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Cost of porcine reproductive and respiratory syndrome virus at individual farm level – An economic disease model

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ABSTRACT

Porcine reproductive and respiratory syndrome (PRRS) is reported to be among the diseases with the highest economic impact in modern pig production worldwide. Yet, the economic impact of the disease at farm level is not well understood as, especially in endemically infected pig herds, losses are often not obvious. It is therefore difficult for farmers and veterinarians to appraise whether control measures such as virus elimination or vaccination will be economically beneficial for their farm. Thus, aim of this study was to develop an epidemiological and economic model to determine the costs of PRRS for an individual pig farm. In a production model that simulates farm outputs, depending on farm type, farrowing rhythm or length of suckling period, an epidemiological model was integrated. In this, the impact of PRRS infection on health and productivity was estimated. Financial losses were calculated in a gross margin analysis and a partial budget analysis based on the changes in health and production parameters assumed for different PRRS disease severities. Data on the effects of endemic infection on reproductive performance, morbidity and mortality, daily weight gain, feed efficiency and treatment costs were obtained from literature and expert opinion. Nine different disease scenarios were calculated, in which a farrow-to-finish farm (1000 sows) was slightly, moderately or severely affected by PRRS, based on changes in health and production parameters, and either in breeding, in nursery and fattening or in all three stages together. Annual losses ranged from a median of € 75′724 (90% confidence interval (C.I.): € 78′885–€ 122′946), if the farm was slightly affected in nursery and fattening, to a median of € 650′090 (90% C.I. € 603′585–€ 698′379), if the farm was severely affected in all stages. Overall losses were slightly higher if breeding was affected than if nursery and fattening were affected. In a herd moderately affected in all stages, median losses in breeding were € 46′021 and € 422′387 in fattening, whereas costs were € 25′435 lower in nursery, compared with a PRRSV-negative farm. The model is a valuable decision-support tool for farmers and veterinarians if a farm is proven to be affected by PRRS (confirmed by laboratory diagnosis). The output can help to understand the need for interventions in case of significant impact on the profitability of their enterprise. The model can support veterinarians in their communication to farmers in cases where costly disease control measures are justified.

1. Introduction

Porcine reproductive and respiratory syndrome (PRRS) is caused by PRRS virus infection and is reported to be among the diseases with the highest economic impact in modern pig production (Lunney et al., 2010) worldwide. In 2005, production losses due to the disease in the US pig industry were estimated to be as high as US$ 560 million per year (Neumann et al., 2005). A similar more recent study calculated the combined production losses in the breeding and growing-pig herds as being around US$ 663.91 million per year (Holtkamp et al., 2013). Control and eradication have proved to be difficult due to several specific characteristics

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of the virus like its high transmissibility by infected animals, its genetic and antigenic heterogeneity and ability to persist in animals. Nonetheless, different control options such as vaccination and eradication protocols are available, and their effectiveness have been described (Martelli et al., 2009; Zuckermann et al., 2007). In some regions (e.g. Minnesota in the USA), farmers are currently even trying to eliminate the virus at regional level (Corzo et al., 2010) and there are reports of success at a national level in Chile, albeit there was then a reintroduction.

In swine herds which are endemically infected with PRRSV, the damage caused by the disease is often not obvious. It is therefore difficult for farmers to appraise whether control measures such as vaccination will be economically beneficial for their farm. In a study in Great Britain, farmers indicated that the most important drivers for taking measures for disease control were 'pig mortality', 'feeling of entering in an economically critical situation', 'animal welfare' and 'feeling of despair' (Alarcon et al., 2013a).

Besides the calculations of economic losses attributed to PRRS at national level, several reports and studies have been published on the observed impact of PRRS on individual farms: An early Dutch study estimated the costs of a PRRS outbreak, averaged over 91 breeding and/or farrow-to-finish herds, as being around € 97.56 per sow per year (Brouwer et al., 1994). In 2003, Holck and Polson summarized figures available from previous reports from the 1990ies to an average loss of around US$ 250 per sow for acute outbreaks, (Holck and Polson, 2003). Costs associated with persistent infections in breeding herds or growing pig herds were calculated by the same authors to range from US$ 6.25–15.25 per pig, again based on different reports from the 90s. A Dutch study from 2012 compared the economic situation in 9 breeding or nucleus herds before and after a PRRS outbreak, with an observation period of 18 weeks, and resulted in costs of € 3–160 per sow per year after the outbreak, including costs for control of PRRS (Nieuwenhuis et al., 2012). A Spanish report from 2013 calculated the loss during 6 months following an outbreak as being US$ 200 per sow or US$ 17.7 per slaughter pig produced for a farrow-to-finish farm and US$ 122 per sow or US$ 13 per piglet (12 kg live weight) produced for a breeding farm (Anonymous, 2013a).

Although many calculations on the impact of PRRS are available, most of them are rather general estimates at industry level, or derived from anecdotal case reports describing the situation observed in an individual farm. Furthermore, most of them were done for the epidemic period i.e. immediately following an outbreak. For porcine circovirus – type 2 (PCV2) associated disease, a model was developed by Alarcon et al., which assesses the costs for individual farms (Alarcon et al., 2013b). In contrast, no study has been published that assesses the economic effect of PRRS in a more systematic way, which would enable predictions of the expected impact for different levels of severity, and especially for endemically infected farms, where the losses caused are often not obvious for farmers and veterinarians.

Thus, the aim of this study was to develop an epidemiological and economic model to determine the costs of PRRS for an individual pig farm. The model is intended to help farmers and veterinarians to calculate the losses for their specific farm setting and to understand the need for interventions in case of a significant impact on the profitability of their farm.

2. Material & methods

A simulation model was developed to estimate the farm level cost of PRRS. The model was built in four steps: I. a production model that simulates farm population and management dynamics over time was created. II. a literature review identified and estimated the key parameters for the impact of PRRS at farm-level. III. epidemiological data were added into the production model to incorporate changes in the system due to disease status; and IV. A farm-level economic model was developed to estimate net losses due to disease (production losses, control costs and overall changes in productivity) and their impact on system profitability. Models were developed in Excel 2010 (Microsoft Corporation, Redmont, Washington, USA). Since the purpose of the model is to provide farmers and veterinarians with a user friendly simulator, the model can be adapted to different production systems (breeding farms with or without nursery, nursery farms, fattening farms and farrow-to-finish farms) different types of batch farrowing (one-week- and three-week-rhythm), and lengths of the suckling period (three, four and five weeks). Production performance, disease parameters, prices (optionally vaccination and transport cost etc.), and sow genetics can also be modified by the user, so that the model is easily adaptable to the farm settings as most commonly found in countries with intensive pig production.

Table 1
Characteristics and parameters of an average farrow-to-finish farm in Northern Germany used as an example.

Herd/production characteristics	Value
Average number of working sows	1000
Production rhythm (weeks)	3
Length of suckling period (weeks)	3
Replacement rate per year (%)	35
Feed consumption (gestation) per sow from insemination to farrowing (kg)	275
Feed consumption (lactation) per sow during suckling period (kg)	200
Average days of downtime between turns in nursery	2
Average days of downtime between turns in fattening	5
Average weight of pigs at end of nursery/beginning of fattening period (kg)	30
Average live weight of pigs at finishing (kg)	120

2.1. Pig production model

The production model provides a context for the disease modelling work and simulates the production processes throughout the different stages of pig production at batch and annual level. It consists of three parts: (A) breeding, (B) nursery and (C) fattening. For each part production "outputs" are calculated: e.g. the total number of piglets, nursery pigs and fattening pigs produced and associated live weight sold, the number of piglets which died, the number of sows replaced, died, returned and aborting in a year and the total quantity of feed, water and artificial insemination doses used. The start of the year (=a period of 365 days) was defined as the day when a batch of sows was inseminated, or in the case of nursery or fattening farms, when a batch of pigs entered the nursery or fattening facility. These outputs are then used to calculate the costs and revenue (see section "Economic modelling of disease impact"). By combining the different parts, different production systems i.e. farm types can be modelled. Fig. 1 shows a flow diagram that reflects the production processes in the breeding part; Fig. 2 shows the processes in the nursery part (those in the fattening part are similar and therefore not shown separately).

For the results presented in this paper, an example of a farrow-to-finish farm not vaccinating against PRRSV and housing 1000 sows is used. This is a common farm size in the pig-dense parts of Germany and allows easy conversions of final outputs into standard sow per year units. Further herd and production characteristics of this example farm are given in Table 1.

