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Modelling the economic efficiency of using different strategies to control Porcine Reproductive & Respiratory Syndrome at herd level

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ABSTRACT

PRRS is among the diseases with the highest economic impact in pig production worldwide. Different strategies have been developed and applied to combat PRRS at farm level. The broad variety of available intervention strategies makes it difficult to decide on the most cost-efficient strategy for a given farm situation, as it depends on many farm-individual factors like disease severity, prices or farm structure. Aim of this study was to create a simulation tool to estimate the cost-efficiency of different control strategies at individual farm level. Baseline is a model that estimates the costs of PRRS, based on changes in health and productivity, in a specific farm setting (e.g. farm type, herd size, type of batch farrowing).

The model evaluates different intervention scenarios: depopulation/repopulation (D/R), close & roll-over (C&R), mass vaccination of sows (MS), mass vaccination of sows and vaccination of piglets (MS + piglets), improvements in internal biosecurity (BSM), and combinations of vaccinations with BSM. Data on improvement in health and productivity parameters for each intervention were obtained through literature review and from expert opinions. The economic efficiency of the different strategies was assessed over 5 years through investment appraisals: the resulting expected value (EV) indicated the most cost-effective strategy. Calculations were performed for 5 example scenarios with varying farm type (farrow-to-finish – breeding herd), disease severity (slightly – moderately – severely affected) and PRRSV detection (yes – no). The assumed herd size was 1000 sows with farm and price structure as commonly found in Germany. In a moderately affected (moderate deviations in health and productivity parameters from what could be expected in an average negative herd), unstable farrow-to-finish herd, the most cost-efficient strategies according to their median EV were C&R (€1′126′807) and MS + piglets (€ 1′114′649). In a slightly affected farrow-to-finish herd, no virus detected, the highest median EV was for MS + piglets (€ 721′745) and MS (€ 664′111). Results indicate that the expected benefits of interventions and the most efficient strategy depend on the individual farm situation, e.g. disease severity. The model provides new insights regarding the cost-efficiency of various PRRSV intervention strategies at farm level. It is a valuable tool for farmers and veterinarians to estimate expected economic consequences of an intervention for a specific farm setting and thus enables a better informed decision.

1. Introduction

A multitude of studies have confirmed the vast economic impact of Porcine Reproductive & Respiratory Syndrome (PRRS) on pig production in many countries all over the world (Holck and Polson, 2003; Holtkamp et al., 2013; Neumann et al., 2005; Nieuwenhuis et al., 2012; Pejsak and Markowska-Daniel, 1997). The detrimental effect of the disease is caused by the fact that it impairs performance at several stages of production. Not only does it affect the number of piglets weaned due to increased abortion rates, lower numbers of piglets born alive or a higher pre-weaning mortality; it also leads to increased mortality rates and a reduced growth rate and feed efficiency in nursery and grower pigs (Neumann et al., 2005; Nieuwenhuis et al., 2012; Olanratmanee et al., 2013). Furthermore, the effects described in these

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studies were not only restricted to the period of the acute outbreak, but persisted for a considerable period thereafter.

