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A flexible tool for the assessment of the economic cost of pig disease in growers and finishers at farm level

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ABSTRACT

Pigmeat is the most consumed red meat globally and consumption is expected to continue to increase. The sector is faced by the risk of epidemic and endemic disease impacts and other adverse influences. The aim of this study was to develop a dynamic simulation model of pig growing and finishing that can be used to model the financial and economic impacts of a variety of scenarios both related to disease effects and other influences on production. The model consists of a physical performance module and financial performance module. The core of the physical performance module comprises three stocks to model the flow of pigs from purchase to slaughter. Mortality rates, daily live weight gain and feed conversion ratios influence the dynamics of the physical performance. Since contracts between farmers and slaughterhouses often include large price penalties for over- and underweight pigs, carcase weight distribution is an important determinant of revenues. The physical performance module, therefore, simulates slaughter weight variations. The financial performance module calculates revenue, costs and gross margins. The revenue calculations take into account price penalties for over- and underweight pigs. To demonstrate the capabilities of the model, we apply the model to assess the economic consequences of production impacts associated with respiratory disease. We use estimated production impacts associated with respiratory disease from a study of all-in-all out growing and finishing systems based on pig production data and information from slaughterhouse monitoring in the UK. Our model suggests a reduction in the gross margin of nearly 40 % as a consequence of the estimated production impacts associated with a 10% increase in respiratory disease prevalence. Due to the lack of reliable information on slaughter weight variation, we also simulate the model using different assumptions about the slaughter weight distribution. An increase in the standard deviation of carcase weights from 8 kg to 12 kg, holding average weights constant, more than halves gross margins under our scenarios. We suggest that for all-in-all-out systems, carcase weight variation is likely to be a substantial factor in reducing income in the presence of respiratory disease and the economic impact of respiratory disease may be underestimated if the effects of disease on variation in carcase weights are not included in any analysis.

1. Introduction

Pigmeat is the most consumed red meat globally with an estimated 121 million tonnes (carcase weight equivalent) consumed in 2022. Consumption is expected to continue to increase to 129 million tonnes in 2029 (OECD/FAO, 2022). Although less important in the United Kingdom than globally or in the European Union, pigmeat is also the most consumed red meat in the UK and remains an important part of the UK food sector (Defra et al., 2022).

Both globally and nationally, the pigmeat sector is faced by the risk of epidemic and endemic disease impacts (Niemi et al., 2020; OECD/FAO, 2022; Renken et al., 2021). A review of over 57,000 publications on infectious disease in pigs identified 40 different pathogens as priority pathogens for global pig production (VanderWaal and Deen, 2018). Pig production is inherently an economic activity. Therefore, assessing the financial implications of different diseases on pig production is essential.

Financial implications of pig disease can be assessed based on experiments (Bornhorn, 2007; Kyriakis et al., 2001; Maes et al., 2001; Mateusen et al., 2001; Pallarés et al., 2000; Wellock et al., 2009) but the findings are specific to the settings of the experiment and the financial

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effects studied are often limited e.g. to medication costs and/or feed conversion ratio impacts. In other studies, disease impacts are assessed in terms of impacts on physical production indicators but fall short of assessing their financial impact on the pig production business (Chantziaras et al., 2018; Cornelison et al., 2018; Jäger et al., 2012).

Modeling approaches can be used to assess financial implications of disease for different production systems with different parameters. The models of financial impacts of pig disease are generally disease specific (Alarcon et al., 2013; Bennett and IJpelaar, 2005; Nathues et al., 2017). Due to methodological differences, the financial effect estimates from different models are not directly comparable.

Partly driven by disease control measures, traditional sales practices and auction markets have been replaced by vertically integrated production chains and the adoption of contractual agreements by independent pig farmers for the production and marketing of pigs (Macdonald, 2015; Piewthongngam et al., 2014; Vassalos, 2015). For example, in the UK standard contracts include substantial price penalties if pigs are over- or underweight. As a consequence, revenue depends not only on average slaughter weight but also on slaughter weight variation. The consequences of such contract arrangements for the financial implications of disease have, to the best of our knowledge, not been studied previously even though disease is one of the main factors of variations in weights within a herd (Schulz, 2017).

Models of dynamic systems, such as pig production systems, quickly become complex and difficult to understand for stakeholders. Systems dynamics models include, as an integral part of the modeling approach, the visual representation of the model, which facilitates communication of model characteristics to stakeholders (Lie et al., 2018; Mumba et al., 2017; Sterman, 2002). So it is not surprising that systems dynamics models have been applied to study livestock management (Piewthongngam et al., 2014; Shane et al., 2017; Turner et al., 2013), including disease management (Bennett et al., 2012, 2010; Farrell et al., 2019; Mumba et al., 2017). However, few applications to pig management and disease exist with one notable exception; Piewthongngam et al. (2014) use a systems dynamics model to study the effect of disruptions in an integrated pig production supply chain.

The aim of this study is to introduce a flexible model to assess the economic cost of pig disease in growers and finishers. The model is applied to assess financial implications of pig disease in growers and finishers where this has not been done, or only partially done, in other studies. The model takes into account revenue impacts of slaughter weight variation and is built in a systems dynamics framework to facilitate communication with stakeholders. We apply our model to assess the financial effects of respiratory disease on pig growing and finishing enterprises in the UK. Gray et al. (2021) estimate the production impacts, but not the economic impacts, associated with respiratory disease based on pig production data and information from slaughterhouse monitoring. The reason we have used this publication and data as a base for our study is because (i) respiratory disease has major impacts on animal welfare and farm economics (ii) it is a very recent publication with recent data (iii) it does not consider the economic implications of the disease and (iv) it has disease information gaps which our model can help to address.