To model the production processes, the input parameters and equations as indicated in Table 2 are used. For parameters exhibiting a considerable degree of variability, values are distributed using

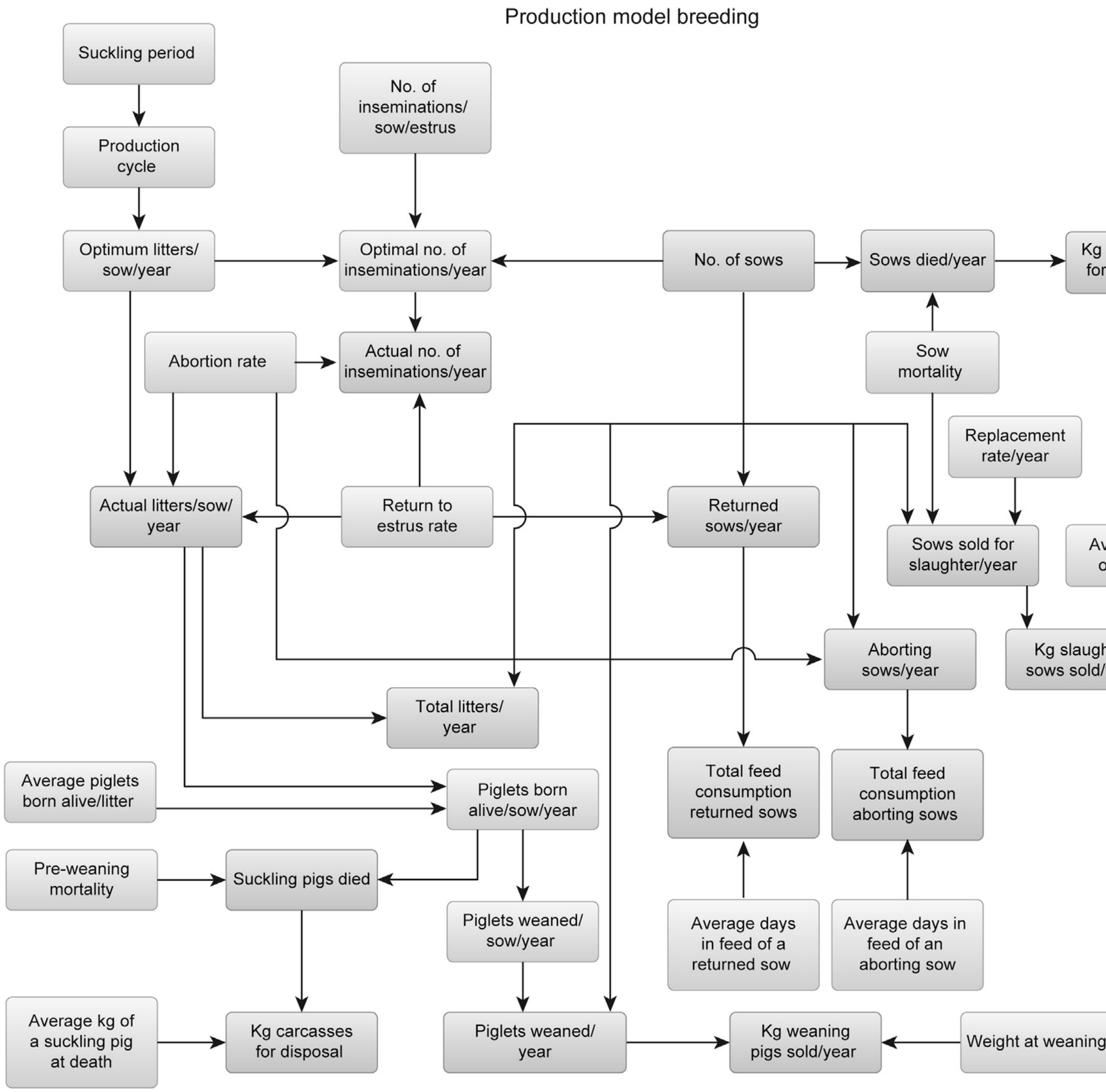

Fig. 1. Schematic production model of the breeding part in a sow herd.

PERT ("Program Evaluation and Review Technique") distributions rather than using fixed values (Dorussen et al., 2005).

To make the model adjustable to varying farm settings (e.g. different weaning weight or slaughter weight, different lengths of suckling period) and ensure a standardization of farm parameters, linear regression equations were created for some of the parameters (see Table 2). As an example, the actual number of litters per sow per year depends on the optimal i.e. maximum possible number of litters per sow and year (OLSY) – a function of the production cycle, which depends on the length of the suckling period – and the return-to-oestrus and abortion rate. A farm's actual number of litters per sow per year (LSY) based on the indicated return-to-estrus and abortion rate can be obtained using the equation given in Table 2. This equation was derived by, first, calculating the ratios between the OLSY and LSY for all possible combinations of return-to-oestrus and abortion rates and, second, fitting a linear regression line to the obtained ratios versus return-to-estrus and abortion rates in R software version 3.3.1 (R Core Team (2016)). The same process was applied to derive the actual number of inseminations per year from the optimal number of inseminations per year (OIY), which depends on the return-to-oestrus and abortion rate as well. Likewise, the average feed conversion ratios (FCR) depend on the end weight (nursery) or on start and end weight (fattening), and were determined fitting a linear regression line to different (start and) end weights of a standard growth curve available from literature. While the FCR in fatteners resulting from that growth curve is a rather theoretical value obtained under ideal conditions, the actual FCR for average farms according to survey data from different countries (Anonymous, 2014a) is slightly higher and also varies from country to country. For this reason, a country-specific correction factor was calculated to adjust the result obtained from the standard growth curve to country-specific field data, and included in the equation of the farm-specific FCR.

The same procedure of fitting through linear regression was done with the days in nursery needed to reach a certain selling weight. The days in fattening could be calculated directly from the total weight gain and an average value for ADG (ADG in fatteners does not vary as much with different start and end weights as it does in nursery pigs). The length of nursery or fattening period was used as a key variable to estimate growth performance of a farm rather than average daily weight gain (ADG), because the latter was assumed not to be exactly known in many farms, thus making comparisons less accurate.

Regarding mortality, it is assumed that the average number of days that a pig spends in a nursery or fattening unit before it dies equals a third of the normal production time of a healthy pig in the

