TOWARDS SUSTAINABLE AGRI-FOOD SYSTEMS:
BALANCING BETWEEN MARKETS AND SOCIETY

A Stochastic Bio-Economic Farm Model for Brazilian Farrow-to-finish Pig Production System

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Abstract

A stochastic bio-economic farm model was developed to assess the impact of innovations on pig farm performance. The model accounts for emissions of greenhouse gases by using the shadow price of CO_2 and for stochastic prices. The model was used to assess the impact of using co-products in pigs' diets on private and social profits for a typical Brazilian farrow-to-finish pig farm. The results show that social profits are 2.2-3.6% lower than private profits in all the standard and alternative cases. The stochasticity of profits is large (with coefficients of variation 52% to 61%) following from the volatility of prices.

Keywords: **Bio-economic model, Stochasticity, Pig, Profit, Environment**

1. Introduction

Brazil is the fourth largest producer and exporter of pork in the world (USDA, 2014). Pig production is based mainly on an intensive system using modern technologies (Mariante *et al*., 2003). In recent years, the pig industry has faced rising feed costs (Embrapa swine and poultry centre, 2016) and environmental problems such as emission of greenhouse gases (GHGs) from feed production and manure (Ali *et al*., 2016; Cherubini *et al*., 2015a). Innovations such as locally adapted production systems using alternative feed sources (Ali *et al*., 2016) and breeding programs better suited to local conditions (Wall *et al*., 2010; Kanis *et al*., 2005) might reduce these problems.

For making informed decisions about feeding and breeding, farmers and their stakeholders need information on the impact of these innovations on farm performance. Bio-economic farm models (BEFMs) have proven to be useful tools for assessing the impacts of such innovations on technical, economic and environmental performances of farming systems (Janssen and Van Ittersum, 2007). BEFMs integrate biological, economic and management components of a system to explore diverse issues of farming. Stochastic BEFMs take into account the variability of components in the system when exploring effects of changing technologies.

Several studies employed BEFMs to assess the impact of improved breeding materials (e.g. Serenius *et al*., 2008; Houška *et al*., 2004; Skorupski *et al*., 1995). These studies have in common that they estimate economic values of traits on the basis of private profit (i.e. total returns minus total costs of production). However, to improve both the economic and environmental sustainability of production systems, the assessment of innovations should be based on social profit rather than on private profit. Social profit refers to private profit minus the environmental costs of production. Next to that, most existing studies (e.g. Houška *et al*., 2004; Skorupski *et al*., 1995) followed a deterministic approach for system parameters, even though some of these parameters are stochastic in nature. For example, the feed price, the price of a replacement gilt and the pork price vary over time. By introducing stochasticity, a BEFM calculates risks associated with fluctuation of these variables. A stochastic BEFM provides expected profit with its associated variance whereas a deterministic model calculates only profit. The incorporation of stochasticity in a BEFM provides insight into the robustness of the outcome of the model in terms of the impact of innovations on farm performance and on the economic values of breeding goal traits.

In the light of the foregoing discussion, the objective of this study was to develop a stochastic BEFM as a tool for assessing the impact of innovations (e.g. alternative feeds, breeding materials) for a typical farrow-to-finish pig farm on private and social profit. The model was applied to the current Brazilian farrow-to-finish production system. The environmental aspect taken into account is GHGs emission. Risks associated with fluctuation of prices are included in the model.

2. Material and methods

2.1 Model design

Bio-economic farm models can take the form of a simulation model or an optimization model (Janssen and van Ittersum, 2007). This paper develops a simulation model rather than an optimization model, since the degree of freedom for optimization is limited in an intensive pig production system. We assume that available farm resources, which are given, (e.g. buildings and equipment) are optimally used and the farm operates at its optimum. The time period taken into account in the model is one year.

Figure 1 depicts the flow of inputs (feed and non-feed inputs) and outputs (both marketable and undesirable) and the production cycle of a sow and her piglets as it is modelled. Reproduction in the model starts with purchased replacement gilts. Replacement gilts are mated after a certain period of time from purchase. Conceived gilts join the sow pool. Gilts with problems (e.g. oestrus, leg, udder, inbreeding/failed conception) are culled. The sow production cycle consists of mating, conception, farrowing, lactation and weaning. After weaning, a sow will be mated or culled depending on her condition and performance. Weaned piglets pass three growth stages— piglets (weaning to 23 kg), growing pigs (23-70 kg) and finishing pigs (70 kg to slaughter weight).