Lots of effort has been undertaken to find ways of how to control PRRSV infection. At farm level, various strategies have been developed and applied in the field to combat PRRS. One approach is to eliminate the virus and create a completely virus-negative herd. Three different methods are commonly applied to achieve this aim. The first possibility is complete herd depopulation and repopulation. This comprises the slaughter or culling of all pigs present at the farm, followed by a restocking with PRRSV-negative animals. While this measure is highly effective, its costs are very high (Corzo et al., 2010). A second and rather cheap method is herd closure and roll-over. The introduction of new and thus naïve animals that were never exposed to the (farm-) specific strain of PRRSV is stopped, resulting in no susceptible animals at one time point and ceased virus transmission (McCaw et al., 2003). The third option is test and removal, where all adult animals are tested and all PRRSV seropositive animals are culled (Dee and Molitor, 1998), making this strategy considerably costly. Besides elimination procedures, various vaccines are on the market to control PRRS. While the protection provided by commercially available inactivated vaccines is currently considered low (Renukaradhya et al., 2015), modified live vaccines (MLV) have successfully reduced clinical impact of PRRSV infection in breeding as well as growing animals, with positive effects e.g. on the number of piglets born alive, mortality in suckling and weaning pigs or average daily weight gain (Alexopoulos et al., 2005; Cano et al., 2007; Kritas et al., 2007; Olanratmanee et al., 2014; Scortti et al., 2006). Vaccination protocols usually comprise the immunization of gilts and subsequent vaccination of sows, either in the form of a mass vaccination in intervals of three or four months, or according to the status of reproduction, most commonly at day 6 after farrowing and at day 60 of gestation. Complementary vaccination of suckling pigs is usually done at two to three weeks of age to reduce shedding/circulation of the virus and improve production parameters from wean to finish (Kritas et al., 2007). Since many factors related to farm internal processes like pig flow, biosecurity, hygiene etc. were proven to play an important role in intra-herd virus transmission and thus the clinical presentation of PRRS in an infected herd (Young et al., 2010), these can also be adjusted for PRRSV control. Related concepts are e.g. an optimized gilt acclimatization (Corzo et al., 2010) or procedures to reduce virus transmission in suckling pigs like “McRebel” (McCaw, 2000).

This broad variety of available intervention strategies makes it difficult to decide which strategy is most appropriate in a given farm situation. Some strategies make sense only under certain circumstances: e.g. test & removal is recommended in sow herds with a low seroprevalence and no acute outbreak history within the past twelve months (Zimmerman et al., 2012). Other strategies are extremely effective but at the same time very expensive, like depopulation-repopulation. This means that farmer and veterinarian need to consider not only the expected effect or success of a measure, but also the costs, and it is not necessarily the most effective measure that turns out to be the most economically efficient one. Many different farm-individual factors like the degree of clinical severity but also the price situation (be it the generated revenue, current expenses or costs of intervention strategies) have an impact on the cost efficiency and the return on investment of each strategy in a given farm. Until to date, the decision which strategy fits best in a certain farm was often based on a veterinarian’s (personal) experience and “gut feeling”, as objective tools for decision making have not been available. Thus, aim of this study was to create a simulation tool to systematically evaluate the economic efficiency of different common PRRSV intervention strategies in endemically affected farms for different farm situations over a period of five years. This tool is intended to be a decision-making tool for veterinarians on the most appropriate intervention strategy for a given PRRSV affected farm. The tool is made available via the “PRRS integrated solutions” website and smartphone app (Merck Animal Health, New Jersey, United States of America).

2. Material and methods

The methodology used is similar to an economic model for post-weaning multi-systemic wasting syndrome created by Alarcon et al. (2013) and is based on a stochastic spread sheet model that estimates the cost of PRRS of an infected farm developed by Nathues et al. (2017) as a baseline.

2.1. Summary of the PRRS herd-level cost model used as baseline

This baseline model estimates the farm-level yearly PRRS losses for five different production systems: (1) breeding farms with sale of piglets at weaning; (2) breeding farms with sale of nursery pigs; (3) nursery farms, (4) fattening farms; and (5) farrow-to-finish farms. The model consists of three parts: breeding, nursery and fattening part, and their different combinations are used to make up the 5 production systems investigated. Since this model was designed as a calculator for farmers and veterinarians, it can be customized to other farm specific settings, e.g. the type of batch farrowing (one-week- and three-week-rhythm) and the length of the suckling period (three, four and five weeks), as well as production performance, disease parameters and prices. Through a literature review process, PRRS epidemiological and production impact parameters were identified and their values assessed. With this, a production model was created that simulates the changes in population dynamics and pig management parameters (i.e. feed consumption) between a PRRS diseased and non-diseased (i.e. PRRSV-negative) farm scenario on a yearly basis, with the underlying assumption that PRRSV is the cause of these changes in health and performance parameters. This production model is supplemented by an economic model to assess the farm’s profitability through gross margin and enterprise budget analyses, and to calculate the net losses from PRRS via partial budget analyses. Full details and parameters can be found in Nathues et al. (2017).

This baseline cost-model was extended by incorporating different intervention strategies. Firstly, the two most commonly applied elimination procedures were considered: 1) depopulation/repopulation and 2) close & roll-over. Secondly, two widely used vaccination protocols were included: 3) mass vaccination of sows, 4) mass vaccination of sows and vaccination of piglets. Lastly, 5) the improvement of (internal) biosecurity and management was evaluated alone and, 6) & 7), in combination with the two vaccination protocols.

