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Using network flow modeling to determine pig flow in a commercial production system

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ABSTRACT

The systematic approach to raising pigs in a multi-site production system, in terms of where the pigs are housed and how long they are fed, is generally called pig flow. This complex process is most often approached in a segmented fashion, not looking at all barns at the same time in relation to each other. Linear programming, the basis of most nutritional formulation packages and logistics services, provides a mathematical means for characterizing pig flow that allows a producer to look at the entire flow of pigs in a system at the same time. We describe a teaching model that provides the foundation to characterize pig flow in a commercial production system. The teaching model is built in Microsoft Excel® and incorporates key components of production such as growth rate, mortality, stocking density, seasonality, packer grid pricing, and marketing. The results from this teaching model are sound and provide the foundation for a larger model that is needed for full implementation within a production system, proving this model behaves as expected. The generalizability of the model and its assumptions allows for the inclusion of more barns, a more precise measure of time, and the ability to change the assumptions utilized in this teaching scenario, which are needed for direct application in a production system.

1. Introduction

Nutritionists in the livestock industry have utilized linear programming to formulate least cost diets for over 40 years (Church et al., 1963; Peart and Curry, 1998). Linear programming is a computer modeling tool for solving optimization problems, such as profit maximization or loss minimization, for a wide array of agricultural, animal science, and other areas of interest. Network flow model is a type of linear programming model most often used to determine optimal pathways for flow of products between different nodes in a network, optimizing a given objective (Bazaraa et al., 1990). Network flow models can be used, for example, to determine the ideal supply or transportation in a flow of products between producers and consumers in order to achieve least cost or shortest distance in a network. However, there have been few applications of this type of modeling that involve complex biological processes such as livestock production. In swine production, the pig flow or movement of pigs as they grow within a production system is characterized as a network flow.

Few models have been developed to describe pig flow through a commercial swine production system. To the authors' knowledge, most models have largely been centered upon production within one segment such as sow farms or solely on marketing strategies, but not on the cycle for a pig from wean to market (Lurette et al., 2008; Khamjan et al., 2013). In addition, only a few models have included production characteristics such as growth performance, stocking density, or multiple sale price grids. Incorporating these characteristics into a model that determines which barns pigs should be placed in, the duration of their stay, and the density at which they should be stocked could provide significant economic incentives for producers since the facility costs are a large proportion of production cost. Therefore, the purpose of this paper is to describe a teaching model that serves as a foundation for future models that can aid managers and producers with decisions concerning pig flow within an entire swine production system. Specifically, this paper will examine the development of a network flow model for pigs in a swine production system, focusing on the cycle for a pig from wean to market. Our specific aim was to develop a learning tool to simulate the complexities of pig flow through a production system.

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2. Materials and methods

The model structure follows that of a multi-product network flow over time and the logic is similar to models examining product movements from manufacturing to distribution to consumers. The base model uses a batch of pigs delivered from a sow farm as the product that moves through the stages of nursery and finisher within a swine operation that is reflective of current US swine production practices. The objective of the model is to determine the barn of placement, the length of stay, and the stocking density of each batch of pigs to maximize profit. The mathematical model developed is general in nature and is easily expandable to different time intervals and sizes of swine operations. For simplification and demonstration purposes, the time interval used in the model is a week.

The network structure of the model consists of nodes, defined by barns in nursery and finisher, and of arcs or temporal paths established by the length of stay in each stage of production (Ragsdale, 2007). The model connects the nodes and arcs, and then determines the body weight of the pig at the end of each length of stay in a particular barn. In this empirical model, a group of pigs has 1092 different available pathways that can be taken in order to maximize profit.

The empirical model describes the flow of pigs from a 6000-head sow farm that would typically wean a batch of 3000 pigs per week. The flow of 7 batches of pigs (21,000 pigs) was characterized through a swine operation over a 33-week production period. The first stage of this model determines how batches of pigs from a sow farm are housed in 4 separate nursery sites with capacity for 6000 pigs for either 6, 7, or 8 weeks (Fig. 1). A different ending weight corresponds to each length of stay. The second stage of the model determines how batches of pigs are placed in 10 finishing sites (10 separate finishing sites with 2–3 barns per site) with capacity for 600–1200 pigs per barn, for either 16, 17, or 18 weeks after the length of stay in the nursery is completed (Fig. 2). At the finisher, the model endogenously determines the stocking density as either 0.86, 0.69, or 0.63 m^2 per pig by determining the number of pigs placed in a barn (Fig. 3).

For the empirical model developed here, the cost of production per unit of weight gain is different for each pathway. The assumed weight gain increases over the length of time and as the number of pigs housed per barn decreases. However, shorter time periods and higher stocking densities may be more profitable than longer periods and lower stocking density, depending on the cost of production and marginal revenue. The model accounts for both economic indicators cost of production and marginal revenue, to determine the ideal pathway and optimize the objective function. Importantly, the model optimizes the objective function even if the market condition is not favorable and inevitably results in negative net revenue, ensuring that all pigs are pulled through the system to market.

2.1. General linear programming model formulation

The mathematical structure of the model is described in Table 1. The type of linear programming model developed is a mixed integer network flow linear programming, with both continuous and integer or binary decision variables. Decision variables are the decisions that the model changes to optimize the objective function. In this model, the objective function is margin over feed and facilities cost (MOFFC) and is maximized by deciding the number of pigs and length of stay in each barn. The MOFFC is utilized for the majority of swine producers as a first-step financial calculation to determine net revenue. The decision variables are subject to a set of constraints which characterizes the production system, i.e. number of pigs available, number of usable barns, capacity of barns, etc. Binary decision variables in this model are characterized by either a 1 (yes) or 0 (no). Using this type of decision variable is how the model eliminates the confusion of groups of pigs taking the same exact pathway. The constraints insure solutions are within limits set by the user and provide solutions that are plausible. The following sub-sections describe the development of the empirical model used to examine the general model formulation, plausibility in an empirical setting, and use for sensitivity analyses.

2.2. Input data and model parameters

Data and assumptions for the empirical model were collected from a large commercial production system located in southwest Minnesota that houses 52,000 sows and markets over 1 million pigs per year. This data was compiled to provide valid estimates of growth rate, seasonality,

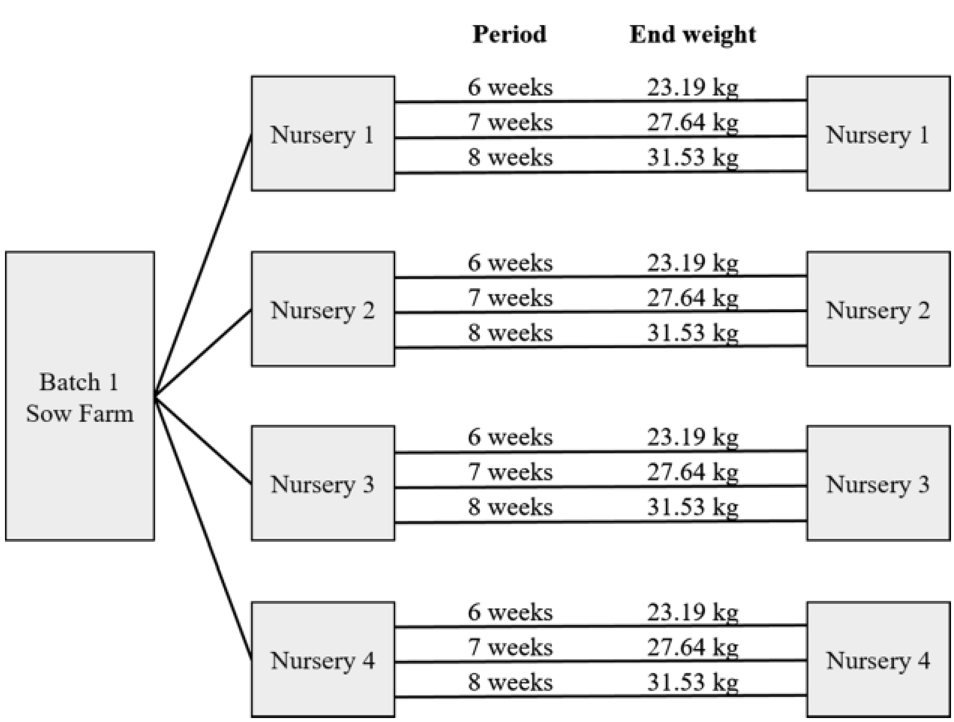

Fig. 1. Representation of the nursery flow diagram for one batch of pigs. A batch of pigs from a sow farm is housed in nursery barns (total of 4 nurseries) for either 6, 7, or 8 weeks. A different end weight corresponds to each period of stay.