2. Material and methods

This section describes the model. The specific parameters used for the application to the Gray et al. (2021) study are specified in the section Model settings and parameterization. The model was built and run using Stella® Architect 1.3.1 (isee systems 2017). The model has been designed to make use of standard industry key performance indicators, for which data are more readily available. It also has in-built flexibility to apply it to data with varying levels of detail. For example, some performance indicators might only be available as averages for the entire production process, while other variables might be available for different stages of the production process, such as post-weaning, growing and finishing. The stages of pig production are defined in terms of average live weight, which is in line with classifications used in farm surveys and industry publications (AHDB, 2021; Duchy College, 2020; Redman, 2020).

The model consists of two modules – a physical performance and a financial performance module.[1]

Fig. 1 shows an overview of the physical performance module. The purpose is to highlight the linkages between the sectors of the module. For more detail about the model see Annex 1, Annex 2 and Annex 3, which include descriptions of variable names, the model code and higher resolution diagrams of the two modules, respectively.

The core of the physical performance module comprises three consecutive conveyor stocks. Conveyor stocks model processes that take time, such as a production process on a conveyor belt but also growing of a finishing pig. Pigs bought by the pig farmer enter the first conveyor stocks, stay in this stock for a certain time – the transit time – and then leave the stock. Pigs then move on to the second stock, stay in the second stock for a certain time, leave the stock and enter the third stock, then stay in the third stock for a certain period of time. The exit from the third stock represents the flow of pigs to the slaughterhouse. The production process is modeled in three stages to add flexibility in the application of the model. By modeling three different conveyor stocks, different parameter values, if available, can be specified for the different production stages.

Each stock has a leakage to represent mortality. Mortality rates are entered into the model as the proportion of pigs that die before they are moved to the next stage or the slaughterhouse. Stella® Architect 1.3.1 (isee systems 2017) requires input of leakage rates per time unit, here weeks. Mortality rates are converted within the model into weekly rates which determine the outflow of the stocks in number of pigs per week.

The three stocks of the physical performance module are determined by the following relationships:

$$Stage1_t = Stage1_{t-dt} + PigsIN_t - Growing_t - MortalityS1_t$$

where *Stage*1 is the number of pigs in the first production stage; *t* is current time, *dt* is delta time, the time between calculations in the model simulation, *PigsIN* is the number of pigs entering the farm; *Growing* is the number of pigs moving to the second production stage; and *MortalityS*1 is the number of pig deaths in Stage 1 calculated based on the weekly mortality rate for pigs in Stage 1.

The main difference between a continuous and all-in-all-out system is in the timing of pigs entering. For an all-in-all-out system, pigs enter in batches at the interval TFP plus one week assuming one week for cleaning and disinfecting between batches. For a continuous system, pigs enter every week.

$$PigsIN_t = \text{IF}AIAO = 1\text{THEN PULSE}(BatchSize, \ -104, \ (TFP+1)\text{ELSE}BatchSize)$$

where *AIAO* is an indicator for the all-in-all-out finishing system that takes the value 1 if the system is an all-in-all-out system and 0 if the system is a continuous finishing system, PULSE is an inbuilt function in Stella® Architect 1.3.1 (isee systems 2017) for intermittent flows, *BatchSize* is the number of pigs in the batch entering, − 104 is the start time of the simulation, *TFP* the total feeding period.

$$Stage2_t = Stage2_{t-dt} + Growing_t - Finishing_t - MortalityS2_t$$

where *Stage*2 is the number of pigs in the second production stage at time *t*; *Finishing* is the number of pigs moving to the third production stage; and *MortalityS*2 is the number of pig deaths in Stage 2 calculated

[1] The growing and finishing model presented here can be combined with a breeding model but in this application only the growing and finishing model is used.