2.2. Example herd and example scenarios

We would like to demonstrate the application of the model presenting estimations for different farm and disease situations. These are based on the following general farm characteristics, which can be seen as typical for e.g. the pig-dense parts of Germany: a sow herd with 1000 working sows, a one-weekly production rhythm (i.e. batch-wise farrowing every week), three weeks of suckling period, an annual replacement rate of 35%, selling nursery pigs at 30 kg live weight (breeding herd) or finishers at 120 kg live weight (farrow-to-finish herd). Due to the one-weekly farrowing rhythm, the farm has 21 sow groups, 7 different age groups of nursery pigs and 17 different age groups of fatteners (depending on the length of nursery and fattening period). The economic efficiency of intervention strategies was assessed for five different scenarios, the details of which are listed in Table 1: we accounted for two different herd types: farrow-to-finish herd or breeding herd with sale of nursery pigs; two different vaccination histories: no current vaccination or mass vaccination of sows; virus detection: field virus detected within the previous twelve months or no field virus detected within the previous twelve months. Whereas in the positive case (virus detected) this corresponds to category “unstable” according to Holtkamp (Holtkamp et al., 2011), in the negative case, the herd cannot necessarily be classified as sustainably stable; it rather indicates that PRRSV circulation has been at low levels. Lastly, we

Table 1
Farm characteristics and performance/disease parameters for five different farm/disease scenarios (ftf = farrow-to-finish herd; brn = breeding herd with nursery pigs; light grey coloured cells indicate slight affectedness, darker grey coloured cells moderate affectedness), and baseline values to characterize a healthy PRRSV-negative farm (in italic).

			Scenario			***Baseline values / negative herd***
Farm characteristics	**1**	**2**	**3**	**4**	**5**	
Farm type	ftf	ftf	ftf	Brn	brn	
Current vaccination (sows)	no	no	yes	No	yes	
Wild type virus in suckling pigs	no	yes	no	Yes	no	
Wild type virus in nursery pigs	no	yes	yes	No	no	
Wild type virus in fattening pigs	no	yes	yes	not applicable		
Performance / disease parameters						
Return-to-estrus rate	11.0%	13.5%	10.0%	13.5%	11.0%	*10.0%*
Abortion rate	2.50%	3.9%	2.0%	3.9%	2.5%	*2.0%*
Average piglets born alive per sow & litter	12.1	11.4	12.7	11.4	12.1	*12.7*
Pre-weaning mortality	12.0%	13.5%	11.0%	13.5%	12.0%	*11.0%*
Weight at weaning (kg)	6	5.5	6	5.5	6	*6*
Days in nursery	48	50	50	45	48	*45*
PRRS morbidity in weaners	10.0%	20.0%	20.0%	0.0%	10.0%	-
Mortality in weaners	5.0%	10.0%	10.0%	3.0%	5.0%	*3.0%*
Days in fattening	122	127	127			*119*
PRRS morbidity in fatteners	10.0%	20.0%	20.0%			-
Mortality in fatteners	2.0%	3.0%	3.0%			*1.5%*
Total losses € per year Median before intervention	**224'878**	**444'381**	**226'219**	**185'715**	**153'176**	

assumed different degrees of disease severity: slightly or moderately affected in breeding, nursery and/or fattening (determined by the values of performance and disease parameters in the respective farm part). Scenario 1 is a farrow-to-finish herd that does not currently vaccinate against PRRS. No field virus has been detected in any of the production parts within the previous year, associated with only slight clinical affectedness in all farm parts. Scenario 2 differs from the first in that field virus was detected in all farm parts, associated with moderate affectedness in all farm parts. In scenario 3, sows are vaccinated against PRRSV, so that field virus detection and clinical affectedness are confined to the later stages of production (nursery and fattening: moderately affected). Scenario 4 is a breeding herd, where the focus of PRRSV impact is in the breeding part (field virus detected in suckling piglets, moderately affected), whereas no effect is seen in nursery. In scenario 5, the breeding herd is vaccinating sows, and PRRSV activity is at low level (no virus detection) but not “0” (slight clinical affectedness) in both breeding and nursery part.

