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Animal (2018), **12:6**, pp 1277–1286 © The Animal Consortium 2017
doi:10.1017/S1751731117002920

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Modelling interactions between farmer practices and fattening pig performances with an individual-based model

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(Received 20 January 2017; Accepted 22 September 2017; First published online 16 November 2017)

European pig production continues to encounter economic and environmental challenges. To address these issues, methods have been developed to assess performances of pig production systems. Recent studies indicate that considering variability in performances among pigs improves the accuracy and reliability of results compared with modelling an average animal. Our objective was to develop a pig fattening unit model able to (i) simulate individual pig performances, including their variability in interaction with farmers' practices and management, and (ii) assess their effects on technical, economic and environmental performances. Farmer practices included in the model were chosen from a typology generated from on-farm surveys focused on batch management, pig allocation to pens, pig feeding practices, practices of shipping to the slaughterhouse, and management of the remaining pigs. Pigs are represented using an individual-based model adapted from the InraPorc® model. To illustrate the model's abilities, four scenarios were simulated that combine two feed rationing plans (ad libitum, restricted to 2.5 kg/day) and two feed sequence plans (two-phase, 10-phase). Analysis of variance was performed on the simulated technical, economic and environmental indicators (calculated via Life Cycle Assessment). The feed rationing plan and feed sequence plan significantly affected all indicators except for the premium per pig, for which the feed sequence plan did not have a significant effect. The 'restricted 10-phase' scenario maximised gross margin of the fattening unit (14.2 €/pig) and minimised environmental impacts per kg of pig produced. In contrast, the 'ad libitum two-phase' scenario generated the lowest margin (8.20 €/pig) and the highest environmental impacts. The model appears to be a promising tool to assess effects of farmers' practices, pig characteristics and farm infrastructure on technical, economic and environmental performances of the fattening unit, and to investigate the potential of improvement. However, further work is needed, based on virtual experiments, in order to evaluate the effects of a larger diversity of practices.

Keywords: fattening pig, model, variability, performance, Life Cycle Assessment

Implications

A model is proposed to simulate the interactions between management, individual pig characteristics and farm infrastructure and their effects on technical, economic and environmental performance of a pig fattening unit. After external validation, this model will be used to compare management strategies and will be included in a decision support tool for on-farm application.

Introduction

European pig production continues to encounter economic and environmental challenges. The increase and variability in feed ingredient prices combined with fluctuations in pig prices reduces the stability of pig farms' economic margins. The cost of feed accounts for 60% to 75% of the total pig production cost, in which fattening feed is a major portion (Mullan *et al.*, 2011). Pig production systems have a significant impact on water eutrophication, acidification, and greenhouse gas emissions (McAuliffe *et al.*, 2016). Two main mechanisms that have been explored to reduce environmental impacts of pig production include improving management of pig nutrition and manure storage and treatment. Reducing impacts of the fattening unit is a major concern because fattening pigs produce ~70% of the phosphorus (P) and nitrogen (N) emissions of farrow-to-finish farms (Dourmad *et al.*, 1999).

To address these challenges, farmers must understand trade-offs between technical, economic and environmental performances of the pig fattening unit. Livestock farming systems are complex because they are structured by

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https://doi.org/10.1017/S1751731117002920 Published online by Cambridge University Press

interactions between biological and human-controlled processes, and their behaviour is not always predictable. Consequently, farmers need decision support systems that rely on dynamic models of the multiple performances of the pig fattening unit. Variability in amino acid and net energy (NE) requirements among pigs greatly influences the heterogeneity in growth performance, nutrient excretion and slaughter weight. A modelling approach is suitable for simulating behaviour of the fattening unit system because it represents interactions among its components. Most published pig fattening models predict effects of nutrition on growth performance of an average pig (Pomar *et al.*, 2003; van Milgen *et al.*, 2008; Niemi *et al.*, 2010) without simulating effects of animal performance on associated economic margin or environmental impacts. A few models associate economic efficiency (Lurette *et al.*, 2008; Niemi *et al.*, 2010) or nutrient excretion (Chardon *et al.*, 2012) with farmers' strategies or consider variability in performance among individuals. Different studies have shown that simulated response of performance of a group of pigs to feeding practices is closer to observed performance when using an individual-based model instead of an average animal model, as individual-based models account for the variability of nutritional requirements among pigs (Pomar *et al.*, 2003; Brossard *et al.*, 2014). The optimisation model of Ferguson (2015) considers variability in performance among pigs and its interaction with feed and shipping practices to calculate technical and economic performances of a batch of pigs. To our knowledge, no dynamic pig fattening unit model considers individual variability in performance among pigs, farmers' feeding practices and animal management and also estimates environmental impacts (calculated using Life Cycle Assessment (LCA)) and economic results of the fattening unit.

Our objective was to develop a pig fattening unit model able to (i) simulate individual pig performance (including its variability) in interaction with farmers' practices and management and (ii) assess effects of all three on technical, economic and environmental performances. This paper describes principles and assumptions of the model and illustrates its potential via application.