< Figure 1 >

Variable costs of gilts and sows comprise costs of purchasing replacement gilts, feed, labour, veterinary, energy, semen, maintenance and repair, transport and others. Boar costs are included in gilt and sow costs. Variable costs of fattening pigs include costs of feed, labour, veterinary, energy, maintenance and repair, transport and others during the three growth stages. Fixed costs (depreciation and interest expenses) are included at farm level. In the social profit function, environmental costs of emission of GHGs from feed production and manure, and the fertilizer value of manure are included. Returns consist of sales from culled gilts and sows, from fattening pigs, and the fertilizer equivalent value of manure.

2.2 Pig growth model

A pig growth model, InraPorc model, is incorporated in the BEFM to account for the biological aspects of growing-finishing pigs using different diets. The model predicts growth performance of pigs (i.e. daily gain, feed conversion ratio, pork quality) for different types of diets used in the growing and finishing growth stages (Van Milgen *et al*., 2008). Protein deposition (PD) and lipid deposition (LD) are the two key state variables related to chemical and physical body composition of pigs for predicting growth response and carcass characteristics. The InraPorc model simulates nutrient partitioning for PD, LD and for other activities such as maintenance, physical activities and PD cost. The rate of PD and LD depends on potential PD, energy and amino acid supplies. Potential PD refers to PD when the pig is capable of expressing its full growth potential under ad libitum feeding. To predict feed intake in the InraPorc model, the equation $Y = aX^b$ was used; where Y is net energy intake in MJ/day, X is body weight in kg, and a and b are parameters. The parameters a and b are estimated within InraPorc from given feed intakes at 50 kg and 100 kg body weights. Other parameters required for simulating growth performance in InraPorc are: initial age, initial body weight, final age or final weight, precocity per day and mean PD per day.

2.3 Environmental cost of feed and manure

Feed production and manure are the largest contributors to global warming potential (GWP) in the pork production chain (Cherubini *et al*., 2015a; Nguyen *et al*., 2012). The environmental costs of GWP, which is caused by emission of GHGs, from feed production and manure, is incorporated in the BEFM. GWP is selected as it generally acts also as an indicator of other environmental categories (e.g. acidification and eutrophication). An efficient use of nitrogen leads to less acidifying and eutrophying substances being released to the environment and lower GHGs emission in the form of N_2O (Röös *et al*., 2013).

Two steps are required to calculate the environmental costs of feed and manure: determining the amounts of GWP from feed production and manure, and monetizing GWP. The GWP of feed productions were taken from Ali *et al*. (2016). GWP from manure depends on manure management and the type of diets used (Rigolot *et al*., 2010; Dourmad *et al*., 2003). The calculation of this GWP for the different diets is presented in section 2.5.4. The three GHGs: CO_2, CH_4 and N_2O were expressed in kg of CO_2 equivalent (CO_2-eq) using weights of 1, 28 and 265 for CO_2, CH_4 and N_2O, respectively (assuming 100 years life span) (IPCC, 2015).

Monetizing GWP was done by using the shadow price of CO_2 emission. Several studies estimated the cost of CO_2 release to the atmosphere (Tol, 2008; Weidema, 2009). These costs are associated with the impact of CO_2 release on the environment, human health and economy. We adopted the shadow price used by Gaitán-Cremaschi *et al*. (2015), where they assessed the sustainability of the Brazilian soybean meal chain. They used the average of estimates of cost of CO_2 release to the atmosphere from existing literature sources (i.e. 0.02 USD per kg CO_2-eq in 2011 prices). By changing it to 2015 prices, we assume that the average shadow price of CO_2 emission is US$0.021 per kg. For manure, we use as environmental cost the difference between its environmental cost due to emission of GHGs and its value as a fertiliser plus the environmental cost of avoided artificial fertiliser (refer to section 2.5.4 below).

2.4 Stochastic variables

The BEFM accounts for the stochasticity of the main economic parameters. The stochasticity of biological parameters (e.g. number of weaned piglets and feed conversion ratio) is not considered as the fluctuation of these parameters over time is assumed to be negligible within a farm. In an intensive pig production system where the impact of the environment (e.g. weather, diseases, feeding) is controlled, the variability in biological parameters within a farm is assumed to be small. Stochastic parameters are the feed prices, the price of a replacement gilt and the selling price of a finished pig. The reason for choosing these as stochastic parameters is that they fluctuate over time and are expected to have substantial influence on the economic results (as feed cost accounts >75% in pig cost of production and as sales of finished pigs are the main source of revenue). Fluctuation in feed prices follow the fluctuation of corn and soybean meal prices (which are the main feed ingredients). Introduction of stochasticity in models requires average values, the variation of the stochastic variables, and the correlation among these variables. Standard deviations and correlation coefficients can be derived from annual data by removing the effect of the trend term.