2.3. Description of considered intervention strategies

1) Depopulation/repopulation (D/R)

Upon start of the intervention (day 0 = one day before the next regular insemination of a sow batch), the farmer stops breeding the sows and instead sends all of them to slaughter as soon as their piglets are weaned. Once the piglets from the last batch of sows are weaned, the farmer sells all remaining animals of the herd, accepting that some batches are sold prematurely i.e. with underweight. After thorough cleaning and disinfection of all facilities and an empty period of at least 6 weeks, the farmer starts repopulating the herd batch-wise with PRRSV-negative gilts, so that the first batch of new gilts will be bred around two weeks later, the first batch of piglets will be weaned roughly one year after start of the intervention, and slaughtered roughly in the middle of the second year (all depending on the length of suckling, nursery and fattening period).

2) Close & roll-over (C&R)

On day 0, the farmer purchases the number of gilts that will be needed for replacement during the next six months, precisely in five different age groups from 75 days of age to 159 days of age. From this day onwards he will not introduce any animals from outside into the herd for a period of six months. To provide simultaneous exposure of all sows at the beginning of herd closure, all sows are vaccinated once with a MLV.

3) Mass vaccination of sows (MS)

After basic immunization of all sows and a booster vaccination four weeks later, the regular protocol comprises the vaccination of the whole sow herd every three months. Incoming gilts are vaccinated twice during acclimatization.

4) Mass vaccination of sows and vaccination of piglets (MS + piglets)

Vaccination of sows is as described under strategy 3); piglets are regularly vaccinated once at day 12–21 after birth.

5) Improvement of (internal) biosecurity and management (BSM)

This intervention comprises a set of different single measures, mainly but not only concerning internal biosecurity, which should be implemented depending on the current situation on the farm. These could be:

- Strict all-in-all-out regime in farrowing, nursery and fattening units with proper cleaning and disinfection.
- Appropriate gilt acclimatization.
- No cross-fostering of suckling pigs > 24 h after birth.
- Change of injection needles at least between litters.
- Facilities to separate sick animals from others.
- Segregated early weaning.
- Treatment of co-infections.
- Gilts/boars/semen from certified PRRS-negative sources (external biosecurity).
- Tn the case of nursery or fattening farms purchase of vaccinated piglets (external biosecurity).

The herd-attending veterinarian decides on what measures need to be implemented after thorough herd examination and identification of the weak points requiring improvement. Goal is that biosecurity and management processes are optimized to a level appropriate for the farm system.

6) BSM in combination with mass vaccination of sows (MS + BSM)

This intervention strategy is a combination of measures 3) and 5).

7) BSM in combination with mass vaccination of sows and vaccination of piglets (MS + piglets + BSM)

This intervention strategy is a combination of strategy 4) and 5).

2.4. Effect of interventions on herd performance and PRRS disease parameters

2.4.1. Degree of improvement

For the two elimination procedures, it is assumed that the herd will become PRRSV-negative (no detection of virus, in the case of 2) C&R termed "provisionally negative" according to Holtkamp (Holtkamp et al., 2011) after completion of the intervention. Thus, all performance and disease parameters will return to baseline values that can be expected in an average healthy farm. These baseline values originating from industry reports (see Nathues et al., 2017) are given in Table 1.

In contrast, vaccination protocols and BSM will most likely not result in a complete elimination of the virus and cessation of clinical signs, but rather in a certain degree of improvement in the PRRSV-affected performance and disease parameters. Value distributions for improvement per strategy and parameter are shown in Table 2. For the strategy relying on sow vaccination only (3), improvements are assumed to take place only in breeding and nursery part. For the vaccination protocol also involving piglets (4) and 5) BSM, improvements are also expected in the fattening part. Furthermore, as concluded from Table 2, relative improvement is assumed to be stronger, if field virus had been detected in the farm part (separately for breeding, nursery and fattening), corresponding to category "unstable" (Holtkamp et al., 2011). Also, a stronger improvement for strategy 4) is assumed, if the farm does not vaccinate at all against PRRSV at the time of assessment.