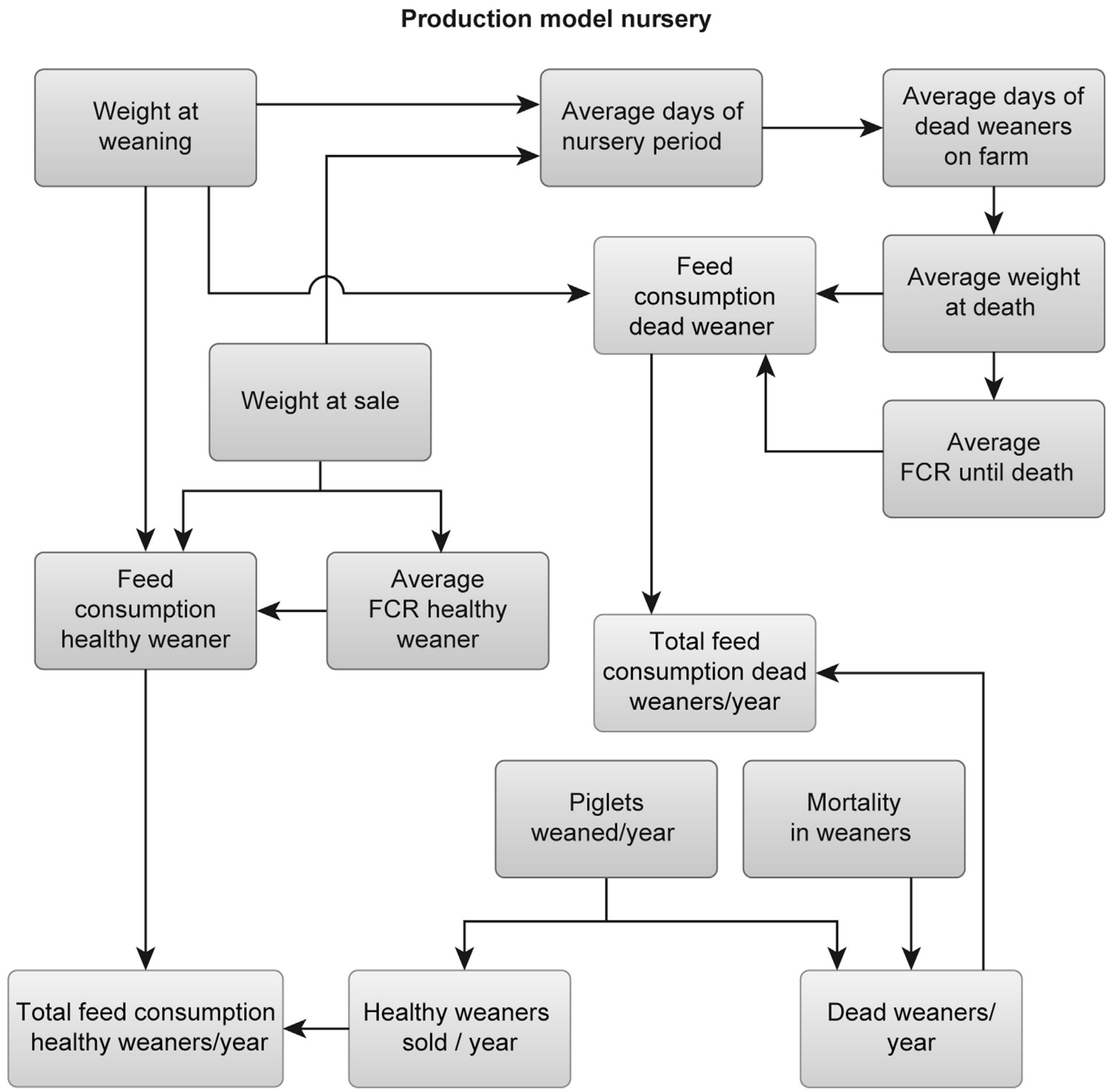

Fig. 2. Schematic production model – nursery part; the fattening part is similar, except (I) that the FCR also depends on the start weight and a correction factor is applied because of a big variation between countries; and (II) that the calculation of days in fattening does not require linear regression with start and end weight, but only takes the total weight gain and standard ADG from literature.

corresponding unit. This accounts for the observation that most of the deaths tend to occur in early stages of each unit (Kritas et al., 2007). Furthermore, dead weaners and fatteners are assumed to have a normal feed intake until they die. Based on this, the calculation of average weight at death and total feed consumed until death is done using the FCR equation described above for fatteners. For weaners, a different equation is needed (Table 2), because the aforementioned equation does not fit for lower weights.

2.2. PRRS epidemiological model

In order to assess the impact of PRRS on the production processes in a farm, this general production model is run twice in parallel: one model represents the processes in the farm in question with its given severity of disease (*diseased model*). This is compared to another model representing the processes if the exact same farm is not affected by PRRSV, ideally negative for the virus corresponding to Holtkamp category IV (Holtkamp et al., 2011) (*negative model*). A literature review was done, first, to identify the parameters assumed to be influenced by PRRS at the different stages of production in European farms and, secondly, to define values for these parameters that could be expected in an average PRRSV-negative farm (*negative baseline values*). These data were obtained from various industry reports from different countries (Anonymous, 2014a,b,c, 2012).

Fig. 3 displays the different impacts of PRRS on the production process from farrowing to finishing: For the breeding part, it is assumed that PRRS affected herds have an increase in return-to-estrus rates and percent abortions. This has an impact on the number of litters per sow per year, but also on the sow feeding regime, as these sows need less gestation feed and sows returning due to PRRS are assumed to have a reduced feed intake for some days. Furthermore it causes extra veterinary and extra labour cost. Other consequences are additional inseminations, a reduction in the number of piglets born alive per litter, an increase in pre-weaning mortality and a reduced average weight at weaning. In

Table 2
General parameters of the production model.

Parameter	Value(s)/equation	Reference/Calculation
Breeding		
Feed consumption/day of a sow baseline (kg) (FCSB)	2.5	Kamphues et al. (2004)
Water consumption (litter/kg feed)	3	Kamphues et al. (2004)
Days in feed of a returned sow	10;21;42[a]	assumption that mostly regular returns
Days in feed of an aborting sow (DFAS)	80;88;105[a]	assumption that most abortions around day 90–2 days less feed consumption due to sickness (grosse Beilage et al., 1992)
Average feed consumption of aborting sow (kg)	= 10 days * 2 kg +(DFAS-10 days) * FCSB + 21 days * FCSB	standard feed consumption according to standard feed curve until abortion + 21 days until next insemination (Anonymous, 2015a)
Sow mortality (per year)	5%	(Chagnon et al., 1991)
Live weight of a sow (kg)	250	(Curtis et al., 1989)
Production cycle (days)	= gestation period (114 days) + suckling period (21/28/35 days) + 5 days empty period	
Optimal litters/sow/year (OLSY)	= year period (365 days)/production cycle	
Actual Litters/sow/year (LSY)	= OLSY * (1.0083862 + return-to-estrus rate * −0.178102 + abortion rate * −0.8773457)	fitted in a linear regression on simulated data
Number of AI doses per sow/estrus (AIS)	2	Anonymous (2012)
Optimal number of inseminations/year (OIY)	=no. of sows * OLPSY * AIS	
Actual number of inseminations/year	= OIY * (0.9783574 + return-to-estrus rate * 1.2434806 + abortion rate * 0.1759786)	fitted in a linear regression on simulated data
Average weight at weaning (kg)	3 weeks of suckling: 6 4 weeks of suckling: 8 5 weeks of suckling: 10	(Anonymous, 2015b, 2012)/depends on suckling period
Average weight of a suckling pig at death	1;1.5;5[a]	assumption (Anonymous, 2012)
Nursery		
Days in nursery	=9.76771 + 2.0477 * nursery end weight – 2.72836 * weaning weight	fitted in a linear regression based on standard growth curve (Anonymous, 2015c)
Average feed conversion ratio of a healthy weaner (FCR)	= 0.0064 * nursery end weight + 1.4701	fitted in a linear regression based on standard growth curve (Anonymous, 2015c) (equation valid for end weights >18 kg)
Total feed consumption of a healthy weaner (kg)	= FCR * (nursery end weight – weaning weight)	
Water consumption (litter/kg feed)	3	Kamphues et al. (2004)
Average days of a dead weaner on farm (DDW)	=days in nursery/3	assumption that mortality occurs mostly in first third (Kritas et al., 2007)
Weight at death (kg)	= 0.524 * DDW + 4.736	fitted in a linear regression based on standard growth curve (Anonymous, 2015c)
Average FCR until death	= −0.0153 * weight at death + 1.9006	fitted in a linear regression based on standard growth curve (Anonymous, 2015c) (equation for weights ≤ 18 kg)
Fattening		
ADG of fatteners until sale (kg) (ADG)	0.8	Anonymous (2014a)
Days of fattening period	=total weight gain/ADG	
Average feed conversion ratio (FCR) of a fattener	=1.09 * (1.261 + nursery end weight * 0.00798 + finishing weight * 0.00897)	fitted in a linear regression based on standard growth curve incl. correction factor for country (Germany: 1.09) (Anonymous, 2015d, 2014a)
Total feed consumption of a healthy fattener until slaughter (kg)	= FCR * (finishing weight – nursery end weight)	
Water consumption (litter/ kg feed)	3	Kamphues et al. (2004)
Average days of a dead fattener on farm (DDF)	= days in fattening/3	assumption that mortality occurs mostly in first third (Kritas et al., 2007)
Weight at death (kg)	= nursery end weight + DDF * ADG	

[a] Values used in a PERT distribution (Minimum; most likely; maximum).

this endemic infections model, sow mortality is not assumed to be increased due to PRRSV, and sows that return or abort due to PRRSV infection are not replaced. Therefore the overall replacement rate of a farm will not be increased due to PRRSV.