Model description

Overview of model structure

The fattening unit model is a discrete event, mechanistic, individual-based model which is stochastic for biological traits (pig intake, growth potential and mortality) and has a 1-day time step. The model, based on object-oriented programming, includes several classes: the '*pig herd*' with fattening '*pigs*', the '*farmer*' with farm management, and the farm infrastructure with fattening '*rooms*' and their associated '*pens*' (Supplementary Material Figure S1). In the following description, the names of classes (e.g. '*farmer*', '*pig*') refer to objects described in the model. The *pig herd* is divided into successive *batches* composed of groups of *pigs* which are the same age and are bred together from fattening to shipping to the slaughterhouse. Farm management is represented by practices and a calendar of events containing tasks to perform. Each day the *farmer* receives information from the *herd* and the calendar of events. Based on this information, the calendar is updated by adding or removing tasks. At each time step in the simulation, the events corresponding to the current day are read in the calendar and processed. The practices include *batch* management, allocation of *pigs* to pens, feeding practices and slaughter shipping practices. The model simulator was implemented using Python 3 language.

The *farmer* uses practices, the main inputs of the model (Supplementary Material Table S1), to determine farm management: the interval between the arrival of two successive *batches*, how *pigs* are grouped in *pens* (e.g. at random, according to sex and/or BW), the feeding plan, and how to plan shipping and select the *pigs* which are shipped to the slaughterhouse (Figure 1). Other inputs include animal profiles (which describe variability among *pigs*), *building* characteristics and feed composition. Information about farm management, fattening *rooms* and animal profiles are sent to the growth and slaughter shipping submodel, which simulates *batch* arrival and allocation to *rooms* and *pens*, daily growth of *pigs* and shipping to the slaughterhouse. It sends the *pigs*' performances to the economic and

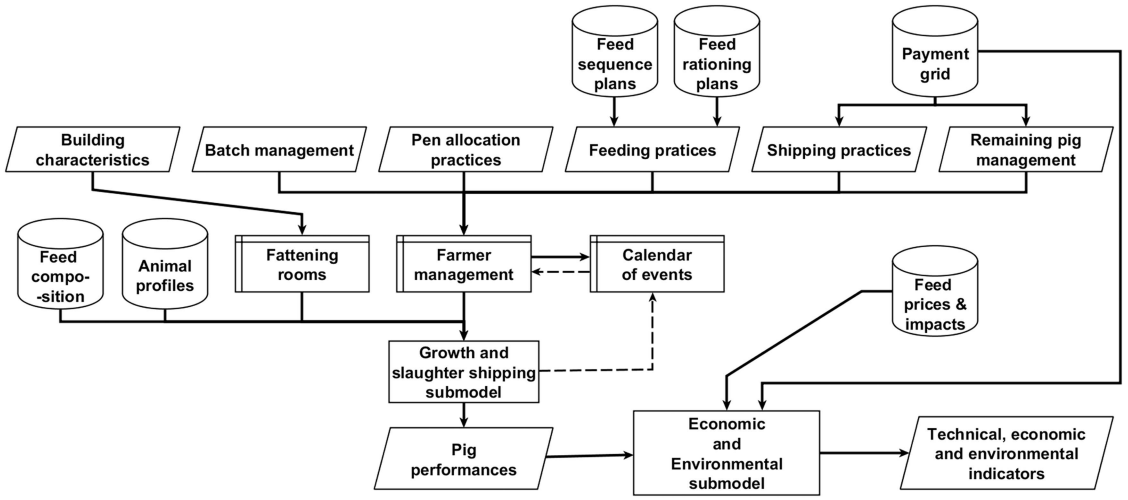


Figure 1 Diagram of the fattening unit model.

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environmental submodel, which calculates technical, economic and environmental indicators.

Buildings and animal housing

The *building* is represented by the number of fattening *rooms*, which is provided as input to the model. Each *room* contains an identical number of *pens*. The area allocated per *pig* in each *pen* is used to initialise the size of the *pen* at the beginning of the simulation. After shipping the last *pigs* in the *batch* to the slaughterhouse or to a buffer room, the *room* is considered empty after a cleaning and disinfection period. A buffer room can be used at the end of the fattening period to finish fattening the lightest *pigs* which have not reached the minimum slaughter weight (SW) without penalties.

Batch management

Upon arrival at the fattening unit, the *pigs* in each *batch* are allocated to a single *room* and distributed among its *pens* to have the same number of *pigs* per *pen*. The interval between the arrival of two successive *batches*, the size of each *batch*, and how *pigs* are allocated to the *pens* are scheduled in farm management by the *farmer*. As mentioned, *pigs* can be allocated to *pens* at random, by weight, by sex or by sex and weight. The allocation by weight means that *pigs* of similar weight are put in the same *pen*, inducing difference of mean weight between *pens*. When allocating by weight, if the number of *pigs* per *pen* is unequal, the *pens* with the lightest *pigs* contain more *pigs* than the *pens* with the heaviest *pigs*. When allocating by sex, each *pen* contains *pigs* of the same sex, except for one *pen* in which sexes can be combined to distribute *pigs* equally among all *pens*. When allocating by sex and weight, each *pen* contains *pigs* of the same sex and similar weight, except for one *pen*, which by default contains the lightest *pigs* and may contain both sexes.

Shipping to the slaughterhouse

The process for planning when to ship a group of *pigs* is based on the range of optimal SWs which have the highest premium in the payment grid. The French payment grid, used by default, is composed of ranges of weights associated with various prices per kg of carcass. In the model, *MinWr* is the minimum SW without cost penalties, and *TarWr* is the target SW, which lies in the middle of the range of SW with the highest premium. The model assumes that there is no limit to the number of *pigs* that can be shipped and that no unforeseen events occur on shipping day.

