Litter size was treated as a random variable to introduce stochasticity into the model, with mean and standard deviation values for each parity sourced from Sell-Kubiak et al. (2019) (Parameter 2). The study included ten farms for each replacement rate, each housing 250 sows, totaling 2,500 data points for each variable and replacement rate.

The collected data underwent an analysis of variance using the general linear model procedure, with a set significance threshold of 5%. The variables analyzed included parity, annual number of piglets born, birth weight, gestational feed intake, annual number of weaned piglets, average piglet weight gain during lactation, piglet weaning weight, and lactation feed intake. Differences between means were evaluated using Tukey's test, with significance determined at P<0.05.

3. Results

The number of gilts introduced annually was 22 and 36% higher in the SC-45 and SC-55 scenarios, respectively, compared to SC-35 (Figure 1). The proportion of sows in early farrowing (up to P3) was 42% for SC-35, 51% for SC-45, and 60% for SC-55. The duration required to completely replace sows in pig farms (from the onset of gilt gestation until the sows' departure) spanned 2.9 years for SC-35, 2.2 years for SC-45, and 1.8 years for SC-55.

The average initial body weight (BW) of gestation sows and the average initial BW at farrowing escalated from P1 to P8 (Table 3). Total body weight mobilization during lactation was 5.7% for P1 and 2.9% for P5. The yearly weaned litter weight for P1 sows was 86.3% and 82.3% relative to P2 and P3, respectively.



Rep. G. - replacement gilt; the total value was divided in six times a year.

Figure 1 - Distribution of sow parity on farms adopting different replacement rates.

Table 3 - Input and output values of productive variables according to parity orders

Module	Trait	P1	P2	P3	P4	P5	P6	P7	P8
Gestation	Average initial body weight (kg)	140.0	186.1	200.1	216.2	231.1	246.9	261.8	269.1
	Average farrowing body weight (kg)	212.8	224.2	235.0	251.7	261.4	276.7	290.9	297.0
	Average feed intake (kg.d^{-1})	2.2	2.3	2.4	2.6	2.6	2.8	2.9	2.9
Lactation	Average body weight at weaning (kg)	180.0	193.9	209.3	225.8	240.6	255.8	270.2	276.5
	Average feed intake (kg.d^{-1})	4.2	5.2	5.5	5.6	5.5	5.6	5.4	5.3
	Body weight loss (kg)	10.3	7.8	8.2	8.4	8.3	8.3	8.1	8.0
Piglets	Average body weight born alive (kg)	1.34	1.43	1.41	1.40	1.40	1.41	1.42	1.44
	Average daily gain (g.d^{-1})	186.4	198.4	197.9	197.7	192.7	192.9	188.2	188.4
	Average body weight of weaned piglets (kg)	6.0	6.4	6.4	6.3	6.2	6.2	6.1	6.2
	Weaned litter weight (kg.year^{-1})	164.0	190.0	199.3	202.4	197.5	195.4	187.9	181.1
	Daily litter gain (kg)	2.2	2.5	2.6	2.6	2.5	2.5	2.4	2.3
	Number of weaned piglets[1] (year^{-1})	27.8	29.9	31.6	32.2	32.0	31.6	30.9	29.6

P - parity.
The energy diets were 3.3 and 3.4 Mcal.kg^{-1}, for gestation and lactation, respectively;
[1] Average number of piglets born alive multiplied by 2.4 (parity sow per year).
The input values for each sow were obtained through simulation of the proposed models.

The scenario significantly affected the average parity of the farm (P<0.001) (Table 4), indicating that higher replacement rates corresponded to lower average parities. The scenarios also affected the average birth weight of piglets (P<0.015), with SC-35 having heavier piglets compared with SC-55, and SC-45 showing intermediate and comparable weights to the others. The average daily feed intake of sows during gestation showed a decrease (P<0.001) from SC-35 to SC-55. Regarding the average daily gain of piglets, there was a significant difference (P<0.001) between SC-35 and the other scenarios.

Table 4 - Values obtained with effects of different scenarios on productive performance of the farm after simulation

Trait	SC-35	SC-45	SC-55	SEM	P-value
Average parity	4.23a	3.62b	3.08c	0.040	<0.001
Number piglets born alive (litter)	13.61	13.67	13.72	0.098	0.698
Number piglets born alive[1] ($year^{-1}$)	32.83	32.99	33.11	0.235	0.698
Average birth weight (kg)	1.41a	1.40ab	1.39b	0.003	0.015
Average feed intake in gestation ($kg.d^{-1}$)	2.54a	2.48b	2.43c	0.007	<0.001
Average feed intake in lactation ($kg.d^{-1}$)	5.25	5.24	5.21	0.029	0.530
Number of weaned piglets ($year^{-1}$)	30.49	30.63	30.72	0.209	0.735
Average daily gain ($g.d^{-1}$)	193.0b	193.6a	194.0a	0.156	<0.001
Daily litter gain ($kg.d^{-1}$)	2.43	2.45	2.47	0.016	0.372
Average body weight of weaned piglets (kg)	6.23	6.24	6.24	0.007	0.494
Weaning litter weight ($kg.year^{-1}$)	188.74	189.90	190.62	1.180	0.528

SC-35, SC-45, and SC-55 mean 35, 45, and 55% of replacement per year of the herd, respectively; SEM - standard error of the mean.
[1] Average number of piglets born alive multiplied by 2.4 (parity sow per year).
The energy diets were 3.3 and 3.4 $Mcal.kg^{-1}$, for gestation and lactation, respectively.
a-c - Means followed by different letters within a row differ significantly by Tukey's test (P<0.05).