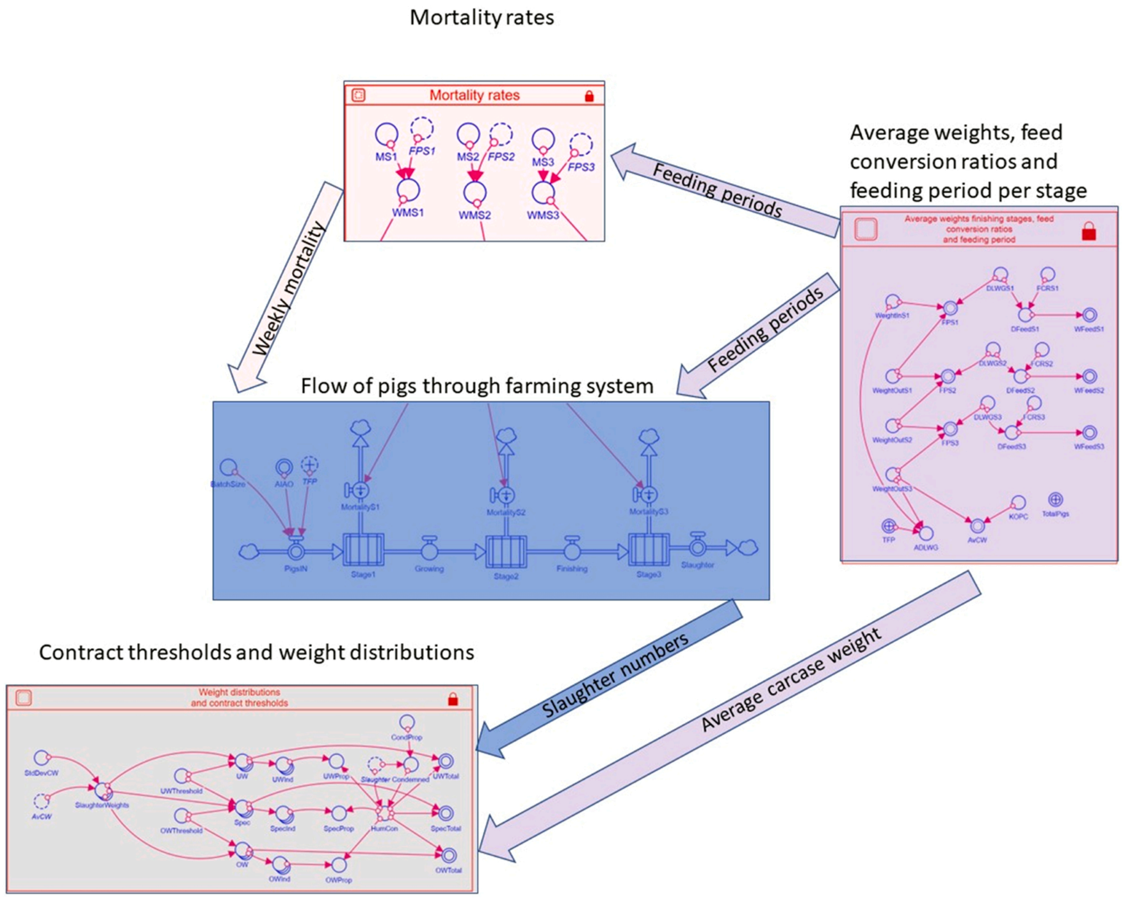

Fig. 1. Model diagram of the sectors of the physical performance module.

based on the weekly mortality rate for pigs in Stage 2.

$$Stage3_t = \quad Stage3_{t-dt} + \quad Finishing_t - Slaughtger_t - \quad MortalityS3_t$$

where *Stage*3 is the number of pigs in the third, and final, production stage; *Slaughter* is the number of pigs going to slaughter; and *MortalityS*2 is number of pig deaths in Stage 3 calculated based on the weekly mortality rate for pigs in Stage 3.

The time it takes pigs to move through each stage is derived as:

$$FPS_i = \frac{(WeightOutS_i - \quad WeightInS_i)}{DLWGS_i \quad \times 7}$$

where FPS_i is the feeding period in weeks of Stage i, with $i = 1, 2, 3$; $WeightOutS_i$ is the average weight of pigs leaving Stage i, with $i = 1, 2, 3$; $WeightInS_i$ is the average weight of pigs entering Stage i, with $i = 1, 2, 3$; and $DLWGS_i$ is the average daily live weight gain in Stage i, with $i = 1, 2, 3$.

The total finishing period, *TFP*, is $TFP = \sum_{i=1}^{3} FPS_i$.

In order to calculate feed costs, information on feed rations is required. Feed ration information might be directly available, or it can be derived if data on daily live weight gain and feed conversion ratios are available. The model can be adapted to make use of the data available. In this version of the model, weekly feed rations are calculated based on feed conversion ratio and daily live weight gain.

$$WFeedS_i = \quad DLWGS_i \times \quad FCRS_i \times 7$$

where $WFeedS_i$ are weekly feed rations in kg in Stage i, with $i = 1, 2, 3$; $FCRS_i$ are feed conversion ratios in Stage i, with $i = 1, 2, 3$.

For each time period, the number of pigs going into the human consumption chain are

$$HumCon = \quad Slaughter \times \quad Condemned$$

where *HumCon* is the number of pigs for human consumption; *Slaughter* is the number of pigs sent to the slaughterhouse; *Condemned* is the number of pigs condemned at the slaughterhouse. *Condemned* is the outcome of a binomial random variable with parameters *Slaughter* and *CondProp*, the proportion of pigs condemned.

Standard contracts with slaughterhouses in the UK apply price penalties if pig carcase weights fall outside a specified weight band. As a consequence, the distribution of carcase weights needs to be modeled to adequately calculate revenues. The weights of pigs for human consumption are simulated as the outcomes of draws from a statistical distribution with a mean equal to the average carcase weight of slaughter pigs.

Based on the simulated weights and lower and upper limits of the specified weight band, the total carcase weight for the three weight categories (overweight, within specification, and underweight) are calculated as the sum of the weights of pigs for each weight category and enter the financial performance module as inputs.

Fig. 2 shows an overview of the model diagram of the financial performance module to highlight the linkages between the sectors of the module.

The financial performance module consists of three elements – Costs, Revenue and Gross margins.

Costs calculates feed costs, purchase costs for pigs at entry and other costs. Each of these is calculated for every delta time step and weekly, annual/batch and per pig aggregates are then derived.

For each of the three stages, weekly feed costs are:

$$WFeedCostsS_i = \quad Stage_i \times \quad WFeedS_i \times PigFeedPricekg$$

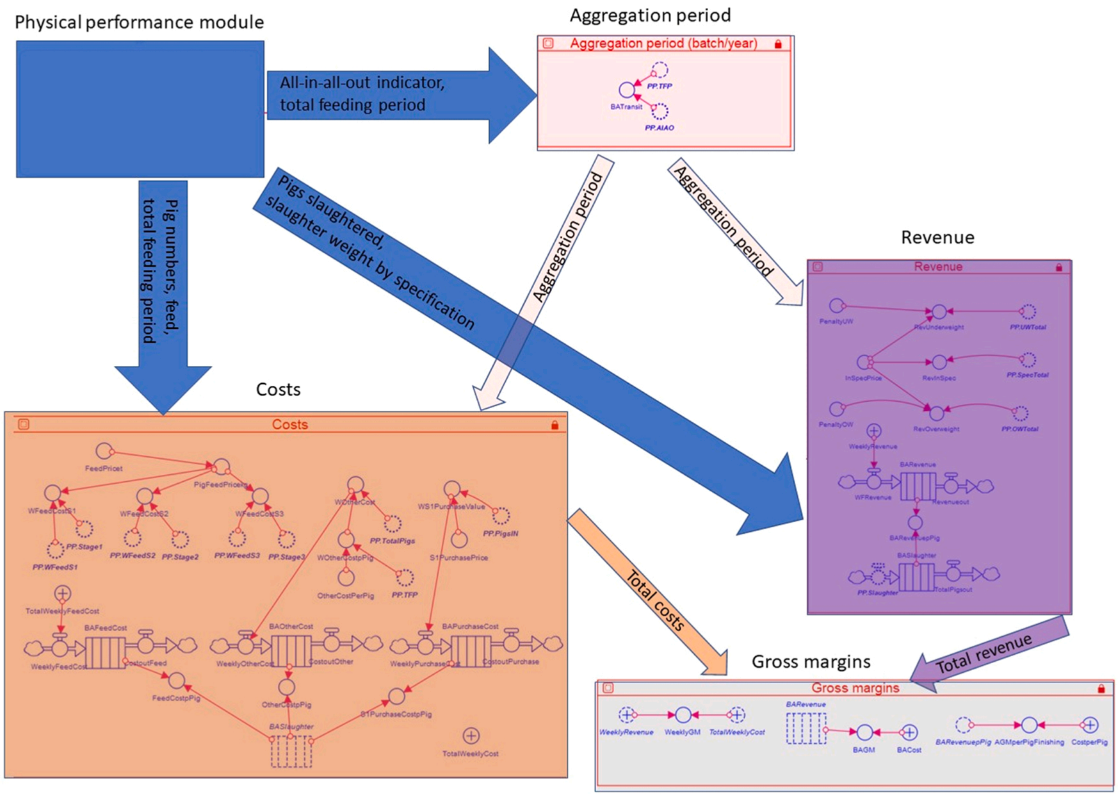

Fig. 2. Model diagram of inputs and the sectors of the financial performance module.

where $WFeedCostsS_i$ are the feed costs over the previous week for pigs in Stage i, with $i = 1, 2, 3$; $Stage_i$ is the average number of pigs in Stage i during the week as calculated in the physical performance module, $WFeedS_i$ is the weekly feed ration per pig in Stage i as calculated in the physical performance module; and *PigFeedPricekg* is the price of one kilogram of pig feed.

Weekly costs of pigs entering are calculated using the price per pig purchased multiplied by the number of pigs entering the farming system in the physical performance module. Other costs are based on information on a per pig basis and converted to weekly costs. Conveyor stocks with transit time 52 calculate the respective annual values for continuous systems. Conveyor stocks with transit time TFP plus one week calculate per batch values for all-in-all-out systems. Values per slaughter pig are derived as annual/per batch costs divided by the total number of pigs slaughtered over the same period.

The Revenue element calculates revenue for the three categories of slaughter pigs – underweight, in specification and overweight as follows:

$$Revenue_j = (InSpecPrice - Penalty_j) \times TotalWeight_j$$

where j = spec (in specification), OW (overweight) and UW (underweight); $Penalty_j$ is price penalty specified in the contract for category j; $TotalWeight_j$ is the sum of the simulated slaughter weights of all pigs for human consumption in category j.

The Gross Margins element derives gross margins as the difference between revenue and variable costs on a weekly, annual/batch and per slaughter pig basis.

2.1. Model settings and parameterization

The model uses weeks as main time units. Parameters that are generally not available as weekly values are entered in the model using the most commonly used time units and then converted to weekly values within the model. For example, live weight gains are input into the model as daily live weight gain, the standard time unit used in industry. The model converts daily live weight gain to weekly live weight gains.

To make the model robust to different starting values of the stocks, the model is run with a lead-in time of 104 weeks to make sure that a steady state is reached at time t = 0. Delta time, dt, the time between calculations in the model simulation, is set to 1/10. This means that the stocks and flows are calculated for 10 sub-periods of the week, which increases precision of the simulation. The results are presented on a per slaughter pig and per batch basis.

The model uses standard industry key performance indicators. Data for the UK on key performance indicators for the UK pig industry are available, for example, from the Agricultural and Horticultural Development Board (AHDB) and the John Nix Farm Management Pocketbook (AHDB, 2021; Redman, 2020). These sources are regularly updated and thus our model can draw on updated data sources over time. Therefore, data gaps can be filled using standard industry indicator data.

Here we apply our model to assess the economic consequences of pig performance impacts associated with respiratory disease for all-in-all-out pig growing and finishing enterprises in the UK based on Gray et al. (2021). Gray et al. (2021) link carcase inspection data from the Food Standards Agency on respiratory disease and pig performance data from 49 all-in-all-out growing and finishing farms. Higher prevalence of respiratory disease was found to be linked to higher mortality, lower average daily live weight gain and lower carcase weight. In the application of our model to the findings in Gray et al. (2021), we therefore use parameters from Gray et al. (2021), where available. In the baseline scenario, parameter values are reported averages for the 49 farms in Gray et al. (2021). In some instances, data from Gray et al. (2021) is lacking and alternative sources have been used. Additional information is based on Redman, (2020) rather than AHDB (2021) because parameters available from Gray et al. (2021) are more similar to those in Redman, (2020) than AHDB (2021). For example, average daily live weight gain is 780 g/day, 809 g/day and 867 g/day in Gray et al. (2021), Redman, (2020) and AHDB (2021), respectively. These data sources provide information in the form of averages over the growing and finishing production stage and thus, parameters for stages 1, 2 and 3 are all set to average values.