As scientific literature did not have enough information on the degree of improvement on single parameters for each intervention, an expert poll was conducted. An online questionnaire was created in LimeSurvey software (LimeSurvey Project Hamburg, Germany), and 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 selected European and US-American pig experts from science and industry/private practice). The survey asked the experts to which level a certain parameter (e.g. abortion rate, piglets born alive, PRRS morbidity) would improve, compared to its current status, if strategy 1) – 6) were implemented. Answers were received from eleven participants. For each question, minimum, median and maximum values were calculated for all answers. These values formed the base to parametrize PERT distributions indicating the degree of improvement for each performance and disease parameter and each intervention strategy (see Table 2 and section 'Stochasticity'). For the combined strategies 6) & 7), the level of improvement for each parameter was calculated as the product of the values of improvement of each strategy alone: e.g. if 3) MS alone reduces the PRRS morbidity to 80% of its current status and 5) BSM alone to 90%, the combined strategy 6) will result in an improvement to 72%.

2.4.2. Probability of success

Besides the level of improvement, the probability of success, i.e. the probability that the anticipated improvement is achieved, determines the value of an intervention strategy. For 1) D/R, given that the measure is carried out correctly, it is believed that the probability of success, i.e. that the strategy will lead to complete elimination of the virus from the farm, is 100%. For 2) C&R, this probability is assumed less than 100%. The corresponding probability distribution was obtained from literature review and expert opinion, see Table 3. Distributions or ranges for vaccination and BSM strategies, where improvement is less a question of "all or nothing" but exhibits variability between and within parameters – expressed as distributions – already incorporate a probability of success. Therefore, a probability of success as separate factor was not necessary to be accounted for, and thus was set to 100%.

2.5. Applicability of strategies

Since it does not make sense to evaluate every strategy for every possible farm situation, the following assumptions and restrictions were made: Elimination procedures are only applicable to herds holding sows, not for specialized nursery or fattening farms. Strategy 3) MS is only evaluated if at the time of assessment the farm does not vaccinate against PRRSV. Strategy 4) MS + piglets is evaluated if the farm does not vaccinate at all against PRRSV or if, at the time of assessment, it vaccinates only sows. The same applies to combinations of vaccination and BSM.

2.6. Economic modelling of each intervention strategy

A separate production model is calculated for the farm at its current status as well as for each intervention strategy to reflect the situation after completion of the intervention, i.e. the final status.

2.6.1. Final status

In the production models for the elimination procedures, the baseline performance and disease parameters in Table 1 are used. In the models for the other intervention strategies, the current values of disease and performance parameters are multiplied by the expected degree of improvement as indicated in Table 2. As an example, a current abortion rate of 15% will decrease to a median of 10.5% (70% of its current value) after implementing strategy no. 3) mass vaccination in sows. A current weight at weaning of 5 kg will increase to a median of 5.75 kg (115% of its current value) following implementation of 4) MS + piglets. However, the model does not allow the achieved improvement to exceed the baseline value as defined for a negative farm:

Table 2
Minimum (Min), most likely (ML) and maximum (Max) values for the degree of improvement in each performance and disease parameter for intervention strategies 3) – 5), as derived from expert opinion and used in PERT-distributions.