To schedule shipping (Figure 2), the 'counting ready *pigs*' function counts how many *pigs* can or must (when emptying the room) be slaughtered on the next possible shipping day (according to their weight and age). A given number of days

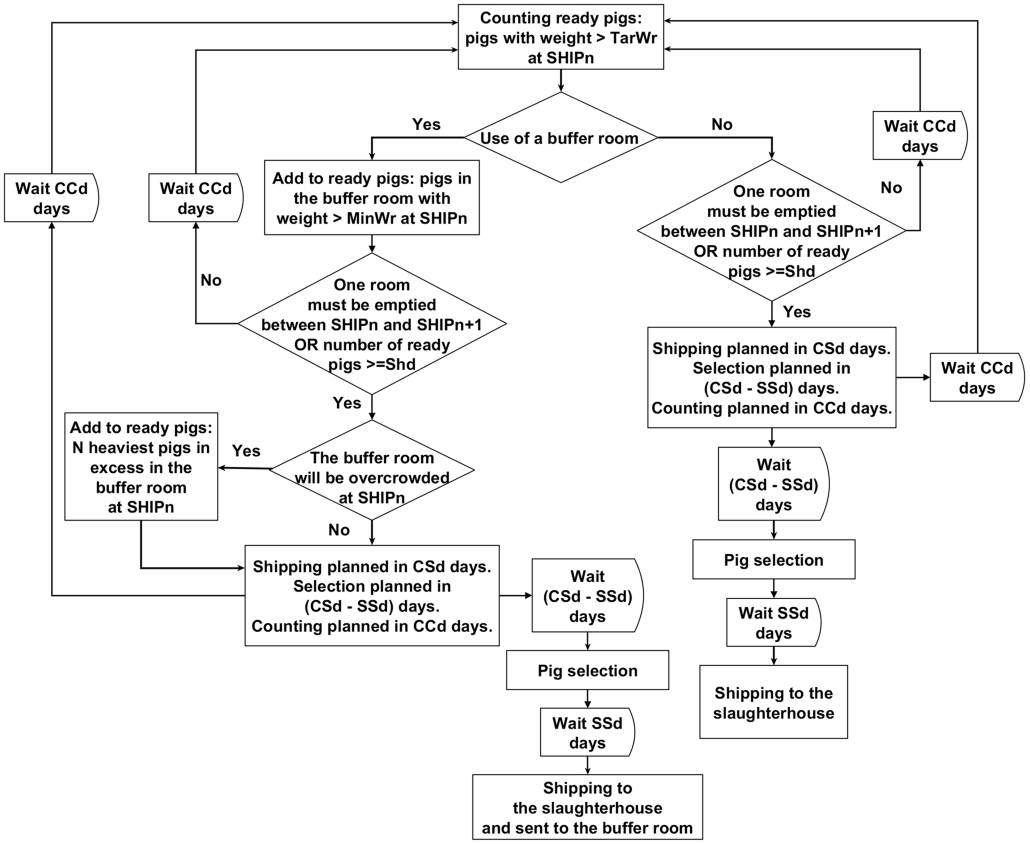


Figure 2 Diagram of the farmer's process for planning shipping to the slaughterhouse. Diamond boxes represent the decisions to take (i.e. the answer is yes or no); rectangular boxes represent actions; curved boxes represent delays between actions and/or decisions. TarWr = target slaughter weight; MinWr = minimum slaughter weight without payment penalties; SHIPn = current shipping; SHIPn + 1 = next shipping; Shd = minimum number of ready pigs required to plan shipping; CSd = interval between counting and shipping to the slaughterhouse; SSd = interval between selecting pigs and shipping to the slaughterhouse; CCd = interval between current and next counting.

https://doi.org/10.1017/S1751731117002920 Published online by Cambridge University Press

before shipping, the '*pig* selection' function selects the *pigs* that will be slaughtered (according to their weight and age) to determine slaughter groups. For this purpose, the model uses the discrete event simulation method, that is a discrete time step in which events are planned which modify the state of the system at a predefined time. In our model, counting and selection of *pigs* to determine the slaughter groups and shipping to the slaughterhouse are planned by placing their dates of occurrence in a calendar of events.

Management of the remaining fattening pigs

When a *room* must be emptied because a new *batch* is planned, the *farmer* applies the management practice chosen for the *pigs* which have not reached *MinWr*. In the 'without buffer room' option, all *pigs* are sold when the *room* must be emptied, even the lightest *pigs*, which incurs payment penalties. In the 'with buffer room' option, the lightest *pigs* are moved to the buffer room until they reach the optimal SW range or the maximum duration allowed for remaining in the buffer room.