Publicly available information on contractual arrangements and weight distribution is sparse. For those parameters we draw on information collected during the summer of 2020 investigating contractual arrangements in the UK pig industry as well as a dataset made available to the authors by a large pig company. Contractual arrangement information is based on unpublished, confidential information collected by the authors. Data were collected using an online survey, which was returned by 14 respondents. The survey included questions on the type of contractual arrangements used. All but one pig producer were either contract pig farmers or used forward contracts with a reference price and price penalties. However, only one farmer provided detailed information about their marketing contract. Additional data on the price structure and penalties commonly included in marketing contracts were collected in five telephone interviews two with representatives from industry bodies, two with pig producers and one with a pig veterinary surgeon. The data collection has been reviewed according to the procedures specified by the University of Reading Research Ethics Committee and has been given a favorable ethical opinion for conduct.

Information on slaughter weight variation is based on two confidential datasets provided by one large pig company. The first dataset contains slaughter weights from 239 different herds.[2] It contains 694 slaughter batches with a total of just over 100,000 pigs. The mean of the mean carcase weights by batch is 84.5 kg, so a somewhat higher mean than the average carcase weight in Gray et al. (2021) of 80.80 kg. A second, smaller dataset contains information on just under 35,000 pigs slaughtered in 37 batches from 30 different herds.

Carcase weight distribution by batch look reasonably close to being normally distributed with one clear mode for all batches and, with few exceptions, close to symmetric distributions. Deviations from symmetry are not consistent i.e. are neither always right- nor always left-skew. Weights in our model are therefore simulated as a normally distributed variable with mean of the average carcase weight and standard deviation derived from this dataset.

The upper and lower limit for the weight band of in-specification pigs are based on information we collected in our interviews. The upper limit is also in line with the Red Tractor Assurance Scheme up to 2019. The limit has since been increased but because the data in this study predates 2019, we use the 100 kg limit. The Red Tractor Assurance scheme covers over 90% of UK pork production (James, 2019).

Gray et al. (2021) found that higher prevalence of respiratory disease was linked to higher mortality, lower average daily live weight gain and lower carcase weight. We compare the baseline scenario to + 10% respiratory disease scenario using estimated effects on mortality, daily live weight gain and carcase weight associated with a 10% higher prevalence of respiratory disease.Table. 1.

Gray et al. (2021) find that a 10 % higher prevalence of respiratory diseases is not linked to a change in the total feeding period. For all-in-all-out systems, the opportunity cost of keeping slower growing pigs longer is probably prohibitive because it would delay the entry of the following batch. It reasonable to assume that, therefore, higher disease prevalence is associated with an increase in the standard deviation of carcase weights. We use the upper quartile of the standard deviations in the confidential datasets for the + 10 % prevalence scenario.

Fig. 3 shows the resulting density function of carcase weight distribution for the baseline and + 10 % prevalence scenarios.

Table 2 shows parameter values that are changed in the 10 % higher respiratory disease prevalence scenario based on Gray et al. (2021). In addition, due to the lack of reliable data, we carry out sensitivity analysis on the impact of a 10 % higher respiratory disease prevalence on the standard deviation of slaughter weights and the proportion of condemned carcases as set out in Table 2.

The model was validated against standard industry sources for production, price and gross margin information (AHDB, 2021; Duchy College, 2020; Redman, 2020). Using averages available from these sources, the model produces comparable gross margins to those published. Changes from the values available in industry sources, such as adding carcase weight distributions and changing the timing of mortality, lead to changes in gross margins in the expected direction.

3. Results

Table 3 shows the main results for the financial performance of the pig finishing enterprise under the baseline and 10% higher prevalence assumption.

Our scenario analysis suggests that the main impact of an increase in respiratory disease is on revenue with much smaller impacts on costs. Gross margin per slaughter pig decreases by just over £ 3 per pig, which is a drop in gross margin of 38 %. For the batch size of 1362 pigs this translates into a reduction in the gross margin per batch of just over £ 4500.

To show the impact of pig weight variation on gross margin when price penalties are applied, the baseline and 10 % higher prevalence scenarios were also run with the standard deviation of carcase weight set to zero. Without price penalties for over- and underweight pigs, carcase weight variation, while keeping the mean carcase weight constant, has no impact on revenue.

With no variation in weights the gross margin per slaughter pig in the baseline is £ 8.19, which is 23 pence higher than in the main baseline scenario. In the 10 % higher prevalence scenario, the gross margin is £ 6.43 without variation in carcase weight, which is £ 1.50 higher than in the main scenario where variation in carcase weights is taken into account. Without the variation in slaughter weight, therefore, the estimated impact of a 10 % higher respiratory disease prevalence is £ 1.76 compared to £ 3.03 with the assumed increase in carcase weight variation. Therefore, about£ 1.27 of the £ 3.03 reduction in gross margin can be attributed to a reduction in revenue due to slaughter weight variation in conjunction with the price penalties, about £ 1.41 to the reduction in average carcase weight and £ 0.35 to increased costs.

Fig. 4 shows gross margins from the sensitivity analysis on the standard deviation and the percentage of condemned carcases.

The sensitivity analysis shows that the effect of more than doubling the percentage of condemned carcases on gross margin is marginal in magnitude and masked by the random variation in carcase weight. An increase in the standard deviation carcase weights from 8 kg to 12 kg, by contrast, results in the gross margin decreasing by more than 50%.

In the main results, we have assumed that the increased estimated mortality associated with a 10% higher prevalence of respiratory disease is spread evenly over the production process due to a lack of information on the timing of mortality. If the higher mortality happens in Stage 1, in the first third of the production process, costs per pig in the disease scenario are 8.6 pence lower, mainly due to reduced feed costs, and the gross margin per pig is 8.6 pence higher. If the increased mortality is in pigs in Stage 3, costs are 8.4 pence per pig higher in the 10 % higher respiratory disease scenario.