2.5 Model application

The developed model is applied to a farrow-to-finish pig farm in Minas Gerais to assess the impact of using alternative feed sources on private and social profits. Pig producers in Minas Gerais (and the southeast region) generally follow a farrow-to-finish production system. All computations are made using the reference year 2015.

2.5.1 Definition of cases

A reference case and two alternative cases (macaúba and co-products cases) are designed to assess the impact of using co-products in the diets of finishing pigs on private and social profits. The reference case represents the current feeding practice in Minas Gerais, Brazil. Table 1 shows the complete diet compositions used in the three cases. A three phase feeding is assumed for fattening pigs: piglets (weaning to 23 kg live weight), growing pigs (23 kg to 70 kg) and finishing pigs (70 kg to slaughter weight). The three cases have a common part (i.e. the diets for sows, piglets and growing pigs) and a specific part (i.e. diets for finishing pigs). The growing pig and the reference finishing pig diets are formulated to represent the current feeding practices in Minas Gerais (Rocha, 2016). The finishing pig diet in the reference case mainly consists of corn and soybean meal. In the macaúba and co-products cases, a macaúba kernel cake and a co-products based diets are used during the finishing phases, respectively. The alternative finishing pig diets were taken from Ali *et al*. (2016). Net energy intakes are equal in the three cases.

< Table 1 >

2.5.2 Management, biological and economic input parameters

In Minas Gerais (southeast Brazil), the size of farms vary significantly ranging from 50 sows to more than 5000 sows. We assume that a typical farm owns 1500 productive sows with annual replacement rate of 45% (Martins *et al*., 2012). Embrapa poultry and swine centre (www.embrapa.br/en/suinos-e-aves/cias) also assumes 1500 productive sows in their monthly reports of swine cost of production for Minas Gerais. Table 2 presents the values of management and biological input parameters of the model. Total net energy intakes are equal in the three cases (through the parameters net energy intake at 50 kg and 100 kg live weights). Pigs are allowed for higher feed intake under alternative cases to realise the same net energy intake as the reference case.

< Table 2 >

The economic input parameters of the model are presented in Table 3. The expected prices of replacement gilts and of finished pigs are the averages of annual prices in the period 2006-2015. Annual prices of feeds for piglets, growing pigs, finishing pigs and sows were only available for the year 2015 from Ali et al. (2016) who computed them using information on the composition and the prices of feed ingredients. Other information available were the annual feed costs of finished pigs from a database of Embrapa poultry and swine centre for the entire period 2006-2015. The missing feed prices in the period 2006-2014 were computed in two steps. First, we computed the annual percentage change in the feed costs of finished pigs for the period 2006-2015. Next, we used the annual changes in feed cost to compute feed prices for the period 2006-2014 from the 2015 prices of feeds. By doing this, we assumed that the annual changes in feed cost per finished pig over the period 2006-2015 are entirely due to changes in feed prices between the same years. Since there were no historical data on the prices of macaúba and co-products based finishing feeds, we assumed that the price changes for these feeds over 2006-2015 were the same as for the reference feed as corn and soybean meal are the main ingredients in all the three feeds.

< Table 3 >

2.5.3 Stochastic economic input parameters

Feed prices, the price of replacement gilts and the selling price of finished pigs were assumed to be stochastic in the BEFM. Annual data (2006-2015) were used to compute the means, standard deviations and correlations among these stochastic parameters. Prices were de-trended (i.e. the systematic increase or decrease in prices was removed from the original prices) to generate a price series that was used for computing the standard deviations and correlations. A normal distribution was assumed for these stochastic parameters. Table 4 summarizes the mean values, standard deviations and correlation coefficients of these stochastic parameters. We assume that the standard deviations of the prices of the three finishing phase diets are equal as corn and soybean meal are main feed ingredients in these diets. For the mean values, however, diet specific prices were used (Table 3).