Intervention strategy/parameter	Change to (%)					
	Min	ML	Max	Min	ML	Max
3) Mass vaccination of sows						
non-conception rate	100%	80%	20%			
abortions	99%	70%	10%			
average piglets born alive per sow per litter	101%	120%	170%			
pre-weaning mortality	100%	70%	10%			
weight at weaning (kg)	100%	115%	180%			
weaners clinically affected by PRRS	100%	80%	30%			
weaners mortality	100%	90%	20%			
ADG weaning to sale (kg)	100%	110%	170%			
4) Mass vaccination of sows and vaccination of piglets	**With previous sow vacc.**			**No previous vacc.**		
non-conception rate	100%	80%	20%	100%	80%	20%
abortions	99%	70%	10%	99%	70%	10%
average piglets born alive per sow per litter	101%	118%	170%	101%	120%	170%
pre-weaning mortality	100%	73%	10%	100%	70%	10%
weight at weaning (kg)	100%	115%	180%	100%	115%	180%
weaners clinically affected by PRRS	95%	80%	30%	99%	80%	30%
weaners mortality	96%	85%	20%	99%	85%	20%
ADG weaning to sale (kg)	104%	110%	170%	102%	110%	170%
fatteners clinically affected by PRRS	100%	90%	50%	100%	90%	50%
Fatteners mortality	100%	95%	50%	100%	96%	50%
ADG fatteners until sale (kg)	100%	109%	150%	100%	108%	150%
5) Improvement of internal biosecurity and management	**Virus detected**			**No virus detection**		
non-conception rate	97%	80%	20%	100%	85%	20%
abortions	99%	80%	10%	99%	90%	10%
average piglets born alive per sow per litter	101%	120%	170%	101%	110%	170%
pre-weaning mortality	98%	70%	10%	100%	90%	10%
weight at weaning (kg)	100%	110%	180%	100%	105%	180%
weaners clinically affected by PRRS	100%	390%	30%	100%	90%	30%
weaners mortality	100%	90%	20%	100%	90%	20%
ADG weaning to sale (kg)	100%	110%	170%	100%	110%	170%
fatteners clinically affected by PRRS	100%	90%	50%	100%	90%	50%
Fatteners mortality	100%	95%	50%	100%	95%	50%
ADG fatteners until sale (kg)	100%	108%	150%	100%	105%	150%

Table 3
Parameters relevant for specific interventions including their minimum (Min), most likely (ML) and maximum (Max) values, to parametrize PERT-distributions.

Strategy/parameter	Min	ML	Max	Reference
2) Close & roll-over				
% of sows that drop out because they do not meet the selection criteria	10%	20%	25%	assumption
Average live weight of a sow that drops out kg	105	110	115	assumption
Probability of success	30%	85%	95%	expert opinion
Strategies 1) & 2)				
% permanent increase in total costs for permanently improved external biosecurity after virus elimination from herd	0.1%	1%	5%	expert opinion

e.g. if the current weaning weight is 5.5 kg and the baseline value for a negative farm is 6 kg, strategy 4) will return the weight to 6 kg and not 6.33 kg, which equals 115%. These calculations will result in the different production outputs for each intervention, e.g.: the number of sows slaughtered, the number of piglets weaned, nursery pigs sold and finisher pigs slaughtered, the number of inseminations or kg feed needed, the number of diseased or died animals, and so on, per batch and year.

The outputs of the production models are used to conduct a series of gross margin analyses (GM) as well as enterprise budget analyses (EB) to assess revenue, variable costs and fixed costs of producing (a) a batch of pigs under the current disease status and (b) a new batch of pigs in the final status for each type of intervention per batch and per year, using the same methodology as described in Nathues et al., 2017. The subsequent partial budget analysis then indicates extra losses and benefits per batch and per year for each intervention strategy in comparison with the current status of the affected farm (Eq. (1)).

$$\begin{aligned} \mathit{Partial\ budget}\,(PB) &= (\mathit{cost\ saved} + \mathit{extra\ revenue}) \\ &\quad - (\mathit{extra\ cost} + \mathit{revenue\ foregone}) \end{aligned} \tag{1}$$

This calculation also incorporates intervention-specific costs occurring after completion of the intervention; so these are the costs incurring regularly throughout the whole period of observation:

2.6.1.1. Costs related to elimination strategies. Farms that implemented strategy 1) or 2) will in most cases have to increase their levels of **external biosecurity** to minimize the risk of PRRSV re-introduction. This is likely an extra cost. To account for this fact, a small proportion of the total current cost is added to the calculated costs of a farm after elimination (value given in Table 3).

2.6.1.2. Costs related to vaccination strategies. Regular costs for strategies 3) and 4) consist of vaccination costs according to the vaccination protocol (used prices per dose see Table 4): for the mass vaccination of sows every three months, the required number of doses per year corresponds to four times the total number of sows. Further costs comprise the vaccination of all incoming replacement gilts twice during acclimatization. For piglet vaccination, the number of doses required corresponds to the number of piglets weaned per year (it is assumed that most of the suckling pig mortality occurs in the first days of life, so that piglets reaching vaccination age will also reach the weaning age). Total costs for strategy 4) depend on the current

Table 4
One-time and recurring costs for the different intervention strategies used in the example.