4. Discussion

We apply our economic model to assess the financial consequences of production effects associated with a 10% higher prevalence of respiratory disease in growing and finishing pig enterprises.

In many studies, disease impacts are assessed in terms of impacts on physical production indicators but fall short of assessing their full financial impact on the pig production business (Chantziaras et al., 2018; Cornelison et al., 2018; Jäger et al., 2012). When financial impacts are assessed, models of financial impacts of disease are often disease specific (Alarcon et al., 2013; Bennett and IJpelaar, 2005; Nathues

[2] Herds are defined as having different herdmarks.

Table 1
summarizes the parameters used in the baseline scenario.

Variable Description	Variable Name	Value	Source	Explanation
Number of pigs in a batch	BatchSize	1362	Gray et al. (2021)	
Pig weight at start of stage 1 (kg)	WeightInS1	35.26	Gray et al. (2021)	
Pig weight leaving stage 1 and starting stage 2 (kg)	WeightOutS1	59.70	NA	One third of total weight gain.
Pig weight leaving stage 2 and starting stage 3 (kg)	WeightOutS2	84.14	NA	Two thirds of total weight gain.
Live weight of pigs going to slaughterhouse (kg)	WeightOutS3	108.58	Gray et al. (2021)	Derived from start weight, daily live weight gain and days on farm.
Daily live weight gain, stages 1, 2, 3 (kg)	DLWGSi, with i = 1,2,3	0.780	Gray et al. (2021)	
Feed conversion ratio, stages 1, 2, 3	FCRSi, with i = 1,2,3	2.65	(Redman, 2020)	
Mortality rate (%)	MSi, with i = 1,2,3	0.756	Gray et al. (2021)	Average of 30.9 deaths for average batch size of 1362 pigs split evenly across the three production stages.
Killing-out percentage	KO	0.744	Gray et al. (2021)	Finisher live weight at slaughter calculated above as 108.58 and deadweight of 80.80 kg leads to killing out % of 80.80/108.58 = 0.744.
Standard deviation of carcase weights (kg)	StdDevCW	6.8065	Confidential datasets	Median standard deviation of weight by batch. We use the median here because of high outliers that unduly influence the mean.
Upper threshold of weight specification band (kg)	OWThreshold	100	Telephone interviews	
Lower threshold of weight specification band (kg)	UWThreshold	65	Telephone interviews	
Proportion of condemned carcases	CondProp	0.001	Confidential datasets	
Price of one tonne of pig feed (£)	FeedPricet	270	(Redman, 2020)	
Price per pig purchased at start of stage 1 (£)	S1PurchasePrice	55	(Redman, 2020)	
Other cost per pig purchased (£/per pig)	OtherCostPerPig	7.3	(Redman, 2020)	
Dead-weight price for pigs within weight specification band (pence/kg)	InSpecPrice	155	(Redman, 2020)	
Price penalty for overweight pigs (pence/kg)	PenaltyOW	50	Telephone interviews	Penalties in contracts also depend on probe. Approximate average value.
Price penalty for underweight pigs (pence/kg)	PenaltyUW	30	Telephone interviews	Penalties in contracts also depend on probe. Approximate average value.

Table 1: Parameter values in the baseline scenario

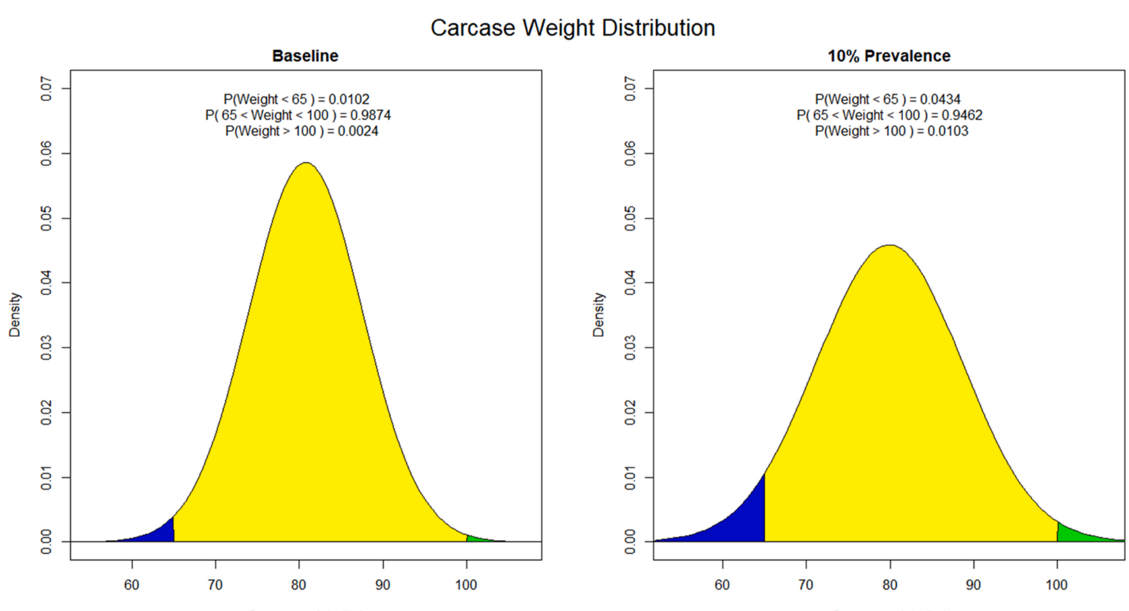

Fig. 3. Density function for carcase weight distribution in baseline and + 10% prevalence scenario, Note: The area in blue (left tail) represents the probability that the carcase weight falls below the underweight threshold, the area in yellow represents the probability that the carcase weight is within specification and the area in green (right tail) represents the probability that the carcase weight falls above the overweight threshold.

et al., 2017). Our tool is not disease specific and can be used to model a large range of different pig diseases and scenarios because it is capable of representing the main relationships and parameters of importance to physical and economic impacts of the disease in question.