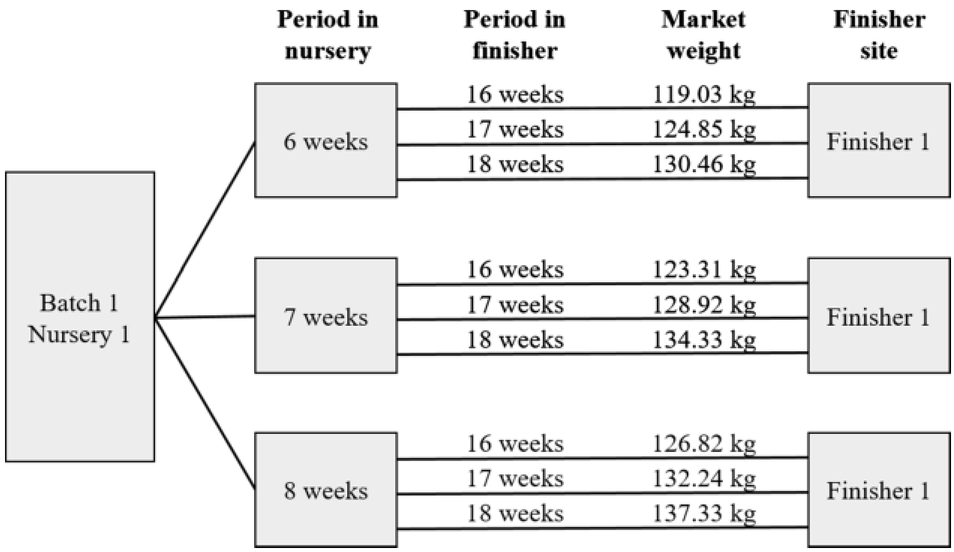

Fig. 2. Representation of the finisher flow diagram for one nursery site. After the period of stay in the nursery is completed, pigs are placed in finishing sites (total of 10 finishing sites with 2–3 barns per site) for either 16, 17, or 18 weeks. A different ending weight corresponds to each length of stay.

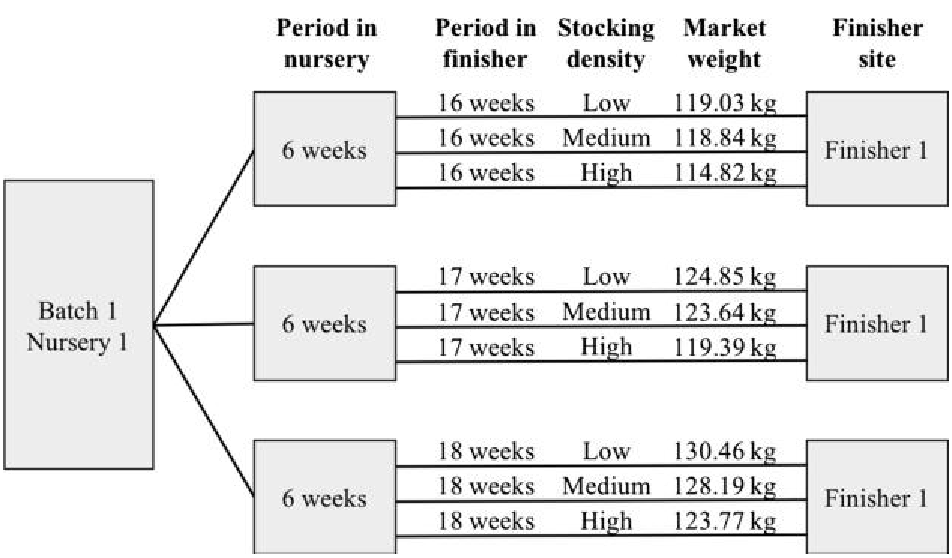

Fig. 3. Representation of the stocking density flow diagram in finisher for one period of stay in nursery. After the period of stay in the nursery is completed, pigs are placed in finishing sites and the stocking density is determined by the number of pigs placed in a barn: Low = 600–800 pigs at 0.86 m^2/pig; Medium = 800–1000 pigs at 0.69 m^2/pig; and High = 1000–1200 pigs at 0.63 m^2/pig.

mortality, and stocking densities for pork production in the model. Additionally, data from research groups, field experiments, and literature were included in the model. The estimates are kept as constants in the model for simplicity and demonstration purposes, but it is acknowledged that in practice they are not. The input equations for growth rate, floor space allowance, feed efficiency, marginal revenue, and cost of production used in the empirical model development are detailed in Table 2.

2.3. Growth period lengths and seasonality

The different lengths of stay for the nursery (6, 7, or 8 weeks) and finishing (16, 17, or 18 weeks) stages were selected based on average weights and time periods at the end of each stage relative to a commercial production system. Growth data was used to create a growth curve using a non-linear mixed model and Gompertz function in order to determine growth patterns and weight gain (Table 2) (Strathe et al., 2010). Growth parameters were determined for mixed sex and were not distinguished for barrows and gilts separately.

Seasonality was incorporated in the model by summarizing the fluctuations in mortality and growth rate of finishing pigs for 3700 barn close-outs in a commercial production system. Summarizing this data on a week-of-placement basis allowed the model to flow groups of pigs differently during certain times of year. Typically, the reduction in growth during the summer months causes a reduction in market weight or limits barn space as pigs need more days to reach market weight.

2.4. Stocking density

A low, medium, and high stocking density of, respectively, 0.86 m^2 per pig (600–800 pigs per barn), 0.69 m^2 per pig (800–1000 pigs per barn), and 0.63 m^2 per pig (1000–1200 pigs per barn) was incorporated in the model. In order to allow for the incorporation of different stocking densities, a weight:space ratio termed the *k*-factor was used to describe the effects of floor space allowance on average daily gain (ADG) of finishing pigs (Table 2) (Gonyou et al., 2006). A *k*-factor value below 0.0336 is associated with reduced ADG, but ADG is not improved beyond the growth curve when the *k*-factor is greater than 0.0336 (Gonyou et al., 2006). In the model described herein, when pigs are housed in a finisher facility at low stocking density (0.86 m^2 per pig) and weigh on average 129 kg at the first marketing event, the *k*-factor is 0.0336. Therefore, no increase or decrease in ADG should be observed. When stocking density is increased in the same finisher facility to allow 0.69 m^2 or 0.63 m^2 per pig, the *k*-factor is 0.0270 and 0.0246 and would be associated with a 5.4% and 7.3% reduction in ADG, respectively.

Table 1
General linear programming model formulation.