< Table 4 >

2.5.4 Environmental cost of feed and net return from manure

The GWP (including emissions from direct land use change) of feed ingredients were taken from Ali *et al*. (2016). Using the emission factors of feed ingredients and diet compositions (Table 1), GWP of each diets were derived. Manure is the second source of GHGs emission in pig production. Open slurry tank (without a natural crust cover) is the most commonly used form of pig manure management system in Brazil. The liquid manure is assumed to be removed daily or weekly from the channels of the building through pipes to the external deposit (slurry tank) where it is kept for about 120 days for partial stabilization and subsequent field application (Cherubini *et al*., 2014). For estimating CH_4 and (indirect) N_2O emissions from manure, tier 2 approach of Intergovernmental Panel on Climate Change (IPCC) was used by using country and diet specific data and IPCC (2006) default values. The country specific data used are for volatile solids and nutrient excretions of sows and piglets. For sows and piglets, these country specific data were taken from Cherubini *et al*. (2014) and Diesel *et al*. (2002). For the growing and finishing phases, the mathematical models of Rigolot *et al*. (2010) and Dourmad *et al*. (2003) were included in the BEFM to calculate the amounts of volatile solids and nutrient excretions for the specific diets used. There is no direct N_2O emission since manure is stored in an open slurry tank without natural crust cover (IPCC, 2006; Cherubini *et al*., 2014).

In Brazil, manure is applied on land as organic fertilizer and thereby avoids the production and use of artificial fertilizer (Cherubini *et al*., 2015a; Cherubini *et al*., 2015b). We assume that the avoided fertilizers are urea (46% N), superphosphate (42% P_2O_5) and potassium chloride (60% K_2O). Efficiency rates of 0.75 for urea (Nguyen *et al*., 2010), 1 for superphosphate and 1 for potassium chloride were assumed to estimate the amounts of avoided fertilisers. The amounts of avoided chemical fertilisers are calculated as:

$$F_N = \frac{0.75 * N_{Manure}}{0.46} \quad (1)$$

$$F_{P2O5} = \frac{1 * P2O5_{Manure}}{0.42} \quad (2)$$

$$F_{K2O} = \frac{1 * K2O_{Manure}}{0.60} \quad (3)$$

where F_N is the amount of urea, N_{manure} is the total N excretion in the manure adjusted for N volatilisation during storage, F_{P2O5} is the amount of superphosphate, $P2O5_{Manure}$ is the amount of P_2O_5 in the manure, F_{K2O} is the amount of potassium chloride and $K2O_{Manure}$ is the amount of K_2O in the manure. Then, the net return from manure is computed as:

$$Net\ return\ from\ manure = \sum P_i * F_i + \sum SP * GWP_{F_i} - SP * GWP_{manure} \quad (4)$$

where P_i is price of artificial fertilizer i; i refers to N, P_2O_5 and K_2O; F_i is amount of avoided fertilizer i; SP is the shadow price of GWP; GWP_{F_i} is GWP of artificial fertilizer production and GWP_{manure} is GWP of manure. The first term ($\sum P_i * F_i$) refers to the fertilizer value of manure, the second term ($\sum SP * GWP_{F_i}$) implies the avoided environmental cost due to the avoided production of artificial fertilizer and the last term ($SP * GWP_{manure}$) is the environmental cost of manure.

3. Results

The simulated pig growth performance results and nutrient excretions for the three cases are given in Table 5. Carcass characteristics (i.e. slaughter weight, protein and lipid masses) are equal among the three cases. The reference case resulted in better feed conversion ratio than the alternative cases since the net energy content of the reference finishing pig diet (10.26 MJ/kg) is larger than the alternative finishing pig diets (9.83 MJ/kg). Since pigs were allowed for equal net energy intake under the three cases, total feed intakes are larger under the alternative cases (244.3 kg) compared with the reference case (238.9 kg). The excretions of volatile solids are greater under the macaúba (27 kg/pig) and co-products (26 kg/pig) cases than the reference case (18 kg/pig) due to the higher fibre contents in the alternative diets of finishing pigs (97.1 g/kg for macaúba kernel cake based diet and 73.3 g/kg for co-products based diet) compared with the reference diet (23.3 g/kg). The nitrogen excretions are comparable among the cases as the crude protein contents of the diets are comparable.

< Table 5 >

Revenues, costs, private profit and social profit are presented in Table 6 for the three cases. Expected annual private profit is about 10.5% higher for the macaúba case than the reference case, whereas it is about 3.1% lower for the co-products case. The former is due to the higher price of the reference finishing pig diet (R$0.57/kg) than the macaúba kernel cake based diet (R$0.50/kg). The higher feed intake in the co-products case outweighs the small cost-price advantage of the co-product based finishing pig diet (R$0.01/kg feed).