Here we make use of our model to assess the financial implications of respiratory disease in the UK. Gray et al. (2021) estimate the production

Table 2
Parameter changes in the + 10% prevalence scenario compared to baseline.

Variable Description	Variable Name	Baseline	+ 10 % prevalence	Explanation
Based on Gray et al. (2021) estimation for 10% increase in prevalence				
Live weight of pigs going to slaughter (kg)	WeightOutS3	108.58	107.37	Deadweight decrease from 80.8 kg to 79.9 kg. With the same killing out percentage this leads to a finisher live weight at slaughter of 107.37 kg.
Daily live weight gain, stages 1, 2, 3 (kg)	DLWGSi, with i = 1,2,3	0.780	0.765	
Feed conversion ratio, stages 1, 2, 3	FCRSi, with i = 1,2,3	2.65	2.70	Derived from daily weight live gain and assumption that daily feed rations remain unchanged: FCR = Daily Feed ration/ DLWG = 2.067/0.765.
Mortality rate (%)	MSi, with i = 1,2,3	0.76	0.8972	The mortality rate increases to 36.66/1362 × 100 = 2.6916 %. Split across the production phases.
Standard deviation of carcase weights (kg)	StdDevCW	6.8065	8.6927	No information on effect of respiratory disease. Upper quartile of standard deviation of weight by batch. Additionally sensitivity analysis with values 8, 10 and 12.
Proportion of condemned carcases	CondProp	0.001	0.0015	No reliable information. Additionally sensitivity analysis with values 0.00125, 0.002 and 0.003.

Table 3
Financial performance under the baseline and 10% higher prevalence scenario at the end of the simulation period.

	Gray et al. (2021) baseline	Gray et al. (2021) + 10 % prevalence	% change
Revenue per slaughter pig	£ 124.97	£ 122.29	-2.1 %
Purchase cost per slaughter pig	£ 56.26	£ 56.50	0.4 %
Feed cost per slaughter pig	£ 53.35	£ 53.47	0.2 %
Other costs per slaughter pig	£ 7.40	£ 7.39	-0.1 %
Gross margin per slaughter pig	£ 7.96	£ 4.93	-38 %
Gross margin per batch (1362 pigs)	£ 10,591	£ 6539	-38 %

impacts of respiratory disease based on pig production data and information from slaughterhouse monitoring. Slaughterhouse monitoring, which does not include economic and financial information, has become an important source for pig disease monitoring and epidemiological studies in many countries including the UK, Italy, Austria and the Philippines (Barnes et al., 2021; Correia-Gomes et al., 2017; Eze et al., 2015; Guardone et al., 2020; Klinger et al., 2021; Merialdi et al., 2012). We apply our model using data from Gray et al. (2012) as a base, showing how our model can add value by exploring and estimating the economic implications of estimated production effects associated with respiratory disease.

In addition, 'what if' analyses can explore possible variations in key parameter values, for example, as a result of information uncertainties and data paucity. This is particularly valuable when considering pig producer contracts. Over the past decades, traditional sales practices and auction markets have been replaced by vertically integrated production chains and the adoption of contractual agreements by independent pig farmers for the production and marketing of pigs (Macdonald, 2015; Piewthongngam et al., 2014; Vassalos, 2015). Contractual agreements for the marketing of pigs of independent pig producers has not been given much attention in the literature. The consequences of those arrangements for the economic cost of disease have, to the best of our knowledge, not been studied previously. As Hueth et al. (2007, p. 1276) notes "Unfortunately, data tend to fail us when we attempt to address questions regarding the effects of contracts. Any changes induced by contracts necessarily depend on the specific provisions of actual contracts, and these can be difficult to summarize in a useful way." We suggest that broad characteristics of marketing contracts can, and should be, incorporated into economic analysis of disease costs and we show how it can be done using the example of contracts in the UK pig production sector. Moreover, the model is capable of incorporating specific contractual arrangements (e.g., for a specific producer or group of producer) where these are known.

We apply systems dynamics modeling, which is often used to make conditional projections of behavior under "what if" scenarios rather than to make precise predictions (Duggan, 2016). As noted above, information on contractual agreements is sparce and disease impacts are often difficult to estimate precisely. Conditional "what if" projections provide invaluable insights when precise data are not available. So it is not surprising that systems dynamics models have been applied to study livestock management (Piewthongngam et al., 2014; Shane et al., 2017; Turner et al., 2013), including disease management (Bennett et al., 2012, 2010, 2013; Farrell et al., 2019; McClement and Bennett, 2006; Mumba et al., 2017; Pessoa et al., 2021). However, few applications to pig management and disease exist with one notable exception; Piewthongngam et al. (2014) use a systems dynamics model to study the effect of disruptions in an integrated pig production supply chain.