Intervention/cost	Value	Reference
Strategies 1) & 2)		
Price of a replacement gilt	350.00 €	Anonymous (2015)
Cleaning and disinfection after depopulation/sow (incl. water, energy, chemicals etc.)	10.00 €	assumption
Extra labour cost/sow during depop./repop. Procedure	30.00 €	assumption
Transport cost/sow	5.00 €	Anonymous (2015)
2) Close & roll-over		
Extra cost (building etc.) for providing space to all replacement gilts needed for the following 6 months (time period of herd closure)/sow	30.00 €	assumption
Discount from regular price for the purchase of younger gilts, % per 3 weeks younger age (baseline = 180 days)	1%	assumption
Strategies 3) – 7)		
Price per dose PRRS vaccination (sow) incl. labour	1.00 €	Linhares et al. (2015)
Price per dose PRRS vaccination (piglet) incl. labour	0.80 €	
5) Improvement of internal biosecurity and management		
Overall% permanent increase in total costs for permanently improving internal biosecurity and management	2%	expert opinion

vaccination scheme: For herds without PRRS vaccination, additional costs consist of costs for sow and piglet vaccination, whereas for herds already vaccinating sows, only costs for piglet vaccination will be counted as additional costs.

2.6.1.3. Costs related to BSM. Regular costs related to strategy 5) are the costs for **permanently improving internal biosecurity and management**. Here, the level of expenditure very much depends on the measures necessary in a given farm, and it is assumed that these measures involve rather long-term and recurring than just one-time costs. Therefore, the farmer or veterinarian is asked to indicate his/her estimate of the regularly accruing BSM-related expenses as a percentage of the current total costs, which will be added to the current costs (percentage used in this example in Table 4).

2.6.1.4. Costs related to combined strategies. Regular costs for 6) and 7) combine the costs for vaccination with the BSM-related expenses as described under 3) – 5).

The difference obtained in EB net margins between current status and intervention represents the total net benefit or loss due to an intervention, i.e. “net value of change” per year in the final status, once the intervention is completed and the final level of improvement reached.

However, for all intervention strategies, a transition phase needs to be accounted for, in which the intervention is being implemented but not yet effective: during this time period, there will be no improvement in the disease and performance parameters yet, and temporary changes or disruptions in production processes as well as one-time costs or costs different from those in the final status will occur. Therefore, the yearly production models for the final status cannot be applied one-to-one for this transition period. As a consequence, two separate partial budget calculations are needed for each intervention: one for the transition phase and one for the years in the final status after completion of the intervention. Since it was assumed that the intervention procedure should be completed at some point in time within the first year after its initiation, the first year was defined as transition period. Consequently, the calculated net value of change described for the final status applies to the years 2–5 of the observation period. An exception is strategy 1) D/R, where the transition period was set to two years, because it takes more than one year until first new batch produced is sold for slaughter (see section “Example herd and example scenarios”).

2.6.2. Transition period

For the transition period, a separate series of partial budget analyses is performed to assess the extra cost, revenue foregone, cost saved and extra revenue of implementing the intervention for each batch in the first year: for this purpose, the batch production, i.e. the numbers of batches produced every week in the first – and for 1) D/R also the second – year is simulated in a mathematical model (see Supplementary material S1). Day 1 in the model corresponds to the day of insemination of a sow group. The day when a batch is weaned, leaves the nursery or is sold for slaughter depends on the suckling period, the number of days in nursery and the number of days in fattening. This simulation, besides the number of sow batches inseminated since the start of the intervention, firstly indicates the number of old batches weaned, old nursery batches and old batches sold for slaughter. “Old” designates the batches produced before the intervention i.e. the related improvements become effective. Secondly, the simulation indicates the number of new batches weaned, new nursery batches and new batches sold for slaughter. “New” relates to the batches that are produced after the intervention has become effective and where the final, improved performance is reached. The dates from which these new batches occur depend on the calculated new, i.e. lower numbers of days in nursery and fattening. The switch from old to new batches is assumed to take place gradually: the first new batch weaned will some weeks later become the first new nursery batch and again some weeks later the first new batch sold for slaughter (see following description of each intervention strategy). Since in 1) D/R, some batches are sold prematurely and thus underweight, the number of “unfinished” nursery and fattening batches sold is simulated as well. Furthermore, since this measure requires a temporary complete cessation of production, the number of batches missed in the transition period is calculated as the difference to the number of batches that would have been produced in the same time if no intervention had taken place.