Feeds and feeding plans

Formalisation of feeding practices is adapted from the InraPorc® model (van Milgen *et al.*, 2008), which combines a feed rationing plan, a feed sequence plan, and the level at which these plans are applied (i.e. individual, pen or room level). Each feed sequence plan defines the *feeds* provided to the animals, their relative percentages and the rules to shift from one *feed* to another (i.e. a target weight, a fattening duration or the total amount distributed). Each feed rationing plan defines the amount of *feed* or energy provided to *pigs* as a percentage of *ad libitum* intake or an amount per *pig* and per day for each period of the plan. The model shifts from one period to another in the feed rationing plan according to one of several criteria: fattening duration, age, weight, cumulative quantity of feed consumed or quantity of feed distributed. These rules are applied at the specified level: individual, pen (average value for *pigs* in the same *pen*) or room (average value for *pigs* in the same *room*). The feed rationing plans, feed sequence plans and *feed* composition are determined with the InraPorc software tool (InraPorc®, 2006) and are sent as inputs to the model.

Animals and performance

Pigs are simulated in an individual-based model, also adapted from InraPorc (van Milgen *et al.*, 2008). The model calculates feed intake (FI), protein and lipid deposition, and the resulting growth and nutrient excretion of each *pig* according to its growth potential and feeding plan. Each *pig* is assigned a profile which includes its initial age, initial weight, and four parameters that correspond to its potential FI and growth. The last five parameters are set using a covariance matrix and a multivariate random process (Vautier *et al.*, 2013) to generate the structure of a pig population. By default, the population of growing *pigs* is composed of 50% gilts and 50% barrows. All pig profiles are inputs to the model. Mortality is set at a constant rate throughout the fattening period.

Environmental indicators using Life Cycle Assessment

The environmental indicators are environmental impacts calculated by LCA. The model calculates environmental impacts of the fattening of each slaughtered *pig*, while environmental impacts of producing piglets and breeding sows in upstream farrowing and post-weaning units are calculated according to average performance (IFIP, 2016) and *feed* composition (Supplementary Material Table S2). Impacts of feed ingredients came from the ECOALIM data set (Wilfart *et al.*, 2016) and those of their transport by road to the feed factory were based on distances assumed for pig production in Western France (Garcia-Launay *et al.*, 2016). The amounts of electricity and natural gas required to grind and pelletise the feeds at the feed factory came from Garcia-Launay *et al.* (2014). By default, transport distance of the feed from the factory to the pig farm was assumed to be 30 km. Background data (i.e. impacts of road transport; electricity, light fuel oil and natural gas used in the pig unit) came from the ecoinvent database V3.1 (Weidema *et al.*, 2013).

Environmental impacts of manure use were estimated using a system expansion approach (Garcia-Launay *et al.*, 2014) in which we assumed that the manure produced replaced a certain percentage of mineral fertilisers, indicated as a mineral fertiliser equivalent (MFE, %). We assumed that MFE was 75% for manure N, which was assumed to lose 5% more N as nitrate (NO_3) than mineral fertilisers (Nguyen *et al.*, 2010), and that MFE was 100% for manure P (Sommer *et al.*, 2008). Processes for manure transport and spreading came from AGRIBALYSE V3.1 (Koch and Salou, 2015). The quantities of manure produced and N and P excreted by piglets and sows were calculated according to Rigolot *et al.* (2010a and 2010b).

Ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxide (NO_x) and methane (CH_4) emissions to the air were estimated separately for housing, manure storage and manure spreading. The model calculated amounts of nutrients (N, P, potassium (K)) remaining in manure at the end of each step. Amounts of N, P, copper (Cu), zinc (Zn), K and organic matter excreted by *pigs* were calculated by the growth and slaughter shipping submodel. Methane emissions from enteric fermentation were calculated according to digestible fibre contents of the *feeds* (Rigolot *et al.*, 2010a), while those from manure storage were calculated according to IPCC (2006) and Rigolot *et al.* (2010b). Ammonia emissions from the building and manure storage were calculated according to emission factors developed by Rigolot *et al.* (2010b). N_2O and NO_x emissions from manure storage were calculated according to IPCC (2006) and Dammgen and Hutchings (2008), respectively. During field application, NH_3 emissions were based on Andersen *et al.* (2001), N_2O emissions on IPCC (2006) and NO_x emissions on Nemecek and Kägi (2007). Potential NO_3 and phosphate (PO_4) leaching rates came from Nguyen *et al.* (2012). We calculated

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environmental impacts using the CML 2001 method and total cumulative energy demand V1.08 (non-renewable fossil + nuclear) as implemented in Simapro software, version 8.05 (PRé consultants, Amersfoort, the Netherlands). We considered potential impacts of pig production on climate change (CC, 100-year horizon, kg CO_2 _ eq., 25 CO_2 _ eq. for CH_4 and 298 CO_2 _ eq. for N_2O), eutrophication potential (EP, g PO_4 _ eq.), acidification potential (AP, g SO_2 _ eq.), cumulative energy demand (CED, MJ), and land occupation (LO, m^2 year).

Economic indicators

Gross margin per fattening *pig* is the main economic indicator in the model. It equals revenue from sale of pigs minus expenses related to their feed (Supplementary Material Table S3) and the purchase of piglets. The premium per kg of carcass is calculated according to the French payment grid used by default, which associates a bonus or malus value to each *pig* based on its carcass characteristics (weight and lean content).