In the nursery and fattening part, a proportion of clinically PRRS affected pigs will die as a consequence of the disease and overall mortality will increase. Therefore, the number of pigs produced in the farm is reduced and cost for disposal of dead animals will increase, while feed costs will decrease. Affected herds will have extra labour cost to manage ill pigs and extra veterinary cost due to a higher number of necessary consultative visits by the veterinarian or treatments of secondary infections. PRRS affected pigs have an increased FCR and the batch-level ADG is reduced. As a consequence, extra days on farm are needed to achieve the required live weight for selling. For the model it is assumed that farmers will only sell the pigs once their finishing weight is reached and not sell them prematurely. Quantitative estimates on the described impacts as shown in Table 3 were obtained from literature and an online expert poll conducted with LimeSurvey software (LimeSurvey Project Hamburg, Germany). The link was sent via e-mail to 42 experts (comprising Diplomates of the European College of Porcine Health Management, experts of the EuPRRS.net panel and

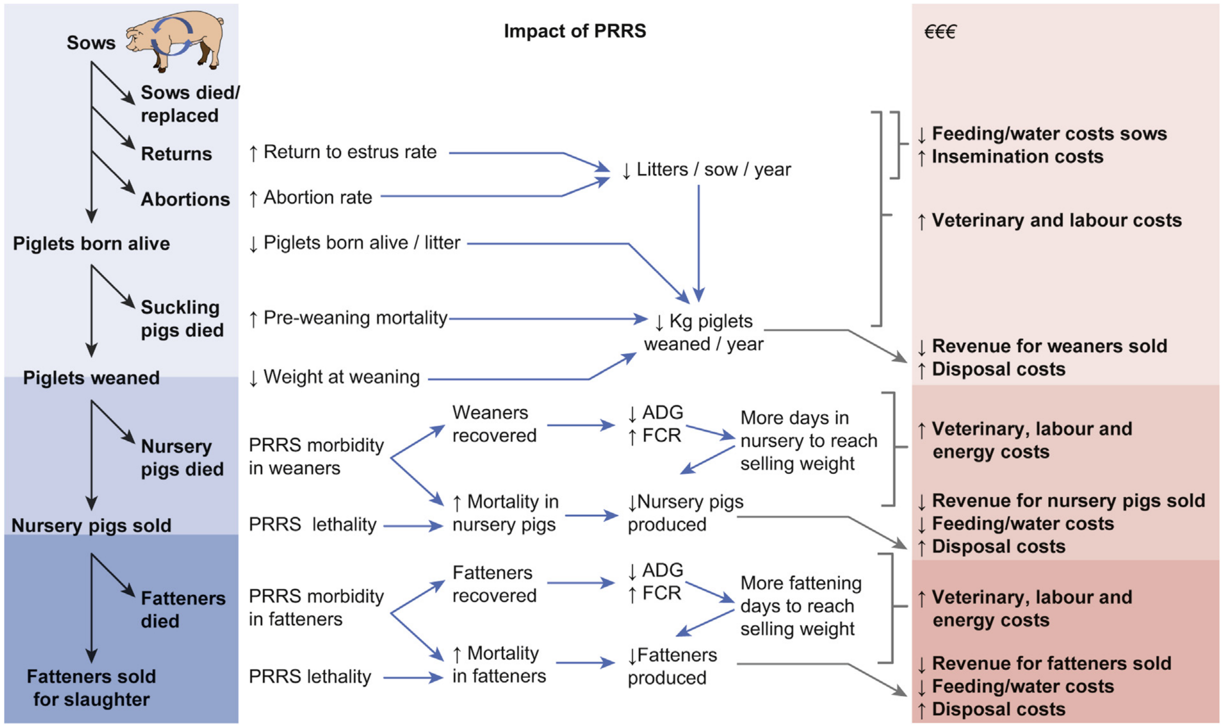

Fig. 3. Flow diagram depicting the production process (left), the influence of PRRSV at the different stages of the production process (middle) and the resulting impact on costs (right). (ADG = average daily weight gain, FCR = feed conversion ratio).

Table 3
Parameters with general change in a PRRS affected farm and their minimum (Min), most likely (ML) and maximum (Max) values used in PERT distributions.

Parameter	Min	ML	Max	Reference
Veterinary cost				expert opinion
Increase in vet cost per sow due to PRRS (%)	8.0	25.0	50.0	
Increase in vet cost per weaner due to PRRS (%)	5.0	25.0	300.0	
Increase in vet cost per fattener due to PRRS (%)	2.0	10.0	50.0	
Labour cost				expert opinion
Extra labour cost per sow per 1 point of severity score (%)	1.0	3.0	10.0	
Increase in labour cost per weaner due to PRRS (%)	2.0	15.0	100.0	
Increase in labour cost per fattener due to PRRS (%)	0.0	5.0	20.0	
Feed consumption				
Days of reduction in feed consumption of a PRRS returned sow	3	7	10	assumption
Reduction in feed consumption of a PRRS returned sow (%)	30.0	50.0	70.0	assumption
Increase in average FCR until sale for a PRRS-diseased weaner (%)	3.0	5.0	8.0	Anonymous (2013b), Anonymous (2017, n.d.); Neumann et al. (2005)
Increase in average FCR until slaughter for a PRRS-diseased fattener (%)	5.0	8.0	10.0	
Lethality in PRRS-diseased pigs				expert opinion
Lethality in PRRS-diseased weaners (%)	0.0	5.0	30.0	
Lethality in PRRS-diseased fattener (%)	0.0	3.0	10.0	

selected European and US-American pig experts from science and industry/private practice), and answers received by eleven. The minimum, median and maximum was calculated over all answers, and used to parametrize PERT distributions.

To assess the PRRS impact in a farm, the two production models – the *diseased model* for the diseased farm and the *negative model* for the same farm without PRRSV – are run in parallel and production and epidemiological outputs etc. calculated for both, such as the number of PRRS diseased pigs and extra deaths, extra number of returns, abortions and inseminations, and changes in feed and water consumption due to disease. To make the estimate as farm-specific as possible, the model coding ensures that if an input value of an affected farm is better than the default baseline value for the negative model, the same input value is also used for the negative model instead of the negative baseline value.

For demonstration purposes we created nine different disease scenarios where the parameters assumed to be affected by PRRS were altered either slightly, moderately or severely, and either in the breeding part only ('Repro'), in nursery and fattening part only ('Respi') or in all farm parts together ('Repro & Respi'). Table 4 gives the default values of production parameters for an average negative farm to which the affected farm is compared, and the exemplary scenarios of clinical affectedness in the corresponding parameters for a PRRS affected farm.

2.3. Economic modelling of disease impact

The economic impact due to the disease at farm-level is calculated in two steps. First, the outputs of the production models are used to conduct a gross margin (GM) and enterprise budget (EB)

Table 4
Different example scenarios used to parametrize the production model of a PRRS affected farm and corresponding default baseline values for a negative farm, assumed to be constant over one year (values for the parameters in sows are per sow group, values for the parameters in suckling, weaning and fattening pigs like morbidity and mortality are cumulative figures over the whole indicated period that animals spend in nursery or fattening).

	Negative farm	Example scenarios for clinical affectedness in a diseased farm								
Parameter	Baseline values[a]	Repro – slightly	Respi – slightly	Repro – moderately	Respi – moderately	Repro & Respi – mod.	Repro & Respi – slightly	Repro – severely	Respi – severely	Repro & Respi – sev.
Return-to-estrus rate (%)	10.0	11.0	10.0	13.5	10.0	13.5	11.0	15.0	10.0	15.0
Abortion rate (%)	2.0	2.5	2.0	3.9	2.0	3.9	2.5	5.0	2.0	5.0
Average piglets born alive per sow per litter[b]	12.7	12.1	12.7	11.4	12.7	11.4	12.1	10.8	12.7	10.8
Pre-weaning mortality (%)	11.0	12.0	11.0	13.5	11.0	13.5	12.0	15.0	11.0	15.0
Weight at weaning (kg)	6	6	6	5.5	6	5.5	6	5	6	5
Days in nursery	45	45	48	45	50	50	48	45	55	55
PRRS morbidity in weaners (%)	0.0	0.0	10.0	0.0	20.0	20.0	10.0	0.0	30.0	30.0
Mortality in weaners (%)	3.0	3.0	5.0	3.0	10.0	10.0	5.0	3.0	15.0	15.0
Days in fattening	119	119	122	119	127	127	122	119	135	135
PRRS morbidity in fatteners (%)	0.0	0.0	10.0	0.0	20.0	20.0	10.0	0.0	30.0	30.0
Mortality in fatteners (%)	1.5	1.5	2.0	1.5	3.0	3.0	2.0	1.5	5.0	5.0

[a] Anonymous (2014a,b,c, 2012).
[b] n the practical use of the model, the corresponding baseline value will be linked to the sow genetic.

analysis to assess the profitability of the different systems, i.e. the affected farm and the negative farm. The structure of the GM and EB analysis are shown in Eqs. (1) and (2):

$$\begin{aligned}\text{GM} = {} & \text{revenue} - \text{replacement cost} - \text{feeding and watering cost} \\ & - \text{veterinary cost} - \text{dead animal disposal cost} - \text{energy cost} \\ & - \text{other variable cost} \end{aligned} \tag{1}$$

$$\begin{aligned}\text{EB} = {} & \text{GM} - \text{building cost} - \text{equipment cost} - \text{inspection,} \\ & \text{levy and insurance cost} - \text{labourcost} - \text{other fixed costs} \end{aligned} \tag{2}$$

For the calculations presented in this publication, the prices and costs given in Table 6 were used.