< Table 6 >

The environmental cost of feed per farm per year is about 5.7% lower for the macaúba case than the reference case and 0.8% lower for the co-products case. The higher feed intakes under the two alternative cases reduce their environmental cost advantages. The environmental cost of manure is about 32% higher for the macaúba case and 27% higher for the co-products case compared with the reference case. This is due to the higher fibre contents in the alternative diets which results in higher methane emissions (Rigolot *et al*., 2010) and to the higher feed intakes in the alternative cases. Social profit is about 9.7% higher for macaúba case compared to the reference case whereas it is 2.5% lower for the co-products case. Results in Table 6 also show that social profit is about 2.8% lower than private profit for the reference case, 3.6% lower for the macaúba case and 2.2% lower for the co-products case. Although the net return from manure is positive, social profit is lower than private profit due to the environmental cost of feed.

The variabilities of profits, measured by the standard deviations, are high relative to the mean values (with coefficients of variation 52% to 61%). The variability of profits is comparable among the three cases since the same standard deviations (and correlations) for the stochastic inputs in the three cases were assumed. The variations in private and social profits are also the same since stochastic parameters are not included in the calculations of environmental costs.

4. Discussion

The expected private profit of pig farming in Minas Gerais (Brazil) is 607 268 US$ per farm per year. This is equivalent to a profit of 0.15 US$ per kg live weight pig. However, this profit does not account for the costs of feed manufacturing (i.e. grinding and pelleting) and feed transport between the feed mill and pig farm. The profit computed in this paper is slightly higher than the profit computed based on the cost of production from Embrapa poultry and swine centre for Minas Gerais. Using the average cost of production (2006-2015) (Embrapa poultry and swine centre, www.embrapa.br/en/suinos-e-aves/cias) and the average selling price of finished pigs (2006-2015) in Minas Gerais (www.agrocotacoes.com.br), average profit per kg live weight was 0.13 US$. The difference could be attributed to the use of different input values (e.g. feed prices due to difference in diet compositions).

The introduction of stochasticity in the BEFM provides more insights about the profitability of pig farming. Although the expected profit of pig farming in Minas Gerais is positive, its variability is substantial due to the stochasticity of prices of finished pigs and feeds. Price volatility affects investment decisions, production levels, profitability, and ultimately long run economic growth (Keay, 2015). Therefore, stabilization of pork and feed prices in Brazil might contribute to the improvement of the pig industry via increased investment.

Although we included the environmental cost of only GHGs emission from feed production and manure (while excluding other environmental impacts and GHGs emission from other stages of production), the results of the current study showed that the social profit of pig farming is lower than the private profit. The inclusion of other environmental costs (e.g. acidification, eutrophication and GHGs emission from other stages of production) would reduce the social profit significantly. The consideration of only emission of GHGs from feed production and manure, however, does not jeopardise this study. This is because mitigation strategies targeting reduction of GHGs emission indirectly contribute to reduction of other environmental categories (Röös *et al*., 2013). Moreover, the emphasis on feed production and manure is reasonable as these are the main contributors to environmental problems in the pig production chain (Cherubini *et al*., 2015a; Nguyen *et al*., 2012).

The net return from manure, the difference between its value as a fertiliser and its net environmental cost, was included in the BEFM. The net return from manure is positive in all three cases. The fertiliser equivalent value of manure was calculated by using the prices of artificial fertilisers. Although we used a lower efficiency rate for the N fertiliser (75%), the use of the prices of artificial fertilisers could still overvalue manure as the efficiency, and convenience for transportation and application are lower for manure compared with artificial fertiliser. Therefore, the results of the social profits are exaggerated following the use of prices of artificial fertiliser for manure. Moreover, we did not take into account processes beyond manure storage. The results of the current study will change if emissions during transport and field application are considered since these emissions are different for manure and artificial fertiliser.

The use of co-products in the diets of pigs including macaúba kernel cake, has other benefits that are not included in this study. For example, the use of co-products reduces the competition for cropland between the feed and food sectors and thereby contributes to food security by making available cropland for food crops production (Ali *et al*., 2016).