Simulation study

Four simulations were performed which combined two feed rationing plans (*ad libitum* (Ad),restriction (Res)) and two feed sequence plans (two-phase (2P), 10-phase (10P)): 2P-Ad, 2P-Res, 10P-Ad and 10P-Res. The 21-day interval set between two successive batches represents the typical batch management of French pig farms. Simulations represent five fattening rooms and a buffer room with 100 places. The size of each batch was set at 400 pigs, in accordance with the mean number of pigs per batch in a French fattening unit (IFIP, 2016). The number of batches per simulation (i.e. replicates for the statistical analysis) was set at five, in order to use each pig profile only once (1000 female profiles for 200 female pigs per batch, and 1000 male profiles for 200 male pigs per batch). The duration of simulation, that is 600 days, has been chosen in order to consider the time required for model stabilisation and the completed fattening of five successive batches.

Pigs were allocated by weight in pens, and were fed according to the mean weight of each pen. The Res rationing plan simulates *ad libitum* distribution of up to a maximum of 2.5 kg of feed per day. Feed intake and nutrient requirements of gilts were used as the reference for feed formulation. Feeds were estimated using InraPorc® (2006) and provided mean reference standardised ileal digestible (SID) lysine requirements of 0.98 g/MJ at 70 days of age, 0.75 g/MJ at 65 kg of BW, and 0.54 g/MJ at 110 kg BW. Soya bean used in the formulation was assumed to be a mix produced in the Centre West (70%) and South of Brazil (30%). Two feeds, A and B, were formulated (Supplementary Material Table S4) on a least-cost basis to contain 9.75 MJ of NE per kg and to meet at least 110% of the SID amino acid requirements of the mean gilt profile (BW70 = 30 kg, $a = 4.45$, $b = 0.0216$/kg, PDm = 143 g/day, BGompertz = 0.0171/day, Brossard *et al.*, 2014) at 30 kg BW (beginning of fattening) and 120 kg BW (target SW), for example 1.13 and 0.55 g SID lysine/MJ NE, respectively. The two feeds were then combined in percentages adequate to meet amino acid requirements at the beginning of each phase in the 2P and the 10P feed sequence plans. The 2P strategy was designed to supply 1.13 g SID lysine/MJ NE from 70 days of age to 65 kg BW (Feed A) and 0.86 g/MJ NE from 65 kg BW until slaughter (combining Feed A and Feed B). The 10P strategy contained 10 feeding phases with a progressive shift from 100% of feed A to 100% of feed B. Feeds for gestating and lactating sows and for the first and second post-weaning phases (to calculate environmental indicators) were formulated according to Garcia-Launay *et al.* (2014), with feed ingredient prices from February 2014 including the cost of transporting feed ingredients (Garcia-Launay *et al.*, 2016).

The selling price of pigs is based on the French market price in February 2014 (1.314 €/kg carcass), and the premium per kg carcass is calculated according to the French payment grid. Piglet value in the simulations is estimated according to the cost of producing piglets in February 2014 (62.10 €/piglet of 30 kg BW).

The four simulations were performed twice: with (Var+) and without (Var−) variability among pigs. Two average animal profiles were used (Brossard *et al.*, 2014), one for gilts (BW70 = 30 kg, $a = 4.45$, $b = 0.0216$/kg, PDm = 143 g/day, BGompertz = 0.0171/day) and one for barrows (BW70 = 30 kg, $a = 5.02$, $b = 0.0189$/kg, PDm = 150 g/day, BGompertz = 0.0194/day) for the Var− simulations, and to generate the structure of the pig population for the Var+ simulations (Vautier *et al.*, 2013).

The average performance per simulation were calculated for the Var− simulations whereas for the results obtained from the Var+ simulations a variance analysis was performed using a linear mixed model with fixed effects of feed sequence plan, feed rationing plan, and their interaction, and random effects of the animal profile within the batch. According to this model, the experimental unit was the batch ($n = 5$). For this analysis, we used the *lme4* package (V1.1, Douglas *et al.*, 2015) and the *lmer* function of R software (R Development Core Team, 2015).

Average performances per batch were calculated (number of shipments per batch, percentage of pigs within the range of optimal SW, average premium per pig and number of pigs moved to the buffer room) and analysis of variance was performed on the results. We used a general linear model to assess effects of the feed sequence plan, feed rationing plan and their interaction. For this analysis, we used the *stats* package (V3.3.0) and the *glm* function of R software.

Results

Table 1 presents the predicted performance obtained for the four simulations, with and without considering variability among pigs.

https://doi.org/10.1017/S1751731117002920 Published online by Cambridge University Press

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Table 1 *Least-square means of the technical, economic and environmental outputs of the model for the four simulations with or without variability among pigs*