Using "What-if" scenarios in our sensitivity analysis on the standard

	CondProp	StdDevCW
Run 1	0.00125	8
Run 2	0.00125	10
Run 3	0.00125	12
Run 4	0.002	8
Run 5	0.002	10
Run 6	0.002	12
Run 7	0.003	8
Run 8	0.003	10
Run 9	0.003	12

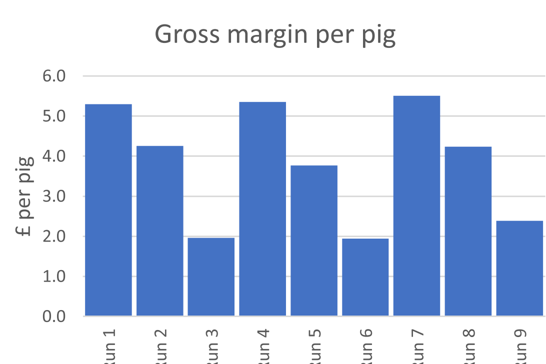

Fig. 4. Parameters and results of the sensitivity analysis on the percentage of condemned carcases and carcase weight variation.

deviation of carcase weights, we show the importance of carcase weight variation, which is likely to increase as a result of respiratory (or other) disease, on the financial outcomes in an all-in-all-out system under contract arrangements with substantial price penalties applied to pigs outside the weight specification, which is the prevailing contracting arrangement for marketing pigs in the UK. An increase in the standard deviation of carcase weights from 8 kg to 12 kg more than halves gross margins under our scenarios – holding average weights constant.

Gray et al. (2021) found that time on farm was not statistically significantly affected by disease prevalence. In a continuous system, common for breeder-finishers, average time on farm might increase and slaughter weight variation might be less affected. This is because in a continuous system slower-growing pigs can be held back at lower cost.

In an all-in-all-out system increasing time on farm for slower-growing pigs increases the time between batches and leads to lost income. Therefore, the main impact of slower- growing pigs due to higher disease prevalence is likely to be reduced slaughter weight and increased slaughter weight variation. However, little information is available on the link between disease and carcase weight variation. Standard deviations of batches from one large pig company show that variations in these magnitudes are seen in slaughter batches. It is reasonable to assume that diseased animals will have a smaller weight gain compared to healthy animals. Thus, it is likely that disease prevalence in addition to decreasing average weight also leads to increased weight variation within a batch but factors other than disease prevalence will also contribute carcase weight variation. Disease is likely to be one of the main drivers for larger standard deviations but, to the best of our knowledge, the drivers of carcase weight variation have not been quantified nor has the impact of respiratory disease on carcase weight variation. In the absence of firm data, our sensitivity analysis sheds light on potential impacts of an increase in slaughter weight variation on the financial performance of grower and finisher herds.

Our results show that, given the prevailing contract arrangements in the UK, ignoring carcase weight variation is likely to overestimate gross margins, especially when disease is more prevalent. As a consequence, ignoring pig carcase weight variation is likely to underestimate the impact of disease on financial performance, especially for all-in-all-out systems.

We also carry out "What-if" scenarios regarding the timing of the mortality in the disease scenario. Increased mortality in the first third of the production process reduces costs and increases gross margins by 8 pence compared to a scenario where the increased mortality is assumed to happen equally throughout the production process.

Our approach has a number of limitations, though. The application of our modeling tool to respiratory disease in finishing pigs using the results presented in Gray et al. (2021), which focused on physical performance, do not take into account increases in veterinary, medicine or labor costs as a result of higher disease prevalence. We do not have any information on cost implications for the farms in the sample. However, it means that the impact of respiratory disease is likely to be higher than shown in our study, which focuses on physical performance impacts. Another important limitation of our application to the data on respiratory disease is the lack of age specific baseline and production effect information for feed conversion ratios, daily live weight gain and mortality. The data sources available to us, from public sources as well as confidential information, do not include age specific parameters. We carried out sensitivity analysis for the timing of mortality effects to show the potential effect of higher mortality in early or late production stages. Also, data on slaughter weight variation is based on two datasets and relates to herds linked to one big pig company and thus might not be representative of herds linked to other pig companies. The dataset does not include information on the type of systems used and thus, it is not known what proportion of the slaughter batches come from all-in-all-out systems. As noted above, for all-in-all-out systems it is economically not viable to hold back slower growing animals within a batch, which is regularly done in continuous systems. Therefore, it seems likely that carcase weight variation is higher for all-in-all-out systems than it is for continuous systems. In addition, all herds are linked to a single pig company. Variation within batches might be higher or lower for herds linked to other pig companies. It is likely though that variation of the carcase weight variation between batches, if anything, will be larger for batches linked to more than one big pig company.

Another limitation is that disease origins are often multifactorial, which makes understanding the origins, control and impacts of disease on production and animal welfare challenging (Chantziaras et al., 2018). These challenges transfer directly to the assessment of economic implications of animal disease based on production impacts.

5. Conclusions

The dynamic model of pig production that we have developed can be used to model a variety of scenarios both related to disease effects and other influences on production. It is capable of simulating both physical and financial aspects of pig production. It can be used to consider a range of business models and types of growing and finishing pig enterprises.

In the scenario(s) considered in this paper, we have explored the financial impacts associated with respiratory disease for pig growing and finishing enterprises, using disease data from Gray et al. (2021) as a starting point. The analysis showed a substantial reduction in gross margin per pig due to respiratory disease of nearly 40 %. In addition, the financial impact of the disease in terms of the variation in carcase weights was considered taking into account common contract arrangements. This showed that greater variation in carcase weights, which is a likely implication of higher disease prevalence, results in pigs outside of the contract weight range and a reduction in revenue per pig. For all-in-all-out systems, carcase weight variation is likely to be a substantial factor in reducing income in the presence of respiratory disease. Thus, the economic impact of respiratory disease may be underestimated if the effects of disease on variation in carcase weights are not included in any analysis. The impact is likely to be much smaller for continuous systems for which an increase in time of farm is expected to be more important.

Possible extensions to our analysis are the application of the current model to different production systems and diseases as well as expanding the analysis to include pig breeding and rearing. Future research in relation to the effect of pig production contracts on the economic impact of pig diseases is needed to ensure that this important consideration is not neglected.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.prevetmed.2022.105757.

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