Model component	Equation	Purpose
Objective function: Margin Over Feed and Facility Cost (MOFFC)	$\sum_n \sum_b \sum_s \beta y_{nbs} NR_s + \sum_f \sum_n \sum_b \sum_s \sum_t \sum_q X_{fnbstq} FR_{bstq}$	The sum of the total MOFFC from the nursery and the finisher for each pig going through the swine operation
Constraints		
Pathway constraint	$\sum_n \sum_s y_{nbs} \le 1, \forall (b)$	Insures that two batches of pigs cannot take the same exact pathway
Nursery capacity constraint	$\sum_{\{(b,s):b \le k \le b+s-1\}} y_{nbs} \times \beta_k^{(1-\varphi_n)} \le c_n, \forall (k, n)$	Determines the number of batches of pigs that can be housed in nursery n for week k. It also incorporates the expected mortality φ that would accompany the pigs in each time period s that includes week k
Nursery flow constraint	$y_{nbs}(1-\varphi_n)^s = \sum_f \sum_t \sum_q X_{fnbstq}, \forall (n, b, s)$	Insures that pigs from nursery n and batch β housed for s weeks, minus the pigs lost due to mortality φ_n, are transported to finisher f
Finisher capacity constraint	$\sum_{\{(b,s,t):b+s-1 \le k \le b+s+t-1\}} X_{fnbstq}(1-\theta_f)^{(k-b-s+1)} \le d_f, \forall (f, n, t, q)$	Determines the number of pigs that can be housed at a finisher site f for week k. It also incorporates the expected mortality θ_f that would accompany the pigs in each week over the time period t the pigs are at the finisher
Stocking density constraint #1	$Z_{fnbstq}(min_q + 1) \le X_{fnbstq} \le Z_{fnbstq}(max_q), \forall (f, n, b, s, t)$	Determines the minimum min_q, and maximum max_q number of pigs X_{fnbstq} that can be put in a finisher barn at site f for each stocking density level q
Stocking density constraint #2	$\sum_q Z_{fnbstq} = 1, \forall (f, n, b, s, t)$	Insures that a set of pigs flowing through a barn at finisher site f is stocked at a set density level q in the barn on the site
Site constraint	$\sum_n \sum_b \sum_s \sum_t \sum_q Z_{fnbstq} = \alpha_f, \forall (f)$	Insures the number of groups of pigs moving through the finisher site f is less than α, the absolute number of barns the finisher site f has available
Demand constraint	$\sum_f \sum_n \sum_b \sum_s \sum_t \sum_q X_{fnbstq} \le Demand$	Insures all of the pigs are pulled through the system to market.
Non-negativity constraint	$X, y, Z \ge 0$	Prohibits any of the decision variables from taking a negative value
Integrality constraint	y, Z **must be Binary**	Insures the binary variables only take values of 0 or 1
Decision variables and parameter definitions		
b	Index for the set of batches from the sow farm	
n	Index for the set of nurseries	
s	Index for the set of weeks of stay options in the nursery	
k	Index for weeks of operation for the period of interest	
f	Index for the set of finisher sites	
t	Index for the length of stay at the finisher sites	
q	Index for the stocking density level at a finisher site	
β_k	Batch size of incoming pigs from the sow farm that is available to the system in week k	
c_n	Parameter for the capacity of nursery n	
φ_n	Parameter for the mortality rate in nursery n	
α	Parameter for the number of finishers at site f	
d_n	Parameter for the capacity of finishers at site f	
θ_f	Parameter for the mortality rate for finishers at site f	
y_{nbs}	Binary variable indicating if pigs from batch b are put in nursery n for s weeks	
Z_{fnbstq}	Binary variable indicating if pigs from batch b from nursery n for s weeks are placed at finisher site f for t weeks at q stocking density level	
X_{fnbstq}	Decision variable deciding the number of pigs at a finisher site f for t weeks and at q stocking density level from batch b from nursery n stocked for s weeks	
min_q	Minimum number of pigs allowed in a barn at q stocking density level	
max_q	Maximum number of pigs allowed in a barn at q stocking density level	
NR_s	Margin over feed and facility cost for a pig from a nursery housed for s weeks	
FR_{stq}	Margin over feed and facility cost for a pig from a finisher staying t weeks at a stocking density q from a nursery where the pig stayed s weeks	

Therefore, the reduction in growth performance at each stocking density is dramatically different.

2.5. Marketing strategies

A marketing strategy that is commonly performed by U.S. producers is to sell pigs out of a barn over multiple weeks during the end of the finishing stage. Producers use multiple marketing events due to limited space towards the end of the finishing period, logistical issues, shackle space at the plant, and as an attempt to reduce variability in carcass weight (Schinkel et al., 2002; Li et al., 2003; Khamjan et al., 2013). The economic literature has argued that one and even two marketing events before the barn close out may be economically optimal depending on market prices and feed costs (Flohr et al., 2016). The model uses a marketing strategy consisting of two marketing events prior to the barn close out, where the heaviest 10% of pigs in a barn are marketed 4 weeks before the barn close out, followed by the next heaviest 15% marketed 2 weeks before the barn close out. The reason for deciding the marketing strategy as 10%, 15%, and then 75% in the model is to demonstrate the possibility of marketing by individual semi loads or larger groups of pigs. In the empirical model, it was assumed that sorting accuracy is 100%, but most likely is not the case in reality. The sorting accuracy is dependent on the sorting skills of the marketer and the utilization of automatic sorting technology, which is not currently utilized on a large scale (Li et al., 2003). An array of marketing strategies and sorting accuracy could be accommodated in the modeling framework, but it is beyond the current scope of the model.[1]

To determine the weight of the pigs at each marketing event, a

[1] The distribution of weights of pigs in the barn is normally distributed and the first marketing event represents the top 10% of pigs in that distribution. Assuming a marketing event with the heaviest 10% pigs in the barn and an accuracy of P%, the first marketing event would randomly select P% of the top 10% of pigs. Then, to represent sorting inaccuracy, one could randomly select the remaining 1-P% from the next 10% below that. This would make the model stochastic in nature and require a simulation approach for modeling, which is beyond the current modeling framework.

Table 2
Input equations used in the empirical model development.

Title	Equation	Source
Growth curve	$\text{Weight, kg} = \left(482.86e^{-e^{-\frac{(d-132.50)}{85.92}}}\right) \times 0.454$, where d is day of age,	KSU Swine Research
k-factor	$k = \frac{\text{Area, m}^2}{\text{BW, kg}^{0.667}}$	Gonyou et al. (2006)
k-factor reduction	If $k < 0.0336$, ADG reduction, % = 817 × *k* + 72.55	Gonyou et al. (2006)
Marginal revenue	= (final BW, kg × carcass yield, % × carcass price, \$/kg) − (initial BW, kg × 75% × carcassprice, \$/kg)	KSU Swine Research
Adjusted feed efficiency	= input F:G + (initial input BW, kg − initial model BW, kg) × 0.011 + (final input BW, kg − final model BW, kg) × 0.011	Goodband et al. (2009)
Nursery feed cost	= (final BW, kg − initial BW, kg) × adjusted F:G × diet cost/kg	KSU Swine Research
Finisher feed cost	= (total feed to 113 kg × early finishing diet cost) + (total feed from 113 kg to market × late finishing diet cost)	KSU Swine Research
Facility cost	= pig days × \$0.10	KSU Swine Research
Mortality cost	$= \frac{\text{pigs placed} \times (\text{mortality, \%} \times \text{lenght stay, wk}) \times (\text{feed cost} + \text{facility cost} + \text{wean pig cost})}{\text{pigs placed, n} \times (1 - \text{mortality, \%} \times \text{lenght stay, wk})}$	KSU Swine Research
Nursery MOFFC	= marginal revenue − facility cost − feed cost − mortality cost − weaned pig cost	KSU Swine Research
Finisher MOFFC	= marginal revenue − facility cost − feed cost − mortality cost	KSU Swine Research

normal distribution around the average barn weight was calculated using the Kansas State University Swine Weight Variation Calculator (Kansas State University, 2014). The coefficient of variation (CV) increases as the mean weight in the barn increases. However, as the heaviest pigs in the barn are marketed the CV begins to decrease (DeDecker et al., 2005; Patience and Beaulieu, 2006; Beaulieu et al., 2010). As a result, a CV of 10% was utilized for the first marketing event, 9% for the second marketing event, and 8% for the barn close out. The CV may decrease at a steadier rate, but the present model adopts a conservative approach. At the end of the finisher period, no reduction in price was given to cull pigs or light weight pigs.

2.6. Economics

The economic indicators included in and accounted for in the model were marginal revenue and production cost (Table 2). Marginal revenue is based on carcass gain, market price and packing grid. Multiple packer grids were incorporated into the model to allow the determination of pig flow based on the packing company, as this could impact the optimal solution to the model. Although some marketing strategies allow to market to multiple packers at a time, the current model was based on an integrated system that typically market to one packer at a time. Accordingly, the model uses one packing grid selected by the user, but provides flexibility by allowing the choice of which packer the operation solely markets to. Marginal revenue was calculated for the weight gain at the nursery and for each marketing event at the finisher.

Production cost was determined by feed, facility, and mortality cost, and was subtracted from marginal revenue in order to determine the MOFFC at nursery and finisher (Table 2). Adjusted feed efficiency (Goodband et al., 2009) was used to calculate feed cost as it typically represents the largest proportion of the production cost. Facility cost per pig was used to determine housing cost, which typically includes rent or construction of the barn space, water, electricity, maintenance, and labor. In the current model, the value of \$0.10 per pig space per day was calculated based on the facility cost estimated with the Kansas State University Cost-Return Budget. Users have the ability to change input pricing and feed efficiency information, increasing the flexibility of the model to be incorporated into a multitude of performance scenarios (Goodband et al., 2009).

Mortality cost tends to be determined differently across production systems. In this model, it is assumed that half of the expected mortality occurs before the midpoint of nursery or finishing and the other half afterwards. The mortality cost is calculated by determining the feed and facility cost that a pig would accrue for half of a nursery or finishing turn. For example, if nursery pigs were housed for 7 weeks and accrued a total input cost of \$52.50 that included feed, facility, and the initial cost of the pig, it would be divided across the entire group of pigs for each pig lost. For a nursery group of 3000 pigs with 2.0% mortality, the total number of pigs lost is 60 and the total mortality cost is the product of \$52.50 by 60 pigs divided by 2, or \$1575. Thus, the mortality cost per live pig moved out of the nursery is \$0.54. This does not account for the lost opportunity or revenue potential from the pig. This same calculation is made for finishing pigs marketed at each marketing event and barn close out.