5. Conclusions

The objective of the paper was to develop a stochastic bio-economic farm model for assessing the impact of innovations on private and social profits of a typical farrow-to-finish pig farm. The developed model is a generic model which can be used to assess the impacts of a wide range of innovations such as alternative feed sources and breeding materials on farm performance. It can also be used as a tool by breeding programs to estimate economic values of breeding goal traits. We used the model for assessing the impact of using co-products in the diets of finishing pigs on private and social profits of a Brazilian pig farm. Social profits are lower than private profits due to the net environmental costs of feed and manure. Other benefits of co-products (e.g. improving land use efficiency and reducing emissions from land use change) should also be taken into account to utilise co-products. The stochasticity of profits is large (with coefficients of variation 52% to 61%) following from the volatility of prices.

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7. Tables and figures

Table 1 *Diet compositions for pigs in Minas Gerais, Brazil (% of diet in kg product)*

	The same for all cases			Reference case	Macaúba case	Co-products case
	Sows[1]	Piglets[1]	Grower pigs[2]	Finishing pigs[2]		
Maize	60.23	55.02	72.25	80.15	64.71	47.35
Soybean meal	22.66	22.20	23.30	16.70	12.03	12.81
Macaúba kernel cake					20.00	10.00
Soybean oil			1.40	0.60		
Wheat middlings						15.00
Citrus pulp, dried						5.00
Sugarcane molasses						4.00
Animal fat	2.12	3.43			0.56	3.65
Animal meal		3.28				
Rice bran meal	5.24					
Soybean hulls	6.42					
Maize gluten meal		3.00				
Dicalcium phosphate	0.99	0.45	1.20	0.90		
Monocalcium phosphate					0.52	0.38
Sodium bicarbonate					0.34	
Salt	0.49	0.26	0.46	0.46	0.17	0.38
Limestone	1.17	0.58	0.59	0.53	0.63	0.42

L-Lysine HCl	0.14	0.33	0.33	0.27	0.40	0.36
Dl-Methionine		0.03	0.10	0.03	0.12	0.11
Threonine 98%	0.03	0.10	0.08	0.07	0.11	0.13
Mineral and vitamin premix	0.30	7.17	0.30	0.30	0.40	0.40
Phytase[3]					0.01	0.01
Other ingredients[4]	0.21	4.15				
Total	100.00	100.00	100.00	100.00	100.00	100.00
Nutritional values						
Net energy (MJ/kg)	-	-	10.25	10.26	9.83	9.83
Std. dig. lysine (g/kg)[5]	-	-	9.99	8.00	8.14	8.14

[1] Cherubini *et al*. (2015). [2] The growing and reference finishing pig diets were formulated by prof. Gabriel Rocha, Department of Animal Sciences, UFV , Brazil. The alternative finishing diets were taken from Ali *et al.* (2016). [3] Equivalent to 500 FTU phytase per kg diet. [4] Mycotoxin binders, flavours and sweetener agent (not included in the environmental impact analyses). [5] Standardised ileal digestible lysine.

Table 2 *Management and biological inputs of pig production in Minas Gerais, Brazil*

Parameters	Values	Reference
Number of sows per farm	1 500.00	Embrapa poultry & swine centre
Annual replacement rate of sows (decimal)	0.45	Martins *et al*. (2012); Dias (2016)
Age of gilts at purchase (days)	150.00	Dias (2016)
Age of replacement gilt at first oestrus (days)	180.00	Dias (2016)
Number of oestrus at first mating	3.00	Martins *et al*. (2012); Dias (2016)
Extra days open due to reproduction problems (days)	1.20	Dias (2016)
Farrowing rate (decimal)	0.88	Agriness (2015)
Service repetition rate (decimal)	0.07	Agriness (2015)
Gestation length (days)	114.00	Martins *et al*. (2012); Dias (2016)
Lactation length (days)	28.00	Martins *et al*. (2012)
Interval between weaning and oestrus (days)	7.00	Assumption (range: 4-10)
Feed usage of gilts, gestating and dry sows (kg/day)	2.80	Dias (2016)
Feed usage of sows during lactation (kg/day)	6.81	Dias (2016)
Mortality of replacement gilts till conception (decimal)	0.01	Dias (2016)
Mortality of sows (decimal)	0.05	Dias (2016)
Culling of replacement gilts till conception (decimal)	0.08	Dias (2016)
Culling of sows (decimal)	0.36	Own calculation
Weaning-culling interval (days)	35.00	Dias (2016)
First insemination-culling interval (days)	17.50	Dias (2016)
Live weight of culled gilts (kg/gilt)	135.40	Dias (2016)
Live weight of culled sows (kg/sow)	225.00	Dias (2016)
Piglets born alive per sow per farrowing	12.25	Agriness (2015)
Weight of piglet at birth (kg/piglet)	1.34	Dias (2016)
Pre-weaning piglet mortality (decimal)	0.082	Agriness (2015)
Piglet weaning weight (kg/piglet)	7.50	Martins *et al*. (2012)
Feed usage of piglet (kg/piglet)	25.00	Martins *et al*. (2012)
Body weight of piglet (at 63 days age) (kg/piglet)	23.00	Martins *et al*. (2012)
Mortality of piglets and growing pigs (decimal)	0.02	Own calculation
Mortality of finishing pigs (decimal)	0.03	Dias (2016)
Net energy intake at 50 kg body weight (MJ/kg)	21.07	Monteiro *et al*., 2016
Net energy intake at 100 kg body weight (MJ/kg)	28.94	Monteiro *et al*., 2016
Precocity per day (decimal)	0.0105	Monteiro *et al*., 2016
Mean protein deposition (g/day)	131.00	Monteiro *et al*., 2016
Duration in growing-finishing stage (days)	105.00	Rocha (2016)