For each type of variable cost, the costs for a given affected farm and the costs for the corresponding negative farm are calculated based on the indicated input value per animal and the calculated number of animals in each production model. For this reason, when using the same input value per individual cost (Table 5) in every scenario as we did for reasons of simplicity, the calculated GM and EB of the negative farm will be different in each disease scenario. This is because the corresponding value in the negative model depends on the disease severity in the diseased model: e.g., a severely affected farm with currently € 2.00 veterinary cost per weaner sold will have a much stronger decrease in veterinary costs if negative than a slightly affected farm with the same current veterinary costs of € 2.00 per weaner sold.

Consumption outputs from the production models are used to calculate feeding and watering costs. These are calculated separately for healthy pigs, PRRS diseased and recovered pigs sold and pigs that died. In the breeding units feeding and watering cost are estimated for sows that farrowed, returned and aborted, separately for sows with clinical PRRS and sows unaffected by PRRS. Likewise, disposal and transport costs are calculated based on the actual numbers of animals occurring on the diseased and the negative farm.

For veterinary costs, it is assumed that a farmer can give an estimate per animal sold. From this estimate, the "true" veterinary cost per animal is calculated (based on all animals coming in, because also died animals might have received treatments). This value is then used to calculate the veterinary costs of the corresponding negative farm. Additionally, it is assumed that an affected farm generally has a higher veterinary cost per animal than a negative farm. Since this increase due to PRRS varies from farm to farm and cannot be consistently correlated to the degree of clinical affectedness, a flat percentage increase per animal is assumed for a PRRS affected farm compared with a negative farm, independent of the severity of affectedness on that farm (Table 4). To account for inherent uncertainty and variability, this percentage follows a PERT distribution rather than a fixed value.

For energy cost, it is assumed that the estimate a farmer can give per animal is more likely a batch level estimate divided by the average number of animals in a batch rather than a real per animal value. Thus, the costs for the negative farm are calculated taking the batch level cost of the affected farm and correcting it for a potentially shorter duration of the nursery or fattening period.

Labour costs include those for external workers but also the farmer's own labour. They are generally assumed to be fixed costs, i.e. independent of the number of animals, but thought to be affected by PRRS. The impact of PRRSV is considered by adding – similar to veterinary costs – a flat percentage independent of clinical affectedness (morbidity, mortality etc.). Only for the breeding part, the increase in labour cost is assumed to be linked more directly to the disease severity (the higher the number of abortions and returns, the more inseminations, more intensive care for weak-born piglets etc.). Consequently, a score was created based on the return-to-estrus and abortion rate, the number of live-born piglets per litter and the pre-weaning mortality as shown in Table 6. For each criterion, a sub-score of 0–2 is assigned depending on the findings on a farm and sub-scores are then summed up to the final score, ranging from 0 to 8. Thus, labour cost will increase by a certain percentage per each point of severity score (distribution given in Table 3).

Other fixed costs are assumed not to be affected by PRRS and thus equal for an affected and a negative farm.

Second, with these economic outputs, a partial budget analysis is performed to calculate the differences i.e. extra losses (extra cost + revenue forgone) and extra benefits (cost saved + extra revenue) due to disease. The final net value obtained (extra benefits – extra costs) represents the net impact of PRRS on farms.

Impact of PRRS on farm profits is then calculated through comparing gross margin differences between PRRS-negative and disease scenarios (Eq. (3)). The PRRS impact on profits indicates the percentage of profits lost due to PRRS.

$$\begin{aligned}\text{PRRS impact on profits} = {} & (\text{GM with PRRSV} - \text{GM} \\ & \text{PRRSV negative})/(\text{GM PRRSV negative}) * 100 \end{aligned} \tag{3}$$

Lastly, the impact of PRRS on individual costs, e.g. the feed costs or revenue for pigs sold, was assessed by calculating the median difference in these costs between the diseased and the negative model, e.g. the difference in feed costs between the diseased and the negative model.

2.4. Stochasticity and sensitivity analysis

To allow for variability and/or uncertainty in the model and its results, stochasticity was included in the model using @RISK software for Excel version 6.3.1 (Palisade Corporation, Newfield, New York, USA): for parameters with known variability or presenting some degree of uncertainty, PERT distributions were fitted, and model outputs are presented as median values and their 90% prediction intervals. Stochastic simulations were performed with 10,000 iterations per disease scenario.

The impact on individual variables on the final model outputs was assessed in a separate sensitivity analysis for (I) the parameters characterizing disease severity (see Table 4), (II) the parameters undergoing general changes in the case of PRRS (see Table 3), and (III) the prices (Table 5). By varying the values of distributed parameters from their 1st to their 99th percentile or changing baseline values of non-distributed parameters 10% upwards and downwards, the changes in the net loss per farm were assessed in tornado graphs (50,000 iterations; graphs not shown).

We assessed the validity of the baseline model by comparing the results of gross margin and enterprise budget analysis of the negative model with existing data on average farms of the same type and production system found in the literature (Anonymous, 2015f,g; Gross, 2009). In addition, the model was presented to different veterinary practitioners to assess the level of agreement of predicted financial losses with their field experience.

3. Results

3.1. Gross margin & enterprise budget

Table 7 summarizes the results of gross margin and enterprise budget analysis for each of the nine different disease scenarios

Table 5
Prices for different economic parameters in a typical Northern German farm setting (farrow-to-finish herd, 1000 sows).

Parameter	Value (€)	Reference/Calculation
Pig prices		
Price per sow slaughtered	220	Anonymous (2015e)
Price of a replacement gilt	350	Anonymous (2015f)
Price per kg live weight of a piglet sold at weaning	3.7	Anonymous (2015e)
Price per kg live weight of a weaner sold	1.8	Anonymous (2015e)
Price per kg live weight of a fattener sold	1.2	Anonymous (2015e)
Feed and water prices		
Feed price/tonne (gestation)	230	Anonymous (2015f, 2014a)
Feed price/tonne (lactation)	280	Anonymous (2015f, 2014a)
Feed price/tonne (nursery)	320	Anonymous (2015f, 2014a)
Feed price/tonne (fatteners)	280	Anonymous (2015g, 2014a)
Water cost per litre	0.005	Anonymous (2014d)
Veterinary costs		
Total veterinary cost per sow per year (incl. costs for piglets)	80	Anonymous (2015e)
Total veterinary cost per weaner produced	2	Gross (2009)
Total veterinary cost per fattening pig	1.3	Anonymous (2015g)
Dead pig disposal prices		
Disposal cost per kg animal disposed	0.15	Anonymous (2015h)
Insemination prices		
Price per semen dose	3	Anonymous (2015i)
Transport prices		
Transport costs for slaughter sows per sow	5	Anonymous (2015f)
Transport cost per kg live weight pig	0.02	Anonymous (2015f)
Energy prices (incl. water except drinking water for animals)		
Energy cost per sow and year	75	Anonymous (2015f)
Energy cost per weaner produced	0.75	Gross (2009)
Energy cost per fattener produced	2.5	Anonymous (2015g)
Fixed cost prices		
Labour cost breeding per year	200′000	Anonymous (2015f)
Labour cost nursery per year	25′000	Gross (2009)
Labour cost fattening per year	120′000	Anonymous (2015g)
Building cost breeding per year	200′000	Anonymous (2015f)
Building cost nursery per year	60′000	Gross (2009)
Building cost fattening per year	100′000	Anonymous (2015g)
Equipment cost breeding per year	5′000	Anonymous (2015f)
Equipment cost nursery per year	25′000	Gross (2009)
Equipment cost fattening per year	50′000	Anonymous (2015g)
Inspection, levy and insurance cost breeding per year	12′000	Anonymous (2015f)
Inspection, levy and insurance cost nursery per year	12′000	Gross (2009)
Inspection, levy and insurance cost fattening per year	25′000	Anonymous (2015g)
Any other fixed cost breeding per year	30′000	Anonymous (2015f)
Any other fixed cost nursery per year	20′000	Anonymous (2015f)
Any other fixed cost fattening per year	30′000	Anonymous (2015g)

Table 6
Severity score breeding to determine labour cost.