The parameters and input prices in the model were defined based on a stable and moderate market place and on a commercial production system (Table 3). In the nursery stage, different diet costs were used for each length of stay due to the large range in diet cost per ton between nursery phases. In the finisher, the overall diet cost is consistent throughout the finisher phases and well represented by a weighted average of the diet cost. Although ractopamine was not utilized in the model or incorporated in the growth curve function, fluctuation in diet cost still occurs in the last finishing phase when the length of the finishing period is increased. Thus, an average diet cost from entry into the finisher until 113 kg (early finishing) and from 113 kg to market (late finishing) was used in the model to calculate total feed cost during the finishing period.

2.7. Building the linear programing model in Excel®

The empirical model was developed using Microsoft Excel® and was solved utilizing the Open Solver® package available for download from OpenSolver.org (Open Solver, 2014). This solver package can analyze mixed integer linear programming models and handle models with a large number of constraints and decision variables. Given the software package does not provide any sensitivity analysis indicating the largest cost centers of production, sensitivity analyses were completed manually by sequentially solving the model to illustrate how the model solution changes as inputs change. For this model, the flow of 7 batches of pigs (initial size of 3000 weaned pigs per batch) was characterized

Table 3
Parameters and input values for the baseline empirical model.

Parameter	Input value[a]
Market prices	
Weaned pig cost, $/pig	$33.20
Market price, $/kg carcass	$1.65
Diet cost, $/metric ton	
6-week nursery turn	$408.08
7-week nursery turn	$390.22
8-week nursery turn	$378.32
Early finishing (entry to 113 kg)	$270.06
Late finishing (113 kg to market)	$259.04
Feed efficiency	
Nursery	1.68
Finishing	2.89
Mortality, %	
Nursery	2.0%
Finishing	2.5%
Facility cost, $/pig space/day	$0.10
Initial start date of flow	January 1st

[a] Values above were chosen based on prices and parameters that would be seen in a stable and moderate market place and in a commercial production system.

through a swine operation over a production period of 33 weeks. The model used 4 separate nurseries and 21 finishing barns arranged as 10 separate finishing sites with 2–3 barns per site. The nurseries were constrained to a capacity of 6000 pigs at any given time, while the finishing barns were constrained to house between 600 and 1200 pigs per barn. The model structure was made generalizable to allow it to be easily scalable over space and time. The model was constructed with a built-in user interface to allow for customization across production systems and provide a wide variety of sensitivity analysis. The model and overall structure as it was built in Excel® is explained further in Appendix A.

3. Results and discussion

3.1. Baseline model results

The baseline empirical model was run with the input parameters presented in Table 3. These values were chosen based on prices and parameters that would follow a stable and moderate market. The objective function value for the baseline results for MOFFC was $543,997, which equated to $27.20 per pig or $0.16 per kg (Table 4). The average weight of pigs marketed was 131.6 kg with an average nursery turn of 8 weeks and finishing turn of 17.5 weeks. Approximately 6% of the pigs were housed at a low stocking density, while 19% and 75% were housed at either a medium or high stocking density, respectively.

This is similar to what would be found at a commercial production system, with the exception of the percentage of pigs stocked at low stocking density. Typically, producers inherently would not choose to stock at largely different densities in each barn. However, due to variation in weaned pigs per week from a sow farm, a producer could certainly have a small amount of variation in stocking density. In the current model, the amount of variation may be inflated by the ranges in stocking density that were chosen for demonstration purposes.

3.2. Sensitivity analysis

Two sets of sensitivity analysis were completed to demonstrate the performance of the model. The analyses examined the impact of changes in market price and feed cost on model performance because of their significant impact on profitability (Niemi et al., 2010). In addition, these analyses are common in the economic assessment of swine operations (Drum and March, 1999; Stalder et al., 2000).

The first set of sensitivity analysis evaluated the effect of market price on MOFFC when production costs remain constant (Table 5). The range of $0.55–$2.75 per kg of carcass weight was chosen to demonstrate how the model works over a wide range of prices. When market price increases or decreases from the baseline of $1.65 per kg of carcass weight, MOFFC per pig responds in the same direction, such that when

Table 4
Baseline model results[a].

Batch	Nursery barn	Nursery length, wk	Finishing site	Finisher length, wk	Stocking density	Number of pigs housed
1	2	8	10	17	Medium	801
1	2	8	8	17	High	1001
1	2	8	4	18	High	1130
2	1	8	8	17	Low	601
2	1	8	5	18	High	1200
2	1	8	4	18	High	1131
3	3	8	10	18	Medium	801
3	3	8	6	18	High	1130
3	3	8	1	17	High	1001
4	4	8	6	17	High	1131
4	4	8	2	18	High	1200
4	4	8	2	16	Low	601
5	1	8	7	18	Medium	801
5	1	8	5	18	High	1001
5	1	8	3	18	High	1130
6	4	8	10	18	High	1130
6	4	8	9	16	Medium	801
6	4	8	1	16	High	1001
7	3	8	9	18	Medium	801
7	3	8	7	18	High	1001
7	3	8	3	18	High	1130

[a] The model used an initial flow of 21,000 pigs over a 33-week period with an initial weight of 5.7 kg. The objective function (margin over feed and facility cost; MOFFC) for the baseline model results was $543,997 for the entire system, which equated to $27.20/pig or $0.16/kg. The average weight of marketed pigs was 131.6 kg with an average nursery turn of 8 weeks and finishing turn of 17.5 weeks.

Table 5
Effect of market price on margin over feed and facility cost (MOFFC), market weight, length of turn, and stocking density of finishing pigs[a].

Market price, $/kg carcass	$0.55	$1.10	$1.65[b]	$2.20	$2.75
Objective function MOFFC, $	$(1,611,148)	$(562,222)	$547,568	$1,703,339	$2,915,820
MOFFC, $/pig	$(79.94)	$(28.06)	$27.38	$85.18	$145.91
Average market wt., kg	116.7	122.6	131.6	132.3	136.7
Length of barn turn, wk					
Nursery	6	8	8	8	8
Finisher	16.00	16.00	17.47	17.52	18.00
Stocking density[c], barns					
Low	1	0	2	3	0
Medium	6	7	5	6	21
High	14	14	14	12	0

[a] All other cost and parameters were held constant with the baseline model.
[b] Baseline model price.
[c] These values indicate the count or number of barns at each stocking density: Low = 600-800 pigs at 0.86 m^2/pig; Medium = 800-1000 pigs at 0.69 m^2/pig; and High = 1000-1200 pigs at 0.63 m^2/pig.

pigs are worth $0.55 per kg of carcass weight the MOFFC per pig is ($79.94), but when pigs are worth $2.75 per kg of carcass weight the MOFFC per pig is $145.91. When market price is low, the model chooses to place as many pigs as are available at a high stocking density, while still satisfying the capacity constraints for the barns. This flow results because the reduction in ADG from increased stocking density does not impact the overall MOFFC as much as the cost reduction of placing more pigs in a barn.

As price increases past the baseline of $1.65 per kg of carcass weight, pigs are moved from high stocking densities to medium and low stocking densities. As the value of the live gain increases, there is less savings associated with a high stocking density level. However, placing more pigs in low stocking densities begins to become cost effective at prices that are not attainable in current market situations (at prices greater than $6.60 per kg of carcass according to a sensitivity analysis not shown). The length of stay for the pigs in the system is increased as well, with the nursery length increasing first and then the finishing period. This finding is most likely because the cost of retaining pigs in the nursery for an extended period of time is less expensive than in the finisher.

The second set of sensitivity analysis focused on feed costs, which generally accounts for up to 60–70% of the total cost of production. The values used are relative percentages of feed cost compared to that used in the baseline model (Table 6). Not surprisingly, as feed cost increases, MOFFC decreases. Similar to decreasing market prices, as feed cost increases and MOFFC decreases, the average weight of pigs marketed reduced as a result of shorter finishing lengths (Schinkel et al., 2008). Also, because the cost of production increases with higher feed costs, the model adjusts by trying to decrease facility costs, placing more pigs at a higher stocking density level.

4. Conclusions

4.1. Overall summary and findings

The purpose of this paper was to describe a production tool that can aid managers and producers with decisions concerning pig flow within a swine production system. The linear programming model developed was successful at describing the characteristics of pig flow through a commercial swine production system and is adaptable to a multitude of scenarios. Although the size and scope of the model is currently limited in Excel®, the answers produced by Open Solver® provide a learning tool for giving general insight as to length of time in each stage of pig production, stocking density in a barn, and utilization of barns in a system in a multitude of economic scenarios. The general model framework provides the fundamental structure needed for engineering a much larger model capable of providing guidance for larger operations and different types of systems, which has not been done to the authors' knowledge.