Table 3 *Economic input values of pig production in Minas Gerais, Brazil*

Parameters	Values	Remark/reference
Piglet production		
Price of replacement gilts (R$/gilt)	516.24	www.agricultura.pr.gov.br
Semen cost (R$/pregnancy/sow)	23.14	Own computation[1]
Sow non-feed-semen variable cost (R$/day)	2.17	Own computation[1]
Replacement gilt non-feed variable cost (R$/day)	1.80	Assuming 83% of daily sow variable cost (Serenius *et al*., 2008)
Sow feed price (R$/kg)	0.61	Own computation[2]
Piglet feed price (R$/kg)	1.23	Own computation[2]
Price of culled sow (R$/kg live weight)	2.83	Average selling price (2006-2015)[2]
Price of culled gilt (R$/kg live weight)	1.82	Average selling price (2006-2015)[2]
Growing-finishing		
Cost of labour (R$/finished pig)	3.37	Own computation[1]
Cost of veterinary (R$/finished pig)	2.14	Own computation[1]
Cost of energy (R$/finished pig)	1.22	Own computation[1]
Other variable costs (R$/finished pig)	13.69	Own computation[1]
Growing pig feed price (R$/kg)	0.64	Own computation[2]
Finishing pig feed price (R$/kg)		
Reference diet	0.57	Own computation[2]
Macaúba kernel cake based diet	0.50	Own computation[2]
Co-product based diet	0.56	Own computation[2]
Price of finished pig (R$/kg live weight)	3.02	www.agrocotacoes.com.br
Fixed cost per farm (R$/year)	1 016 073	Refer to Supplementary Table S1

[1] Derived from input demands and annual cost of production of finished pig (www.embrapa.br/en/suinos-e-aves/cias). [2] Average feed prices (2006-2015) derived from annual feed cost of finished pig (www.embrapa.br/en/suinos-e-aves/cias). [3] Derived based on the relative price of live weight of culled gilts (R$3.45/kg) and sows (R$2.22/kg) compared to the average price of live weight of finished pigs (R$3.45/kg) from January to July 2016 in Passos, MG.

Table 4 *Mean values, standard deviation and correlation coefficients among stochastic parameters*

Parameters	Mean (R$)	SD (R$)	Correlations					
			a	b	c	D	E	f
Price of finished pig (a)	3.020	0.290	1.000	0.788	0.211	0.211	0.211	0.211
Price of replacement gilt (b)	516.240	27.070		1.000	0.024	0.024	0.024	0.024
Piglet feed price (c)	1.230	0.098			1.000	1.000	1.000	1.000
Growing pig feed price (d)	0.640	0.051				1.000	1.000	1.000
Ref. finishing pig feed price (e)	0.570	0.045					1.000	1.000
Sow feed price (f)	0.610	0.049						1.000

Table 5 *Simulated growth performance and nutrient excretion results of growing-finishing pigs (23 kg to slaughter weight; simulated with InraPorc®)*

Parameters	Reference case	Macaúba case	Co-products case
Total feed intake (kg/pig)	238.90	244.30	244.30
Average daily gain (g/day)	880.00	880.00	880.00
Feed conversion ratio (kg feed/kg gain)	2.58	2.64	2.64
Final live weight (kg/pig)	115.39	115.39	115.39
Protein mass (kg/pig)	17.30	17.30	17.30
Lipid mass (kg/pig)	31.40	31.40	31.40
Nutrient excretions (kg/pig)			
Volatile solids	18.02	26.63	25.74
N	3.57	3.68	3.73