	Degree of clinical affectedness		
Parameter	0 = not affected: below...	1 = slightly affected: between...	2 = severely affected: from...
Return-to-estrus rate (%)	10.0	>10.0–<15.0	15.0
Abortion rate (%)	2.0	>2–<4	4
Live-born per litter	≥ average for genetic	1–10% below average for genetic	>10% below average for genetic
Pre-weaning mortality (%)	11.0	>11.0–<15.0	15.0

Table 7
Median gross margins (GM) and enterprise budgets (EB) per sow per year for the different scenarios, first the outcome for the diseased farm (diseased model) and below in italic the corresponding value if this farm was PRRSV-negative (negative model).

	Negative/healthy	Repro slight.	Respi slight.	Repro & Respi slight.	Repro mod.	Respi mod.	Repro & Respi mod.	Repro sev.	Respi sev.	Repro & Respi sev.
GM (€)										
Diseased	682	603	625	549	493	515	351	403	389	174
Negative[a]	*682*	*704*	*713*	*735*	*712*	*723*	*751*	*718*	*736*	*766*
EB (€)										
Diseased	−232	−311	−289	−365	−421	−399	−563	−511	−525	−740
Negative[a]	*−232*	*−184*	*−189*	*−141*	*−171*	*−178*	*−120*	*−151*	*−166*	*−90*

[a] For an explanation of the differences in the negative model outcomes between the scenarios please refer to Section 3. Economic modelling of disease impact.

for the example of a farrow-to-finish farm not vaccinating against PRRSV and housing 1000 sows. For each disease scenario (and additionally a disease-free control scenario), GM and EB of the diseased farm and GM and EB of the negative farm are presented.

3.2. Losses due to PRRS

The loss due to PRRS per farm part and in total for each scenario is shown in Table 8. Losses increase as severity of PRRS increases. In the case of reproductive problems due to PRRS in the described farrow-to-finish herd, losses in the breeding part occur, whereas no losses but 'saved costs' become visible in the nursery part.

Figs. 4 and 5 indicate losses at individual animal level (sow and pig produced), and Fig. 6 shows the impact of PRRS on farm profits. Overall losses are slightly higher in the reproductive disease scenarios than in the respiratory disease scenarios, whereas losses are highest if both reproductive and respiratory symptoms are present.

The median differences in individual costs between the diseased and the negative model, representing the impact of PRRS on each individual cost, are shown in Fig. 7 for the examples of the moderately affected disease scenarios. The highest difference between diseased and negative model, indicating the biggest loss, is seen in the revenue from the sale of finishers, and is higher in the Repro than in the Respi scenario. The second highest difference is observed in feed costs. These are lower in the diseased than in the negative model and represent savings, which are higher in the Repro than in the Respi scenario.

3.3. Sensitivity analysis

According to the generated tornado graphs (not shown), the variables that caused the broadest variation in the net loss per farm, were (I) for the disease severity parameters, in order of importance: (1) the average piglets born alive per sow per litter, (2) the pre-weaning mortality rate and (3) the mortality rate in nursery. Among (II) the general PRRS related parameters, they were (1) the% increase in labour costs per sow per point of severity score, (2) the% increase in vet costs per weaner due to PRRS and (3) the% increase in vet costs per sow due to PRRS, and (III) a the prices (1) the price per kg live-weight of a fattener sold, (2) the price per tonne fattening feed and (3) the price per tonne weaner feed.

4. Discussion

The model described herein is an epidemiological and economic model to determine the costs of PRRS for an individual pig farm.

The use of this cost model in the field does not require input of any diagnostic data on the occurrence of PRRSV infection (be it from serological or virological examination) in the particular herd of interest. This approach is justified by the fact that (a) the model shall only be used if PRRS has been previously confirmed as the main herd problem, (b) the estimated impact is based only on such parameters that are at most affected by PRRSV, and (c) any direct or indirect detection of PRRSV is non-predictive in terms of disease severity (Young et al., 2010). Thus, instead of trying to indirectly conclude the disease severity from laboratory findings, under the provision of previously confirmed PRRS, we used the more straightforward and parsimonial approach of directly focusing on clinical affectedness.

When comparing the outcome of the newly developed model, e.g. € 126.79 per sow per year (slight reproductive problems) and € 3.77 per fattener (slight respiratory problems) with data from previous studies, our estimates were shown to be well within the range of previous estimates for farrow-to-finish farms, e.g. € 97.56 per sow per year (Brouwer et al., 1994), US$ 200 per sow or 17.7 USD per pig produced during 6 months following an outbreak (Anonymous, 2013a), or US$ 250 per sow for acute outbreaks, (Holck and Polson, 2003). The somewhat higher estimates result from the fact that they were derived from acute outbreak situations, whereas Holck and Polson (2003) estimated losses in persistently infected herds to be US$ 6.25 up to US$ 15.25 per pig, which is even closer to our estimate for endemically infected herds. Even in the case of only slight deviation from the baseline parameters of a healthy PRRSV negative herd, we could show the significance of the economic impact of the infection during the period of one year given that the parameters were stable during this period. This is aggravated by the fact that the current generally difficult economic situation for pig production in many countries makes it difficult even for healthy farms to produce profitably when counting all true costs, e.g. for labour and buildings, which is shown by the negative enterprise budgets. Furthermore, our findings were similar to those of Holtkamp et al. (2013) in that the majority of losses in breeding herds were due to reduced revenue resulting from weaning fewer piglets (Holtkamp et al., 2013). The same was found for growing and fattening herds, where revenue foregone, rather than increased cost, was the primary source of losses attributed to PRRS. The same observation was made in our model, where 'revenue foregone' for the sale of finishers had the main influence on the enterprise budget. In closed systems (i.e. one-site production systems), the 'revenue foregone' is partially compensated by 'costs saved', especially feed costs that do no longer occur with fewer fattening pigs. This is mainly driven by the fact that fewer piglets are weaned and reach the later stages. This is the reason why both effects (i.e. revenue foregone and feed costs saved) were stronger in scenarios with disease already in breeding, compared to scenarios with clinical signs only at later stages.

Our model is based on several assumptions, and might be criticised because of lack of information about the true situation. We addressed the uncertainty regarding input parameters through a stochastic simulation. Moreover, we included expert opinion, wherever we could not obtain data otherwise. Values which have been determined by this method usually attain high reliability (Dorussen et al., 2005). Finally, our assumptions about disease severity fitted well to reports about PRRS that described increases in breeding-herd mortality (1–2 percentage points), late-term abortions (1–2 percentage points), premature farrowing events (1–20 percentage points), dead and mummified piglets in farrowed litters, and variation in breeding and farrowing intervals, as well as increases in pre-weaning mortality by 10–40 percent points and higher prevalence of secondary infections (Anonymous, 1991).

To calculate the impact on potentially PRRS-affected performance and health parameters, we used fixed baseline values characterizing an average healthy farm to compare the present values of a given PRRS affected farm against. This approach does not account for the individual farm performance potential that might differ from farm to farm and might be even higher than the average values used. This is because we deemed it impossible to obtain accurate and reliable individual performance estimates for every farm. Instead, our approach guarantees that the anticipated performance parameters of a healthy farm could be reached by almost every farm given PRRSV negativity and thus gives a conservative estimate of losses, not ignoring that it could be even higher for some farms. Alternatively, a relative impact of the disease could have been modelled. In this case, it would have to be known by which percentage every performance and health parameter is affected by PRRS, i.e. by which percentage that parameter would improve in the absence of PRRSV. This, of course, can never be known with certainty, as it (a) can vary from farm to farm and (b) depends on the individual level of PRRS affectedness of that parameter, as well as (c) the extent to which PRRS and not any other reasons such as co-infections are responsible for the deviation seen in this parameter. It is known that several co-infections can modulate the

Table 8
Loss per year per each farm part and in total for the different PRRS disease scenarios. Within each column, red colour indicates highest loss, green colour lowest. (For interpretation of the references to colour in the legend, the reader is referred to the web version of this article.)