Because of the generalizability of the model, it can easily be expandable over space and time, and incorporate more sophisticated approach to marketing and nutrition. Potentially, other areas of interest such as health and transportation could as well as be included in the model. However, the complexity associated with these approaches would require the use of a more powerful software package.

Table 6
Effect of relative feed cost on margin of feed and facility cost (MOFFC), market weight, length of turn, and stocking density of finishing pigs[a].

Relative feed cost, %	50%	75%	100%[b]	125%	150%
Objective function MOFFC, $	$1,509,966	$1,012,672	$547,568	$105,054	$(329,193)
MOFFC, $/pig	$75.56	$50.64	$27.38	$5.24	$(16.42)
Average market wt., kg	136.4	131.5	131.6	124.5	124.5
Length of barn turn, wk					
Nursery	8	8	8	8	8
Finisher	18.00	17.47	17.41	16.00	16.00
Stocking density[c], barns					
Low	0	2	2	0	1
Medium	20	6	5	7	6
High	1	13	14	14	14

[a] All other cost and parameters were held constant with the baseline model.
[b] Baseline model cost.
[c] These values indicate the count or number of barns at each stocking density: Low = 600 to 800 pigs at 0.86 m^2/pig; Medium = 800 to 1,000 pigs at 0.69 m^2/pig; and High = 1,000 to 1,200 pigs at 0.63 m^2/pig.

4.2. Implications

- This teaching model is successful in determining pig flow through linear programming utilizing a multiproduct network flow over time.
- The model allows the user to see the complexity of pig flow within a swine operation system and to assimilate the factors that exert influence on pig flow.
- The fully functional teaching model gives insight into the influences of MOFFC on pig flow and the impact of pig flow on profitability of a swine production system.
- The flow of pigs is predominantly impacted by market price and feed cost through changing MOFFC. The model provides the foundation for a future decision tool aiming to guide the flow of pigs in order to maximize the return to the swine operation.
- Converting the model to a more powerful software package will allow the model to deal with more realistic scenarios with larger structures and greater number of variables.

Appendix A

Purpose

This appendix describes the layout of the model described in "Utilizing linear programming to determine pig flow in a commercial production system".

Building the linear programing model in Excel®

The model using the mathematical structure and parameterization was developed using Microsoft Excel® and was solved utilizing the Open Solver® package available for download from OpenSolver.org (Schinkel et al., 2002). This solver package analyzes mixed integer linear programming models and can handle models with a large number of constraints and decision variables. Given the software package does not provide any sensitivity analysis indicating the largest cost centers of production, sensitivity analyses were completed manually by sequentially solving the model to illustrate how the model solution changes as inputs change. For this model, the flow of 7 batches of pigs (initial size of 3000 weaned pigs per batch) was characterized through a swine operation system over a production period of 33 weeks. The model used 4 nurseries barns and 10 separate finishing sites with 2–3 barns per site. The nurseries were constrained to a capacity of 6000 pigs at any given time, while the finishing barns were constrained to house between 600 and 1200 pigs per barn.

The current model was only built to handle 7 weeks of production due to the limits created by the software of choice for this type of programming, the Excel®. The intention is to describe the underlying structure for building a more robust model using an alternative type of program that would allow for a model with more complexity and scope. The following sections describe each part of the model and overall structure as it was built in Excel®. These sections help identify each individual calculation in specific detail.

User input page

The user input page allows the model to be flexible across multiple types of production systems (Fig. A1). In this model, input values for each parameter utilized in the model can be changed by the users according to the current situation. The users can input their own information for feed efficiency, diet cost, nursery and finishing length, packer grid, live or carcass price, carcass yield, and mortality rates. The objective function maximized by the parameters is margin over feed and facilities cost (MOFFC).

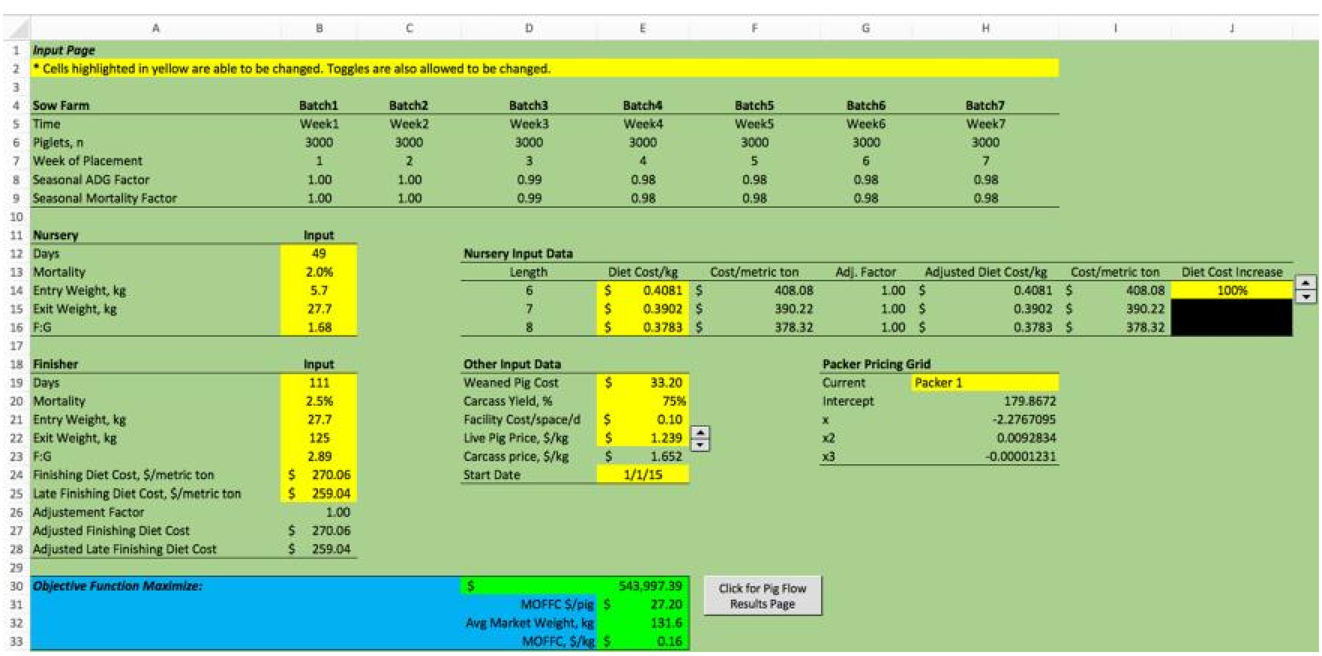

Fig. A1. Objective Function Cell and User Page. In the user input page, the input values (yellow cells) for each parameter in the model can be changed to influence the model results. The objective function margin over feed and facilities cost (MOFFC; cell E30) is maximized and the gray toggle button opens up the results page. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nursery structure

The nurseries and finishers are designated as nodes in the network flow model and were built with the same underlying structure. In the Excel® model, each respective column is used to identify a calculation while each row is associated with a particular arc or temporal pathway in the network flow (Fig. A2). At this stage of the model, binary decision variables (column C) are used to determine which pathways are chosen based on the optimized MOFFC (column M). If the model chooses to use a pathway, the binary variable equals 1 and allows a batch of 3000 pigs to enter the nursery. For example, in row 10, the pathway for pigs in batch 2 (β) is identified as an 8-week length of stay (s) in nursery 1 (n). The pathway constraint is applied in this situation to ensure that two batches of pigs do not take the exact same pathway in the nursery.