	Var − simulations[1]				Var + simulations					*P*-value		
Batches ($n=5$)	2P-Ad	2P-Res	10P-Ad	10P-Res	2P-Ad	2P-Res	10P-Ad	10P-Res	RSD	FSP	FRP	FSP × FRP
Technical performances												
Slaughter weight (kg)	118.3	118.7	118.6	118.9	118.4^{c}	117.6^{b}	117.5^{b}	116.7^{a}	2.40	<0.001	<0.001	Ns
Feed intake (kg/pig)	239.5	236.7	240.7	237.0	236.6^{c}	230.6^{a}	237.4^{d}	231.4^{b}	10.3	0.001	<0.001	Ns
Average daily gain (g/day)	907	878	909	880	901^{d}	881^{b}	887^{c}	868^{a}	33	<0.001	<0.001	Ns
FCR (kg/kg)	2.71	2.67	2.72	2.67	2.68^{c}	2.64^{a}	2.71^{d}	2.68^{b}	0.07	<0.001	<0.001	0.03
Lean content (%)	59.6	60.8	59.3	60.6	60.2^{b}	61.1^{d}	59.7^{a}	60.6^{c}	1.27	<0.001	<0.001	Ns
N excreted (kg/pig)	3.41	3.30	3.02	2.90	3.33^{d}	3.19^{c}	2.99^{b}	2.87^{a}	0.21	<0.001	<0.001	0.01
P excreted (kg/pig)	0.61	0.60	0.58	0.57	0.60^{c}	0.58^{b}	0.58^{b}	0.56^{a}	0.04	<0.001	<0.001	Ns
Pig shipping to the slaughterhouse, per batch												
Number of shipments	2.0	1.0	2.0	1.0	4.0^{c}	3.0^{b}	4.0^{c}	2.4^{a}	0.24	0.007	<0.001	0.007
Number of pigs in buffer room	0.0	0.0	0.0	0.0	21.3^{b}	14.8^{a}	25.8^{c}	19.4^{b}	3.70	0.007	<0.001	Ns
% in optimal slaughter weight	100	100	100	100	97.0^{a}	98.9^{b}	98.5^{b}	99.0^{b}	0.63	0.006	<0.001	0.02
Premium (€/kg carcass)	0.14	0.17	0.13	0.17	0.11^{a}	0.15^{b}	0.11^{a}	0.15^{b}	0.006	Ns	<0.001	Ns
Economic results												
Feed cost (€/pig)	58.3	57.6	55.0	54.2	57.6^{d}	56.3^{c}	54.5^{b}	53.1^{a}	2.34	<0.001	<0.001	Ns
Revenue (€/pig)	132.9	136.6	133.0	136.7	131.1^{b}	133.4^{d}	129.8^{a}	132.2^{c}	3.16	<0.001	<0.001	Ns
Gross margin (€/pig)	12.6	16.8	15.9	20.5	11.3^{a}	15.2^{c}	13.4^{b}	16.9^{d}	4.22	<0.001	<0.001	0.04
Environmental results, per kg live pig produced												
Climate change (kg CO_2 _ eq.)	2.55	2.52	2.46	2.43	2.53^{d}	2.51^{c}	2.47^{b}	2.45^{a}	0.045	<0.001	<0.001	0.001
Acidification (g SO_2 _ eq.)	46.1	45.2	43.6	42.5	45.6^{d}	44.7^{c}	43.7^{b}	43.0^{a}	1.38	<0.001	<0.001	0.003
Eutrophication (g PO_4 _ eq.)	16.6	16.3	15.8	15.5	16.4^{d}	16.1^{c}	15.8^{b}	15.6^{a}	0.44	<0.001	<0.001	0.003
Cumulative energy demand (MJ)	15.2	15.0	14.6	14.4	15.1^{d}	14.9^{c}	14.6^{b}	14.5^{a}	0.27	<0.001	<0.001	0.002
Land occupation (m^2 year)	3.60	3.55	3.52	3.48	3.57^{c}	3.53^{b}	3.53^{b}	3.50^{a}	0.068	<0.001	<0.001	0.006

2P-Ad = two-phase + *ad libitum*; 2P-Res = two-phase + restriction; 10P-Ad = 10-phase + *ad libitum*; 10P-Res = 10-phase + restriction; RSD = residual standard deviation; FSP = feed sequence plan; FRP = feed rationing plan; N = nitrogen; P = phosphorus; FCR = feed conversion ratio.

The significance of the effect of FSP, FRP and their interaction concerns only the individual-based model simulations. Environmental outputs include impacts of farrowing, post-weaning, and fattening units.

[a,b,c,d]Means followed by same letter do not differ ($P>0.05$) according to Fischer's test.

[1]Simulations with (Var +) or without (Var −) variability among pigs.

Effect of the incorporation of variability among pigs

Average SW does not differ between strategies in Var− simulations, whereas it varies from 116.7 to 118.4 kg in Var+ simulations. Feed intake, average daily gain (ADG), feed conversion ratio (FCR), N and P excreted, economic results, and premium are higher in Var− than in Var+ simulations, and lean content is lower. The number of shipments is 1.9 less per batch in Var− than in Var+, with in average 100 *v.* 98.4% of pigs in optimal SW, respectively. Moreover, no pigs were sent to the buffer room in Var− whereas they were in average 20.3 sent to buffer room in Var+. Environmental impacts are in average 0.9% higher in Var− than in Var+ for the 2P scenarios, whereas the opposite is found in the 10P scenarios. In the next subsections, we will focus on the results of the Var+ simulations. Regarding the Var+ simulations, effects of feed rationing and feed sequence plans (FSP and FRP) are significant for all variables, except for the premium with FSP.

Simulation of technical performances

Slaughter weight is heavier in Ad than in Res pigs and is also heavier with the 2P than with the 10P feeding strategy. Average daily gain and excreted N and P experience similar effects. Conversely, lean content is lower in Ad than in Res pigs and is also lower with the 10P than with the 2P feeding strategy. Feed intake and FCR are higher in Ad than in Res pigs and are also higher with the 10P than with the 2P feeding strategy.