Scenario		Loss per year (€) in Breeding	Nursery	Fattening	Total
Repro slight.	**Median**	**41'569**	**-22'313**	**107'533**	**126'789**
	5%ile	26'487	-22'313	107'533	111'707
	95%ile	59'609	-22'313	107'533	144'829
Respi slight.	**Median**	**0**	**24'852**	**75'724**	**100'575**
	5%ile	0	10'220	68'665	78'885
	95%ile	0	38'896	84'050	122'946
Repro & Respi slight.	**Median**	**41'520**	**2'599**	**179'180**	**223'298**
	5%ile	26'640	-12'014	172'054	186'681
	95%ile	59'583	16'632	187'179	263'395
Repro mod.	**Median**	**46'018**	**-45'523**	**249'168**	**249'663**
	5%ile	28'406	-45'523	249'168	232'051
	95%ile	66'256	-45'523	249'168	269'901
Respi mod.	**Median**	**0**	**19'198**	**201'321**	**220'520**
	5%ile	0	5'073	192'216	197'289
	95%ile	0	32'422	210'735	243'157
Repro & Respi mod.	**Median**	**46'021**	**-25'435**	**422'387**	**442'973**
	5%ile	28'543	-39'491	414'003	403'056
	95%ile	66'184	-12'239	431'671	485'616
Repro sev.	**Median**	**59'726**	**-64'473**	**365'443**	**360'695**
	5%ile	36'150	-64'473	365'443	337'119
	95%ile	85'368	-64'473	365'443	386'337
Respi sev.	**Median**	**0**	**13'994**	**345'354**	**359'348**
	5%ile	0	758	334'431	335'189
	95%ile	0	26'807	356'706	383'513
Repro & Respi sev.	**Median**	**59'668**	**-48'135**	**638'557**	**650'090**
	5%ile	35'963	-61'450	629'072	603'585
	95%ile	84'940	-35'226	648'665	698'379

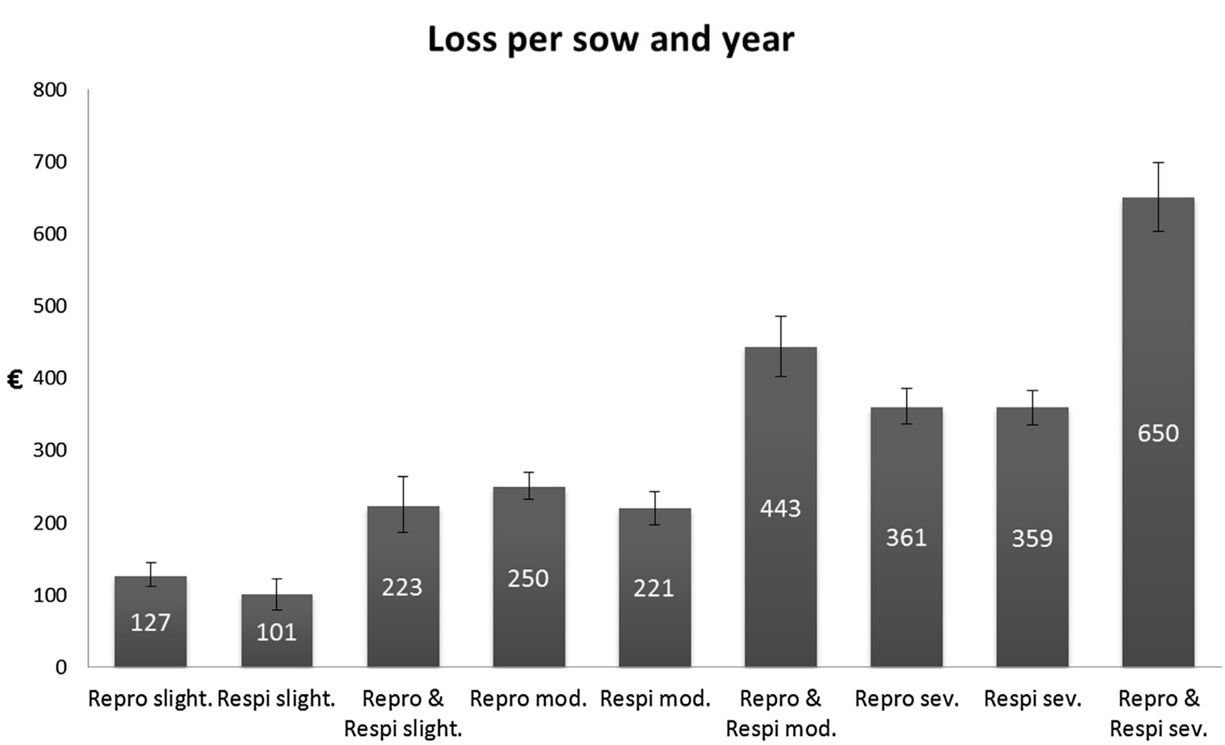

Fig. 4. Median loss per sow and year in a farrow-to-finish herd for different PRRS disease scenarios (5%ile – 95%ile as error bars).

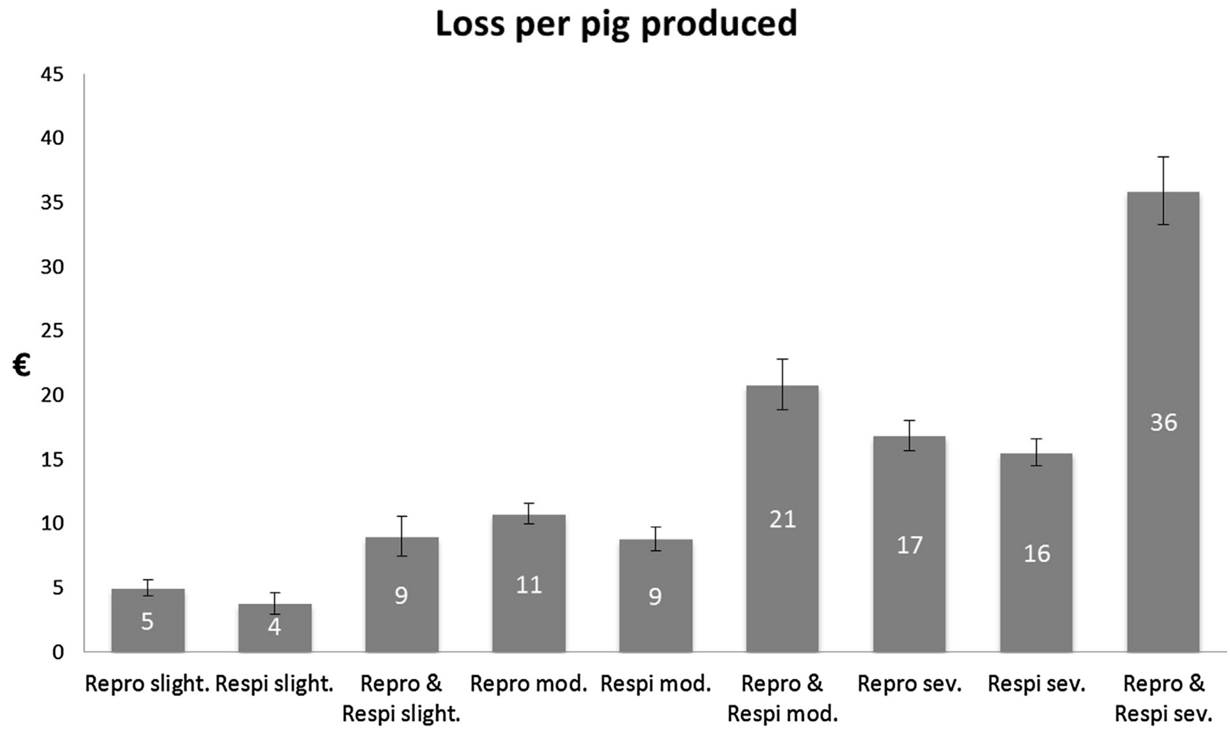

Fig. 5. Median loss per pig produced in a farrow-to-finish herd for different PRRS disease scenarios (5%ile – 95%ile as error bars).