To incorporate the nursery capacity constraint, a matrix was built to calculate the number of pigs in a nursery during each week (Fig. A3). Since batch number signifies the week that a group of pigs enters the network flow, the matrix follows a tiered design. The beginning column in the matrix for a batch in the barn is the same regardless of the length of stay, but the ending column is associated directly with the length of stay. For example,

	A	B	C	D	E	F	G	H	I	J	K	L	M
3	*Nursery 1*												
4	Batch	Week	Binary	Pigs In, #	Initial, kg	Calc. Final, kg	k-factor Adjustment	Actual Final, kg	Mortality Cost/Pig	Feed, $	Facility, $	MR, $	MOFFC,$
5	1	6	0	0	5.7	23.19	1.000	23.19	$ 0.86	11.85	$ 4.20	$ 28.73	$ (21.37)
6	1	7	0	0	5.7	27.64	1.000	27.64	$ 1.07	14.40	$ 4.90	$ 34.25	$ (19.32)
7	1	8	0	0	5.7	32.50	0.970	31.53	$ 1.30	16.62	$ 5.60	$ 39.06	$ (17.66)
8	2	6	0	0	5.7	23.19	1.000	23.19	$ 0.86	11.85	$ 4.20	$ 28.73	$ (21.37)
9	2	7	0	0	5.7	27.64	1.000	27.64	$ 1.07	14.40	$ 4.90	$ 34.25	$ (19.32)
10	2	8	1	3000	5.7	32.50	0.970	31.53	$ 1.30	16.62	$ 5.60	$ 39.06	$ (17.66)
11	3	6	0	0	5.7	23.19	1.000	23.19	$ 0.86	11.85	$ 4.20	$ 28.73	$ (21.37)
12	3	7	0	0	5.7	27.64	1.000	27.64	$ 1.07	14.40	$ 4.90	$ 34.25	$ (19.32)
13	3	8	0	0	5.7	32.50	0.970	31.53	$ 1.30	16.62	$ 5.60	$ 39.06	$ (17.66)
14	4	6	0	0	5.7	23.19	1.000	23.19	$ 0.86	11.85	$ 4.20	$ 28.73	$ (21.37)
15	4	7	0	0	5.7	27.64	1.000	27.64	$ 1.07	14.40	$ 4.90	$ 34.25	$ (19.32)
16	4	8	0	0	5.7	32.50	0.970	31.53	$ 1.30	16.62	$ 5.60	$ 39.06	$ (17.66)
17	5	6	0	0	5.7	23.19	1.000	23.19	$ 0.86	11.85	$ 4.20	$ 28.73	$ (21.37)
18	5	7	0	0	5.7	27.64	1.000	27.64	$ 1.07	14.40	$ 4.90	$ 34.25	$ (19.32)
19	5	8	1	3000	5.7	32.50	0.970	31.53	$ 1.30	16.62	$ 5.60	$ 39.06	$ (17.66)
20	6	6	0	0	5.7	23.19	1.000	23.19	$ 0.86	11.85	$ 4.20	$ 28.73	$ (21.37)
21	6	7	0	0	5.7	27.64	1.000	27.64	$ 1.07	14.40	$ 4.90	$ 34.25	$ (19.32)
22	6	8	0	0	5.7	32.50	0.970	31.53	$ 1.30	16.62	$ 5.60	$ 39.06	$ (17.66)
23	7	6	0	0	5.7	23.19	1.000	23.19	$ 0.86	11.85	$ 4.20	$ 28.73	$ (21.37)
24	7	7	0	0	5.7	27.64	1.000	27.64	$ 1.07	14.40	$ 4.90	$ 34.25	$ (19.32)
25	7	8	0	0	5.7	32.50	0.970	31.53	$ 1.30	16.62	$ 5.60	$ 39.06	$ (17.66)

Fig. A2. Model Structure of Nurseries, Part 1. This figure describes the structure used to build each nursery or each node in the network flow in the spreadsheet. Each column is used to identify a calculation while each row is associated with an arc or temporal pathway in the network flow. Binary decision variables (column C) are used to determine which pathways are chosen based on the optimized margin over feed and facilities cost (MOFFC; column M).

	A	B	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
3	*Nursery 1*																	
4	Batch	Week	MOFFC,$	Week1	Week2	Week3	Week4	Week5	Week6	Week7	Week8	Week9	Week10	Week11	Week12	Week13	Week14	Pigs Out
5	1	6	$ (21.37)	0	0	0	0	0	0									0
6	1	7	$ (19.32)	0	0	0	0	0	0	0								0
7	1	8	$ (17.66)	0	0	0	0	0	0	0	0							0
8	2	6	$ (21.37)		0	0	0	0	0	0								0
9	2	7	$ (19.32)		0	0	0	0	0	0	0							0
10	2	8	$ (17.66)		2991	2983	2974	2966	2957	2949	2941	2932						2932
11	3	6	$ (21.37)			0	0	0	0	0	0							0
12	3	7	$ (19.32)			0	0	0	0	0	0	0						0
13	3	8	$ (17.66)			0	0	0	0	0	0	0	0					0
14	4	6	$ (21.37)				0	0	0	0	0	0						0
15	4	7	$ (19.32)				0	0	0	0	0	0	0					0
16	4	8	$ (17.66)				0	0	0	0	0	0	0	0				0
17	5	6	$ (21.37)					0	0	0	0	0	0					0
18	5	7	$ (19.32)					0	0	0	0	0	0	0				0
19	5	8	$ (17.66)					2991	2983	2974	2966	2957	2949	2941	2932			2932
20	6	6	$ (21.37)						0	0	0	0	0	0				0
21	6	7	$ (19.32)						0	0	0	0	0	0	0			0
22	6	8	$ (17.66)						0	0	0	0	0	0	0	0		0
23	7	6	$ (21.37)							0	0	0	0	0	0			0
24	7	7	$ (19.32)							0	0	0	0	0	0	0		0
25	7	8	$ (17.66)							0	0	0	0	0	0	0	0	0
26			Pigs, #	0	2991	2983	2974	5957	5940	5923	5906	5889	2949	2941	2932	0	0	
27			Capacity	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	
28			Utilization	0.00%	49.86%	49.71%	49.57%	99.29%	99.00%	98.72%	98.44%	98.16%	49.15%	49.01%	48.87%	0.00%	0.00%	

Fig. A3. Model Structure of Nurseries, Part 2. A matrix was built to calculate the number of pigs in a nursery during each week according to the length of stay. The left side of the nursery capacity constraint is the sum all the pigs in the nursery during each week (cells N26:AA26) and the right side is the set capacity of the barn (cells N27:AA27). The total number of pigs at the end of the nursery phase (column AB) will be transported to the finisher.

	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
3	*Finisher 1*												
4	Finisher	Nursery	Batch	Weeks in Nursery	Weeks in Finisher	Stocking Density	Minimum # of Pigs	# of Pigs	Binary	Maximum # of Pigs	Bin Const Min	Bin Const Max	Initial Wt., kg
437	1	3	3	6	16	Low	600	0	0	800	0	0	23.19
438	1	3	3	6	16	Medium	800	0	0	1000	0	0	23.19
439	1	3	3	6	16	High	1000	0	0	1200	0	0	23.19
440	1	3	3	6	17	Low	600	0	0	800	0	0	23.19
441	1	3	3	6	17	Medium	800	0	0	1000	0	0	23.19
442	1	3	3	6	17	High	1000	0	0	1200	0	0	23.19
443	1	3	3	6	18	Low	600	0	0	800	0	0	23.19
444	1	3	3	6	18	Medium	800	0	0	1000	0	0	23.19
445	1	3	3	6	18	High	1000	0	0	1200	0	0	23.19
446	1	3	3	7	16	Low	600	0	0	800	0	0	27.64
447	1	3	3	7	16	Medium	800	0	0	1000	0	0	27.64
448	1	3	3	7	16	High	1000	0	0	1200	0	0	27.64
449	1	3	3	7	17	Low	600	0	0	800	0	0	27.64
450	1	3	3	7	17	Medium	800	0	0	1000	0	0	27.64
451	1	3	3	7	17	High	1000	0	0	1200	0	0	27.64
452	1	3	3	7	18	Low	600	0	0	800	0	0	27.64
453	1	3	3	7	18	Medium	800	0	0	1000	0	0	27.64
454	1	3	3	7	18	High	1000	0	0	1200	0	0	27.64
455	1	3	3	8	16	Low	600	0	0	800	0	0	31.53
456	1	3	3	8	16	Medium	800	0	0	1000	0	0	31.53
457	1	3	3	8	16	High	1000	0	0	1200	0	0	31.53
458	1	3	3	8	17	Low	600	0	0	800	0	0	31.53
459	1	3	3	8	17	Medium	800	0	0	1000	0	0	31.53
460	1	3	3	8	17	High	1000	1001	1	1200	1001	1200	31.53
461	1	3	3	8	18	Low	600	0	0	800	0	0	31.53
462	1	3	3	8	18	Medium	800	0	0	1000	0	0	31.53
463	1	3	3	8	18	High	1000	0	0	1200	0	0	31.53

Fig. A4. Model Structure of Finishers, Part A. In addition to the basic structure, 3 levels of stocking density are incorporated within each length of stay. A binary decision variable (column AL) is used to determine which stocking density is chosen and a continuous decision variable insures the number of pigs allocated (column AK) is between the minimum and maximum capacity for that stocking density level.

batch 1 in nursery 1 begins in column N for each length of stay (6, 7, or 8 weeks), but ends in column S, T, and U for each length of stay, respectively. This matrix design is consistent throughout the entire model in all nurseries and finishers.