4. Discussion

The mathematical model was developed to estimate the impact of varying swine sow replacement rates on selected productivity indicators. This deterministic model employs a simplified system representation, allowing for an approximation of the effects of different replacement rates on pig systems, despite its limitations.

The outcomes of each evaluated scenario are inherently constrained by the underlying assumptions of the simulations. For instance, the maximum parities for females varied across scenarios, leading to distinct sow removal rates between parities. Such variations establish a unique herd structure, significantly influencing productivity.

Black (1995) identified two methods for evaluating a model: first, assess the logical coherence of its mathematical structure by examining its equations; second, confirm that the outputs of the model align with empirical evidence, which can be validated against existing literature.

In evaluating the outputs of the model for each parity (Table 3), we found that the results generally correspond with the findings reported in scientific literature, including NRC (2012), Rostagno et al. (2017), van der Peet-Schwering and Bikker (2019), and Pierozan et al. (2020), particularly regarding the gestation and lactation phases of sows. This correlation is anticipated, given that the theoretical framework of the model closely mirrors the methodologies employed in the referenced studies.

The average parity varied with the scenario (Table 4), showing that a higher replacement rate resulted in a lower average parity. The maximum number of farrowings for sows differed across scenarios, influencing the outcomes. Even when scenarios shared the same maximum parity, an increased herd turnover rate was expected to decrease the average parity due to a higher proportion of females in early parity stages.

The observation that piglets in SC-35 had a greater live birth weight compared with other scenarios is likely due to fewer primiparous sows in the herd, as first-time sows typically have piglets with lower birth weights (Thomas et al., 2018). Additionally, in SC-55, a 13% replacement rate between farrowing allowed sows to remain until P6, a point at which litter size decreases and piglet birth weight tends to increase (Feldpausch et al., 2019).

The quantity of feed in the replacement gilt module correlated directly with the number of gilts, making SC-55 have a higher feed requirement due to more animals. During gestation, feed intake is significantly affected by the sow's body weight, accounting for approximately 65 to 75% of the total energy demand (NRC, 2012; Rostagno et al., 2017). Thus, scenarios with lower replacement rates typically have older, heavier sows (Table 3), affecting feed intake (Barrales et al., 2017; van der Peet-Schwering and Bikker, 2019). Thomas et al. (2018) found that higher-parity sows weigh more and consume more feed. Consequently, younger herds such as in SC-55, are likely to have lower feed intake during gestation (Table 3).

The variation in piglets' average daily gain across scenarios (Table 4) is attributable to differences in sow parities. Optimal piglet production occurs between the 3rd and 5th farrowings (Houška, 2009; Sell-Kubiak et al., 2019). A larger number of piglets typically results in lower individual weights (Feldpausch et al., 2019), which can adversely affect their performance during lactation (Zotti et al., 2017). The SC-35 benefits in this context, with 20% of its herd surpassing parity 6. Interestingly, despite variations in piglet growth rates, the final litter weight at weaning was consistent across scenarios.

5. Conclusions

The deterministic mathematical model formulated in this research serves to simulate the impact of replacement rates on pig farm performance metrics. The absence of notable differences in production performance likely stems from the assumptions employed in defining the various scenarios examined.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: Muniz, H. C. M.; Ceron, M. S.; Pacheco, P. S. and Oliveira, V. **Data curation:** Muniz, H. C. M.; Fraga, B. N.; Gasa-Gasó, J. and Oliveira, V. **Formal analysis:** Muniz, H. C. M.; Fraga, B. N. and Pacheco, P. S. **Investigation:** Muniz, H. C. M.; Fraga, B. N.; Gasa-Gasó, J. and Oliveira, V. **Methodology:** Muniz, H. C. M.; Pacheco, P. S.; Gasa-Gasó, J. and Oliveira, V. **Project administration:** Muniz, H. C. M.; Pacheco, P. S. and Oliveira, V. **Resources:** Oliveira, V. **Software:** Pacheco, P. S. **Supervision:** Ceron, M. S.; Fraga, B. N.; Pacheco, P. S.; Gasa-Gasó, J. and Oliveira, V. **Validation:** Muniz, H. C. M.; Ceron, M. S.; Pacheco, P. S. and Gasa-Gasó, J. **Visualization:** Muniz, H. C. M.; Ceron, M. S.; Fraga, B. N.; Gasa-Gasó, J. and Oliveira, V. **Writing – original draft:** Muniz, H. C. M.; Fraga, B. N.; Pacheco, P. S. and Oliveira, V. **Writing – review & editing:** Muniz, H. C. M.; Ceron, M. S.; Fraga, B. N.; Gasa-Gasó, J. and Oliveira, V.

Acknowledgments

This study was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and CAPES-PrInt/UFSM.

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