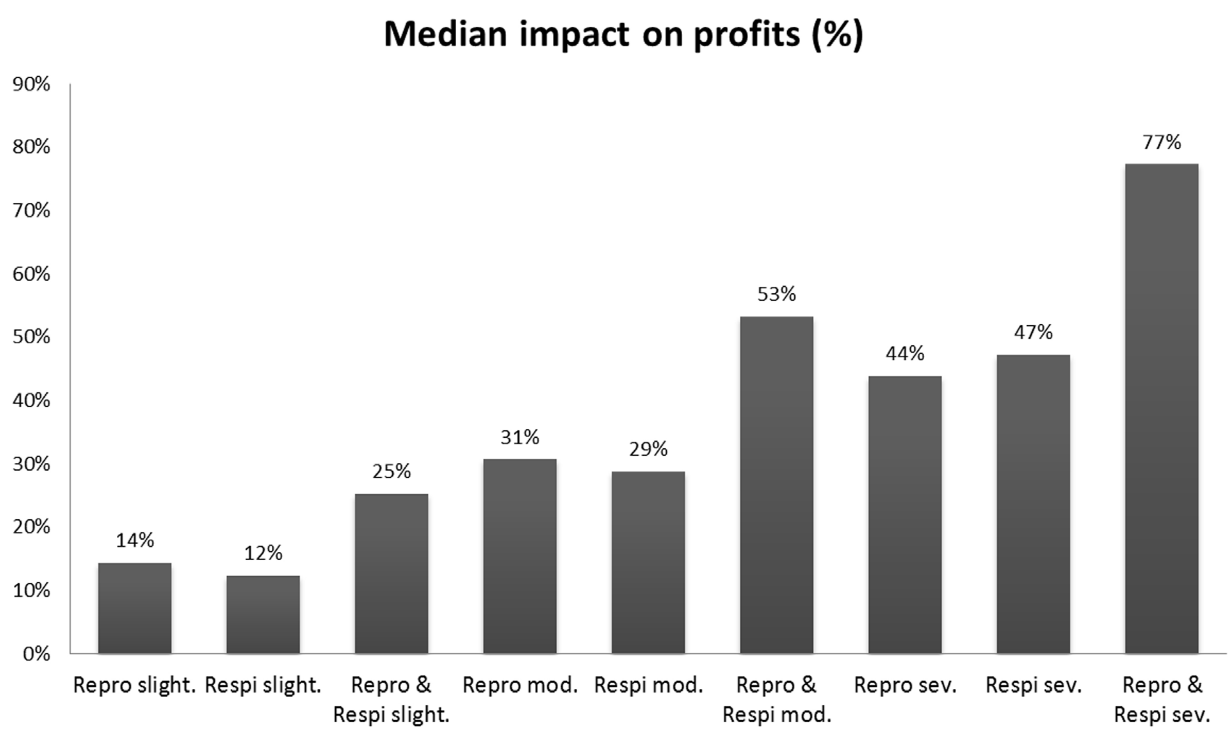

Fig. 6. Median percentage of overall farm profit lost due to PRRS in a farrow-to-finish herd for different PRRS disease scenarios.

course of PRRS in pig farms. This applies to respiratory disease in growing and fattening pigs, as it does to reproductive problems in sows (Zimmerman et al., 2012). For instance, expenses dealing with preventing and treating secondary infections during the 12 months after a PRRS outbreak were on average 60% higher than those found during the previous year in the same system (Pejsak and Markowska-Daniel, 1997). However, in the presented model, we did not account for the effect of specific co-infections, because (a) the quantitative impact of co-infections is rarely described, (b) the confirmation of the type of co-infection would require additional diagnostics, and (c) the integration of co-infections, as the modelling of relative improvement in general, would introduce more uncertainty and demand for more stochasticity and wider distribution ranges in the model. This would make the model as such

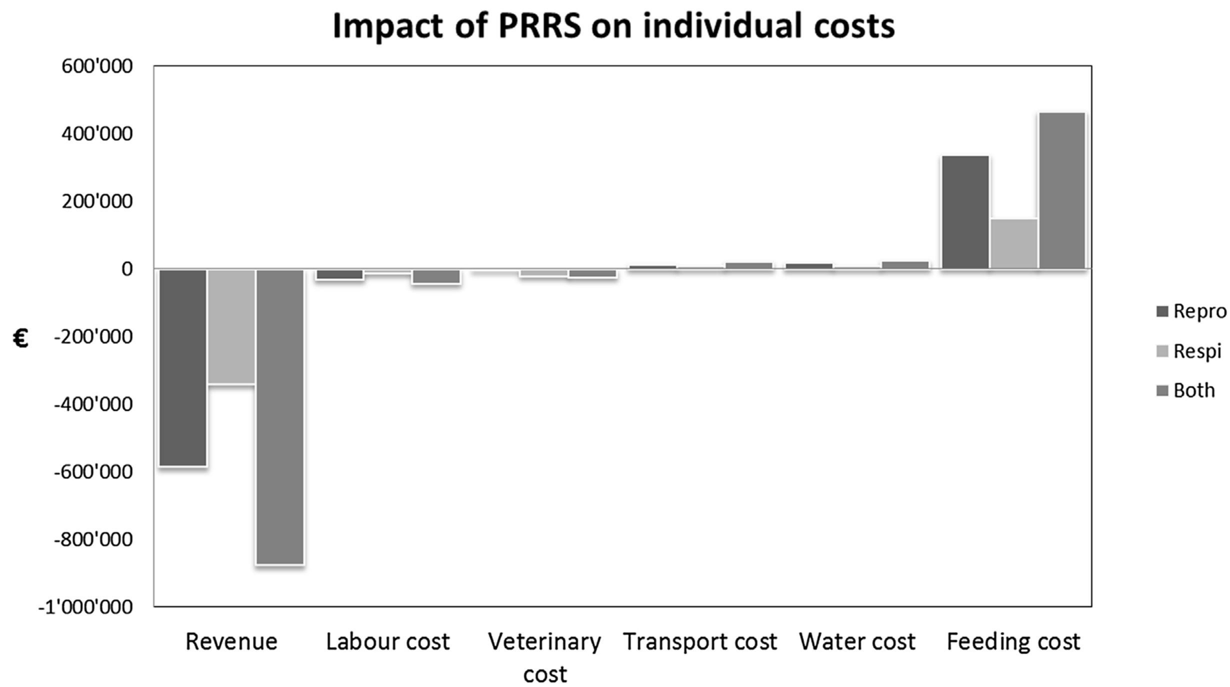

Fig. 7. Differences in individual costs to the negative model for the three different moderately affected disease scenarios (only the six elements with the highest impact shown).

more complex and would lead to more unspecific or vague results that would not really contribute to the understanding of PRRS in a particular pig farm. Furthermore, it is questionable whether the effects of PRRS and co-infections can be seen isolated from each other at all, since there is usually a high degree of interaction between the pathogens, and it was shown in previous studies that a reduction in PRRS also caused a reduction of the impact of co-infections like *Streptococcus suis*, *Haemophilus parasuis*, *Mycoplasma hyopneumoniae*, *Actinobacillus pleuropneumoniae*, and *Salmonella* spp. (Zimmerman et al., 2012). Nonetheless, we considered the fact that veterinary costs might increase after a PRRS outbreak and this includes, of course, the treatment of secondary infections. Other assumptions made in the model relate to the way how specific processes were modelled. For instance, we opted to incorporate the effect of PRRSV on growth performance in nursery and fattening pigs by varying the time necessary to reach the planned selling weight. We are well aware of the fact that in some farms this will not be feasible, because they lack the space capacities to keep pigs longer, and will instead sell them underweight. Nevertheless, we deemed it the most straightforward approach to model it, and we assume that it will not significantly affect the overall cost calculation, because the costs (more precisely the revenue foregone) related to sale with underweight would likely have the same dimension as the currently modelled costs for a longer stay in the barn.

In conclusion, the newly developed model is not an instrument that precisely forecasts the future in a given herd, but, given its prudent use, is a valuable support tool for the decision-making process of farmers and veterinarians, who are facing PRRS in a pig farm and do not know the extent of damage that the disease is causing to the production system. The output can help to understand the need for interventions in case of significant impact of the disease on the profitability of the enterprise. The model can also support veterinarians in their communication to farmers in cases where costly disease control measures are justified.

In a second step, the model will serve as a basis to estimate the impact and economic efficiency of intervention strategies against PRRS in pig farms in order to warrant not just any, but the best decision in the control of PRRS on individual herd level (Nathues et al., 2016 submitted for publication).

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Conflicts of interest

None.

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