Table 6 *Revenues, costs, private profit and social profit per year for a typical Brazilian farrow-to-finish pig farm (×1000 US$)*

Parameters	Reference case	Macaúba case	Co-products case
Revenues			
Sales of finished pigs	3 644 (350)	3 644 (350)	3 644 (350)
Sales of culled gilts and sows	73	73	73
Total revenue	3 717 (350)	3 717 (350)	3 717 (350)
Variable costs			
Sows and gilts costs	699 (23)	699 (23)	699 (23)
Feed cost of fattening pigs	1 888 (150)	1 824 (152)	1 907 (152)
Non-feed costs of fattening pigs	213	213	213
Total variable costs	2 800 (173)	2 736 (175)	2 819 (175)
Total fixed costs	310	310	310
Total costs	3 110 (173)	3 046 (175)	3 129 (175)
Private profit	607 (350)	671 (352)	588 (352)
Environmental cost of feed	122	115	121
Net return from manure			
Environmental cost of manure	44	58	56
Avoided environmental cost[1]	12	12	12
Fertilizer value of manure	137	137	152
Net return from manure	105	91	108
Social profit	590 (350)	647 (352)	575 (352)

Figures in parentheses refer to standard deviations. [1] Avoided environmental cost due to avoided artificial fertilizer production.

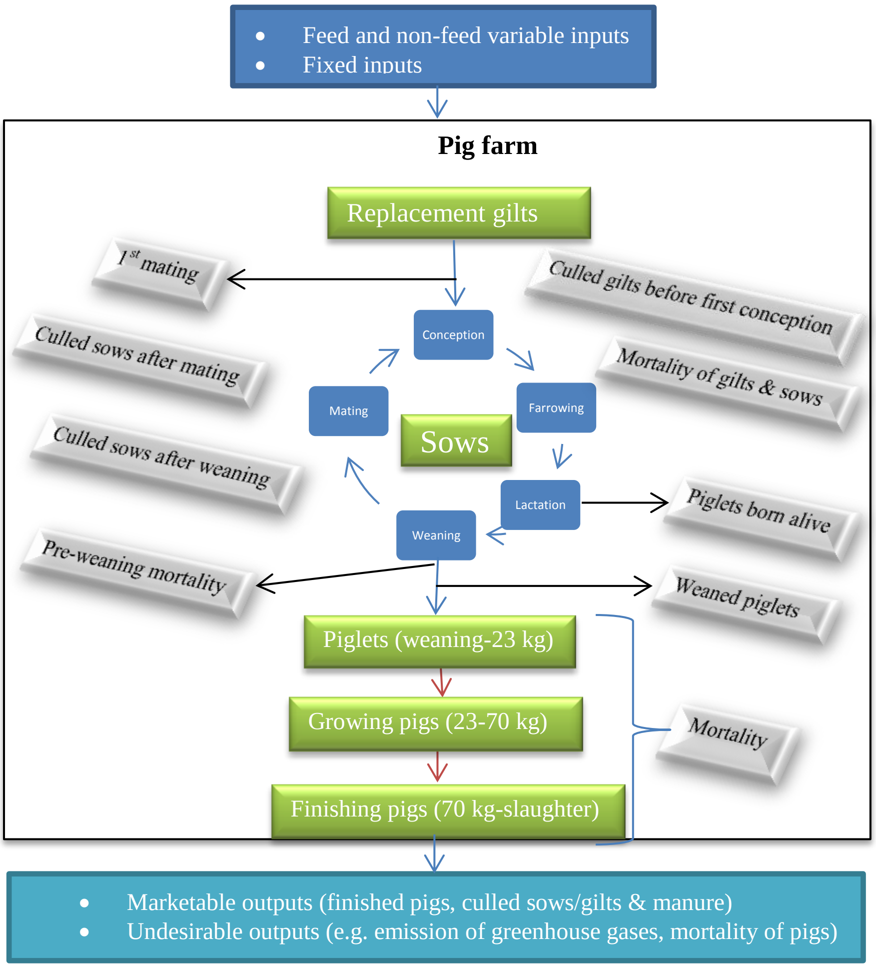

Figure 1 Flow chart of farrow-to-finish pig production system