The nursery capacity constraint determines the number of batches of pigs that can be housed in the nursery n for week k assuming that the right-hand side of the constraint is larger than or equal to the left-hand side of the constraint (Fig. A3). The left side of the nursery capacity constraint is the sum of all the pigs in the nursery during each week (cells N26:AA26). The right side of the nursery capacity constraint is the set capacity of the barn (cells N27:AA27). The percent utilization of the barn on a per week basis is calculated by dividing the number of pigs in the barn by the capacity (cells N28:AA28). The number of pigs decreases each week because the weekly mortality rate φ is incorporated in the constraint. The total number of pigs at the end of the nursery phase (column AB) will be transported to the finisher to comply with the nursery flow constraint.

	AD	AE	AF	AQ	AR	AS	AW	AX	AY	BC	BD	BE
3	*Finisher 1*											
4	Finisher	Nursery	Batch	k-Factor 1 adjustment	k-Factor 2 adjustment	k-Factor 3 adjustment	Barn Wt. 1 w/ Seasonality, kg	Barn Wt. 2 w/ Seasonality, kg	Barn Wt. Close w/ Seasonality, kg	Event 1 Wt. w/ Seasonality, kg	Event 2 Wt. w/ Seasonality, kg	Close Out Wt. w/ Seasonality, kg
437	1	3	3	1.000	1.000	1.000	94.22	106.99	119.18	119.97	130.42	119.18
438	1	3	3	0.997	1.000	1.000	94.04	106.80	118.99	119.41	129.90	118.99
439	1	3	3	0.952	0.957	0.979	90.82	103.03	114.96	115.63	125.62	114.96
440	1	3	3	1.000	1.000	1.000	100.66	113.17	125.00	127.53	137.57	125.00
441	1	3	3	0.986	0.993	1.000	99.55	111.96	123.80	126.08	136.14	123.80
442	1	3	3	0.942	0.948	0.971	96.19	108.05	119.54	121.72	131.33	119.54
443	1	3	3	1.000	1.000	1.000	106.99	119.18	130.62	134.52	144.20	130.62
444	1	3	3	0.975	0.984	1.000	104.91	116.91	128.35	132.18	141.85	128.35
445	1	3	3	0.934	0.941	0.964	101.43	112.89	123.92	127.87	137.07	123.92
446	1	3	3	1.000	1.000	1.000	99.16	111.66	123.50	125.60	135.64	123.50
447	1	3	3	0.986	0.993	1.000	98.13	110.54	122.38	124.11	134.18	122.38
448	1	3	3	0.942	0.948	0.971	95.03	106.89	118.38	120.92	130.44	118.38
449	1	3	3	1.000	1.000	1.000	105.46	117.65	129.09	132.60	142.82	129.09
450	1	3	3	0.975	0.984	1.000	103.53	115.53	126.97	130.82	140.45	126.97
451	1	3	3	0.934	0.941	0.964	100.30	111.76	122.79	127.05	135.62	122.79
452	1	3	3	1.000	1.000	1.000	111.62	123.46	134.48	140.25	149.48	134.48
453	1	3	3	0.966	0.976	1.000	108.78	120.32	131.35	136.96	145.64	131.35
454	1	3	3	0.926	0.934	0.957	105.41	116.46	127.02	132.62	141.38	127.02
455	1	3	3	1.000	1.000	1.000	103.37	115.56	127.00	130.26	140.44	127.00
456	1	3	3	0.975	0.984	1.000	101.59	113.58	125.03	128.43	138.04	125.03
457	1	3	3	0.934	0.941	0.964	98.60	110.07	121.10	124.80	133.72	121.10
458	1	3	3	1.000	1.000	1.000	109.52	121.36	132.38	137.92	147.10	132.38
459	1	3	3	0.966	0.976	1.000	106.87	118.42	129.45	134.56	143.78	129.45
460	1	3	3	0.926	0.934	0.957	103.75	114.80	125.36	130.74	139.48	125.36
461	1	3	3	1.000	1.000	1.000	115.53	126.97	137.56	144.43	153.25	137.56
462	1	3	3	0.958	0.968	0.997	112.00	123.08	133.63	140.74	149.00	133.63
463	1	3	3	0.919	0.928	0.952	108.74	119.36	129.43	136.97	144.71	129.43

Fig. A5. Model Structure of the Finishers, Part B. The average barn weight at the marketing event (columns AW to AY) and the average weight of the pigs marketed at each marketing event (columns BC to BE) were calculated taking the k-factor adjustment and seasonality into account.

	AD	AE	AF	BF	BG	BH	BI	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP	CQ
3	*Finisher 1*			0.10	0.15	0.75																							
4	Finisher	Nursery	Batch	Event 1 Pig #'s	Event 2 Pig #'s	Close Out Pig #'s	# of Pigs Marketed	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24	Week 25	Week 26	Week 27	Week 28
437	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
438	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
439	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
440	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
441	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
442	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
443	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
444	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
445	1	3	3	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
446	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
447	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
448	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
449	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
450	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
451	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
452	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
453	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
454	1	3	3	0	0	0	0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
455	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
456	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
457	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
458	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
459	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
460	1	3	3	98	147	731	976					999	998	996	995	993	992	990	989	987	986	984	982	981	979	978	976	975	
461	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
462	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
463	1	3	3	0	0	0	0					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. A6. Model Structure of the Finishers, Part C. The number of pigs marketed at each marketing event (columns BF to BI) was calculated accounting for mortality rate.

Finisher structure

For the finisher, three levels of stocking density were incorporated into the model in addition to the basic structure (Fig. A4). The level of stocking density (column AI) that each pathway designates and the minimum and maximum number of pigs (columns AJ and AM) in the barn for each respective stocking density were incorporated. The binary variable (column AL) ensures that only one stocking density is chosen in a pathway. The difference in the finisher structure from that of the nursery is that each pathway also has a set of continuous decision variable for the number of pigs entering the barn at each stocking density (column AK). If the model chooses to use a pathway, the binary variable for the stocking density equals 1 (column AL), and the minimum (min_q) and maximum (max_q) binary constraints (columns AN and AO) insures the number of pigs allocated (column AK) is between the minimum and maximum capacity for that stocking density level to comply with the stocking density constraint.

The *k*-factor adjustments (columns AQ to AS) are the associated reductions in average daily gain for the pigs from entry until the first marketing event (*k*-factor adjustment 1), from the first to second marketing event (*k*-factor adjustment 2), and from the second marketing event to barn close out (*k*-factor adjustment 3) considering the length of stay and stocking density (Fig. A5). The average barn weight at the marketing event (columns AW to AY) and the average weight of the pigs marketed at each marketing event (columns BC to BE) with seasonality adjustments are calculated. The number of pigs marketed at each marketing event (columns BF to BI) is also calculated accounting for mortality rate (Fig. A6).

Production cost and marginal revenue for each pathway are shown in Fig. A7. Feed cost is calculated per pig at each marketing event (columns BJ to BL). Facility and mortality cost are calculated on a total per pig basis (columns BN and BO) and subtracted from the marginal revenue. Marginal