Mean live weight decreases each time pigs are shipped (Figure 3). The standard deviation of pig weight, initialised at the beginning of fattening, increased during the simulation. An early shipment of the heaviest pigs appears at 140 days of age in Ad simulations but not in Res simulations (Figure 3). This suggests that performance differ more with the Ad than with the Res feeding strategy.

Simulation of shipping to the slaughterhouse

The mean number of shipments per batch is higher for Ad than for Res pigs and is also higher with the 2P than with the 10P feeding strategy. Conversely, the percentage of pigs within the range of optimal SW is lower for Ad than for Res pigs and is also lower with the 2P than with the 10P feeding strategy. The mean number of pigs moved to the buffer room is higher for Ad than for Res pigs and is lower with the 2P than with the 10P feeding strategy. The average premium per pig is lower for Ad than for Res pigs, but the feed sequence plan has no significant effect on it.

Simulation of economic and environmental indicators

Feed cost per pig is higher for Ad than for Res pigs and also higher with the 2P than with the 10P feeding strategy. Conversely, average revenue per pig is lower for Ad than for

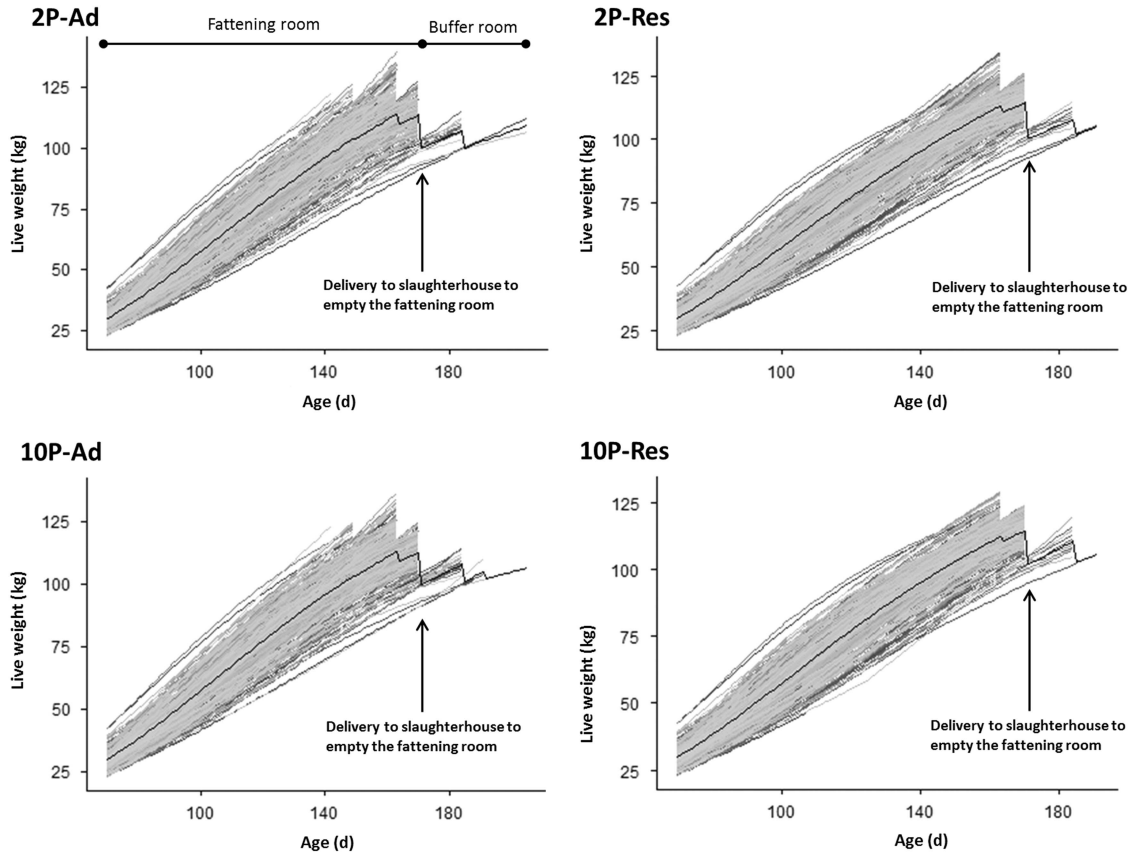


Figure 3 Predicted growth curves of pigs from the same batch from four simulations with representation of the variability among pigs. Each black curve represents the average weight of pigs in the batch. 2P-Ad = two-phase + *ad libitum*; 2P-Res = two-phase + restriction; 10P-Ad = 10-phase + *ad libitum*; 10P-Res = 10-phase + restriction.

https://doi.org/10.1017/S1751731117002920 Published online by Cambridge University Press

Res pigs. Consequently, the gross margin is higher for Res pigs and is also higher with the 10P feeding strategy.

Climate change impact per pig is higher for Ad than for Res pigs and is also higher with the 2P than with the 10P feeding strategy. Similar effects are observed on AP, EU, CED and LO impacts.

Discussion

The model developed in this study is able to simulate dynamics of a pig fattening unit by considering variability in performances among pigs and interactions with farmers' practices and farm infrastructure. Such a model can be used for analyses of scenarios as illustrated in the simulation study provided. Performing the statistical analysis of the results from the scenarios needs to address the issue of the numbers of replicates (i.e. batches) and pigs per batch in a way slightly different from classical animal experiments. As the choice of the number of replicates may change the *P*-values we tested the effect of increasing it from five to 10 with no effect on mean farm results. The simulations required about 7 min computation time per scenario with five replicates. This seems reasonable, although already long, in the perspective of routine use as decision support tool for on-farm advice.