	AD	AE	AF	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU
3	*Finisher 1*														
4	Finisher	Nursery	Batch	Feed Cost to 1st Event	Feed Cost to 2nd Event	Feed Cost to Close Out	Facility Cost, $/day	Facility Cost, $/pig	Mortality Cost, $/pig	MR Event 1	MR Event 2	MR Close Out	MOFFC Event 1	MOFFC Event 2	MOFFC Close Out
437	1	3	3	$ 48.03	$ 59.84	$ 72.02	$ 0.13	$ 14.00	$ 2.97	$ 119.33	$ 132.97	$ 118.27	$ 54.33	$ 56.16	$ 29.28
438	1	3	3	$ 47.87	$ 59.66	$ 71.83	$ 0.10	$ 11.20	$ 2.89	$ 118.59	$ 132.31	$ 118.02	$ 56.63	$ 58.56	$ 32.10
439	1	3	3	$ 45.05	$ 56.07	$ 67.71	$ 0.08	$ 9.33	$ 2.74	$ 113.52	$ 126.81	$ 112.63	$ 56.41	$ 58.66	$ 32.85
440	1	3	3	$ 53.87	$ 65.90	$ 78.15	$ 0.13	$ 14.88	$ 3.35	$ 129.28	$ 141.58	$ 125.99	$ 57.18	$ 57.45	$ 29.61
441	1	3	3	$ 52.84	$ 64.70	$ 76.87	$ 0.10	$ 11.90	$ 3.24	$ 127.40	$ 139.92	$ 124.41	$ 59.43	$ 60.08	$ 32.40
442	1	3	3	$ 49.79	$ 60.86	$ 72.39	$ 0.08	$ 9.92	$ 3.06	$ 121.66	$ 134.10	$ 118.75	$ 58.90	$ 60.26	$ 33.38
443	1	3	3	$ 59.84	$ 72.02	$ 84.26	$ 0.13	$ 15.75	$ 3.76	$ 138.01	$ 148.63	$ 133.22	$ 58.66	$ 57.10	$ 29.45
444	1	3	3	$ 57.86	$ 69.68	$ 81.77	$ 0.10	$ 12.60	$ 3.60	$ 135.16	$ 146.26	$ 130.34	$ 61.11	$ 60.38	$ 32.37
445	1	3	3	$ 54.58	$ 65.63	$ 77.00	$ 0.08	$ 10.50	$ 3.39	$ 129.73	$ 141.00	$ 124.57	$ 61.25	$ 61.48	$ 33.68
446	1	3	3	$ 50.36	$ 62.28	$ 74.42	$ 0.13	$ 14.00	$ 3.17	$ 126.78	$ 139.34	$ 124.02	$ 59.24	$ 59.88	$ 32.42
447	1	3	3	$ 49.42	$ 61.18	$ 73.24	$ 0.10	$ 11.20	$ 3.07	$ 124.83	$ 137.61	$ 122.54	$ 61.14	$ 62.16	$ 35.03
448	1	3	3	$ 46.62	$ 57.62	$ 69.07	$ 0.08	$ 9.33	$ 2.92	$ 120.59	$ 133.00	$ 117.20	$ 61.72	$ 63.13	$ 35.89
449	1	3	3	$ 56.25	$ 68.32	$ 80.45	$ 0.13	$ 14.88	$ 3.57	$ 135.68	$ 147.25	$ 131.29	$ 60.99	$ 60.49	$ 32.39
450	1	3	3	$ 54.42	$ 66.15	$ 78.14	$ 0.10	$ 11.90	$ 3.42	$ 133.47	$ 144.78	$ 128.56	$ 63.72	$ 63.30	$ 35.09
451	1	3	3	$ 51.40	$ 62.38	$ 73.67	$ 0.08	$ 9.92	$ 3.25	$ 128.66	$ 139.32	$ 123.08	$ 64.10	$ 63.77	$ 36.25
452	1	3	3	$ 62.24	$ 74.38	$ 86.44	$ 0.13	$ 15.75	$ 3.98	$ 144.57	$ 153.34	$ 137.97	$ 62.59	$ 59.22	$ 31.79
453	1	3	3	$ 59.44	$ 71.08	$ 82.93	$ 0.10	$ 12.60	$ 3.79	$ 140.88	$ 150.01	$ 134.13	$ 65.04	$ 62.53	$ 34.80
454	1	3	3	$ 56.20	$ 67.11	$ 78.19	$ 0.08	$ 10.50	$ 3.59	$ 135.70	$ 145.77	$ 128.62	$ 65.41	$ 64.57	$ 36.34
455	1	3	3	$ 52.31	$ 64.23	$ 76.22	$ 0.13	$ 14.00	$ 3.35	$ 132.77	$ 144.77	$ 128.60	$ 63.12	$ 63.20	$ 35.03
456	1	3	3	$ 50.64	$ 62.24	$ 74.09	$ 0.10	$ 11.20	$ 3.22	$ 130.44	$ 142.12	$ 126.03	$ 65.38	$ 65.47	$ 37.51
457	1	3	3	$ 47.89	$ 58.75	$ 69.93	$ 0.08	$ 9.33	$ 3.06	$ 125.73	$ 137.05	$ 120.83	$ 65.45	$ 65.90	$ 38.50
458	1	3	3	$ 58.21	$ 70.21	$ 82.12	$ 0.13	$ 14.88	$ 3.75	$ 141.98	$ 151.34	$ 135.41	$ 65.14	$ 62.51	$ 34.66
459	1	3	3	$ 55.65	$ 67.16	$ 78.88	$ 0.10	$ 11.90	$ 3.58	$ 138.06	$ 148.22	$ 131.74	$ 66.94	$ 65.59	$ 37.38
460	1	3	3	$ 52.67	$ 63.46	$ 74.45	$ 0.08	$ 9.92	$ 3.40	$ 133.38	$ 143.72	$ 126.46	$ 67.39	$ 66.94	$ 38.69
461	1	3	3	$ 64.20	$ 76.19	$ 87.97	$ 0.13	$ 15.75	$ 4.17	$ 148.86	$ 156.09	$ 141.57	$ 64.74	$ 59.98	$ 33.68
462	1	3	3	$ 60.65	$ 72.02	$ 83.52	$ 0.10	$ 12.60	$ 3.95	$ 145.09	$ 152.95	$ 136.93	$ 67.89	$ 64.38	$ 36.87
463	1	3	3	$ 57.45	$ 68.13	$ 78.87	$ 0.08	$ 10.50	$ 3.75	$ 140.89	$ 149.13	$ 131.72	$ 69.19	$ 66.75	$ 38.60

Fig. A7. Model Structure of the Finishers, Part D. Calculations for feed, facility, and mortality costs, as well as marginal revenue (MR) and margin over feed and facility cost (MOFFC) on a per pig basis for each marketing event.

Computers and Electronics in Agriculture 155 (2018) 190–202

	CY	CZ	DA
3	***Pathway Constraint***		
4	Batch	Outflow	Supply
5	1	3000	3000
6	2	3000	3000
7	3	3000	3000
8	4	3000	3000
9	5	3000	3000
10	6	3000	3000
11	7	3000	3000

Fig. A8. Pathway constraint. The pathway constraint insures that each batch of pigs takes a unique pathway through the nursery.

revenue is calculated on a per pig basis at each respective marketing event (columns BP to BR). The MOFFC for each pig marketed (columns BS to BU) is then calculated by subtracting the feed, facilities, and mortality costs from the marginal revenue for each marketing event. The total net profit from each marketing event does not consider the nursery cost or revenue.

Network flow constraints

In addition to the barn structure, the network flow constraints are also built into Excel®. The pathway constraint insures that each batch of pigs takes a unique pathway through the nursery (Fig. A8). The nursery flow constraint insures that all of the pigs alive at the end of the nursery period are placed into a finisher (Fig. A9). The site and demand constraints insure that the pigs are moved only to available barns on a site and that all of the pigs are pulled through the system to market, respectively (Fig. A10). The constraints that are not visible in the spreadsheet, such as the capacity constraints for the nursery and finisher, are programmed into the Open Solver® platform. The objective function cell, where MOFFC from the nursery and finisher are summed together, is on the user input page.

	DD	DE	DF	DG	DH	DI	DJ
3	***Nursery Flow Constraint***						
4	Nursery	Batch	Weeks	Inflows	Outflows	Net Flow	Supply/Demand
5	1	1	6	0	0	0	0
6	1	1	7	0	0	0	0
7	1	1	8	0	0	0	0
8	1	2	6	0	0	0	0
9	1	2	7	0	0	0	0
10	1	2	8	2932	2932	0	0
11	1	3	6	0	0	0	0
12	1	3	7	0	0	0	0
13	1	3	8	0	0	0	0
14	1	4	6	0	0	0	0
15	1	4	7	0	0	0	0
16	1	4	8	0	0	0	0
17	1	5	6	0	0	0	0
18	1	5	7	0	0	0	0
19	1	5	8	2932	2932	0	0
20	1	6	6	0	0	0	0
21	1	6	7	0	0	0	0
22	1	6	8	0	0	0	0
23	1	7	6	0	0	0	0
24	1	7	7	0	0	0	0
25	1	7	8	0	0	0	0

Fig. A9. Nursery flow constraint. The nursery flow constraint is responsible for insuring that all of the pigs alive at the end of the nursery period are placed into a finisher.

	DM	DN	DO
3	***Demand Constraint***		
4	Number of pigs to market	Demand	
5	19997	999999	
6			
10			
11	***Site Constraint***		
12	Finisher	Constraint	RHS
13	1	2	2
14	2	2	2
15	3	2	2
16	4	2	2
17	5	2	2
18	6	2	2
19	7	2	2
20	8	2	2
21	9	2	2
22	10	3	3

Fig. A10. Site and demand constraint. The site constraint insures that the pigs are moved only to available barns on a site. The demand constraint insures that all of the pigs are pulled through the system to market.

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