Accounting for variability in performances among pigs provides a way to accurately represent effects of farmers' practices. Most published models simulate only one shipment to the slaughterhouse. With a 21-day interval between two successive batches, in practice, farmers usually organise three to five shipments per batch (Aubry *et al.*, 2016). Using average animal profiles does not allow simulating the occurrence of all shipments and induces an overestimation of the economic results (e.g. by 11% to 21% for gross margin). This is mainly related to the fact that without variability in animal characteristics all pigs from the same gender have the same nutrient requirement and achieve the same growth and carcass performance. This results in maximum two shipments per batch, one for the gilts and one for the barrows. Due to the lack of variability the premium per pig is also higher resulting in improved economic performance. For these reasons, we will focus in the following discussion on the results from the Var + simulations.

The model showed appropriate behaviour when compared with expert knowledge. Results of the 2P-Res simulation, which represents the most common feeding strategy in France, are in the range of the results of French pig farms (IFIP, 2016) for characteristics such as FCR (2.64 *v.* 2.69 ± 0.17 kg feed/kg live weight from 30 to 115 kg), lean content (61.1 *v.* 61.0 ± 0.8%), and average SW (117.6 *v.* 119.6 ±2.9 kg). The relative differences between two-phase and multiphase feeding strategies obtained with the model and in previous studies also suggest that the model adequately simulates the effects of the feeding strategies investigated here. Indeed, the calculated amount of N excreted per pig is 10% lower in multiphase *v.* two-phase feeding strategy with the model, what is in line with previous experimental results: the difference between one-phase and multiphase strategies in Bourdon *et al.* (1995) was 10% and the decrease of nitrogen excreted between a three-phase programme and a daily multiphase programme was 12.5% in Andretta *et al.* (2014). The model (with variability among pigs) also predicted a very slight increase (+1%) of FCR when shifting from two-phase to multiphase strategy what is in accordance with the experimental results of Pomar *et al.* (2014) who did not find a significant increase in FCR between three-phase and daily multiphase feeding. This is also in accordance with Brossard *et al.* (2009) who already found with a simulation approach that using multiphase *v.* two-phase strategy may increase FCR, when the SID lysine content at the beginning of each phase is set at a value lower or equal to 110% of the mean population requirement. Although the model proposed here needs to be further extensively validated against experimental results, this first study suggests that it simulates adequately the effects of these feeding strategies.

Effects of feeding practices on pig performance are often studied in pig production models, but the resulting output at slaughter and the economic indicators are less documented. In our model, feed restriction results in a higher gross margin, due to lower feed cost and higher selling price, than *ad libitum* feeding. Morel *et al.* (2012) studied effects of animal genotype and feed rationing plan on the gross margin of a fattening unit, finding that feed restriction increases the gross margin more than an *ad libitum* feeding, regardless of the genotype.

In our study, use of a 10-phase feed sequence plan results in a lower variability in pig SW, like in Niemi *et al.* (2010), and in a higher gross margin than use of a two-phase feed sequence plan. Morel *et al.* (2012) suggested that pig genotype, especially maximum daily protein deposition potential, has a major influence on technical and economic performances of the unit. Our model includes effects of pig genotype in pig profiles and incorporates the feed cost to estimate effects of a management strategy on technical and economic performances.

As in Garcia-Launay *et al.* (2014), our results indicate that increasing the number of phases in the feed sequence plan reduces environmental impacts. More phases increase the supply of nutrients to pigs and decrease N and P excretions. According to Monteiro *et al.* (2016) and our simulations, increasing the number of phases tended to increase mean FCR and decrease ADG. As they suggested, this could be related to supplying insufficient amounts of amino acids to the highest performing pigs during transition periods.

Conclusion

To our knowledge, our model is the first individual-based model of a fattening pig unit which also calculates economic and environmental performances. This model is promising for exploration of effects of farmers' practices, pigs' characteristics and farm infrastructure on technical, economic and environmental performances of the unit, and simulation of different management practices to improve performances or

https://doi.org/10.1017/S1751731117002920 Published online by Cambridge University Press

reduce costs. In the near future, the model will be used to simulate a virtual experiment to investigate effects of both management and feeding practices, and their interactions with the potential performance of the pig population, on technical, economic and environmental performances of the pig fattening unit. This model is intended for application in France in conventional farms, but it should be usable in other countries with appropriate calibration. Because it is also intended for on-farm advice, the model will be further tested with external data before being included in decision support tool.

Acknowledgements

The authors thank Alain Valancogne for advice during integration of the InraPorc model in MOGADOR. This study was supported by CIFRE Ph.D. funding (agreement in industry for training by research) of the ANRT (National Agency for Research and Technology) with co-funding from the call for projects 'Targeted research and innovation' of the French Ministry of Agriculture, Agrifood and Forestry.

Software and data repository resources

The code to perform the simulations described in this paper is accessible on the ZENODO data warehouse (https://zenodo.org/record/890623#.WcuRoWekFcg). Launching the file 'Animal_MOGADOR.R' using R software will reproduce the paper results.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1751731117002920

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