With the so-derived number of batches, the new costs, costs saved, extra revenue and revenue foregone are first calculated separately i) for the old, unfinished or missed batches and ii) for the new batches. For the new batches, this is simply the net value as derived from batch-wise partial budgets of the final status. For the old, unfinished or missed batches, the costs and revenue are described for each intervention strategy in the next section. The total net value of partial budget analysis (*NVPBA*) of the transition period, i.e. the first (and second) year, is then as follows (Eq. (2)):

$$NVPBA_{transition} = NVPBA_{old/unfinished/missedbatches} + NVPBA_{batchinfinalstatus} *No.\ ofnewbatches_{transition} \tag{2}$$

The outcomes of the batch simulation model and cost calculations for each intervention are explained in the following section, the equations used in the cost calculations can be found in the Supplementary material (S1).

2.6.2.1. Depopulation/repopulation (D/R). The start of the intervention (day 1) is when the first sow batch that would be due for breeding on that day will not be inseminated (see three-weekly batch simulation in Supplementary material S2). In our example herd, the farmer weans the last batch of piglets on day 134 and depopulates the herd. This means that from the start of the intervention until this day, 20 old batches have been weaned, gone into nursery and have been sold for slaughter. Taking scenario 2 with on average 50 nursery days and 127 fattening days before the intervention as an example, there will be seven age groups (= batches) of nursery pigs and 18 age groups (= batches) of fattening pigs present at the farm on the day of depopulation. These will have to be sold unfinished. Roughly 8 weeks later (day 190), the first new gilts are bred, and thus the first new batch of piglets will be weaned around day 326. With the now shorter nursery period (45 days) they enter the nursery at around day 371 and are sold for slaughter after 119 days around day 490 in this example. This means that during the transition period of two years, in the given example, according to S2, there will be a total of 57 new batches weaned (and 25 missed to produce), 51 new nursery batches (24 missed to produce) and 34 new batches sold for slaughter (33 missed to produce).

Extra costs associated with the transition phase include **transport costs** of all sows to slaughter, the **complete re-stocking of the herd** with PRRSV-negative gilts, **cleaning and disinfection** and **extra labour** costs (prices used in Table 2, further details on calculations of extra costs in Supplementary material S1).

Extra revenue is generated by the **slaughter of all sows** (see also S1).

Costs saved during the empty period include **costs for breeding, feed, water, veterinary, labour, disposal, transport and energy** in the breeding unit (for prices of general farm costs see Nathues et al. (2017) and S1); furthermore **feed, water, labour, energy and transport costs saved** for nursery batches and fattening batches that are sold with underweight (**unfinished batches**), based on age and weight at which they are sold, and **batches missed** to produce (see S1).

Revenue foregone for **unfinished batches** is calculated based on age and weight at which they are sold, and for **batches missed** to produce during the empty period. (see S1)

2.6.2.2. Close & roll-over (C&R). Since it was assumed that the intervention becomes effective after the six months period of herd closure, the change from old to new batches happens around day 180, which is when the first new batch is weaned (see S2). This will become the first new batch of nursery pigs 45 days later and the first new batch sold for slaughter 119 days later. In the example of scenario 2 this would result in a total of 25 old batches weaned, 32 old nursery batches, 51 old batches sold for slaughter and 27 new batches weaned, 21 new nursery batches and four new batches sold for slaughter during the first year.

Extra costs include extra **feed, water, labour, energy, treatments** etc. for the gilts needed for the period of herd closure, depending on the number of extra days spent on the farm compared with the normal age at entrance. A **higher number of gilts** have to be bought, due to a higher percentage of drop-outs of negatively selected gilts if purchased at a younger age. This means transport costs for sending these gilts to slaughter (extra percentage and average weight at which drop-outs will be sold for slaughter in Table 3). The provision of **space** for the numerous gilts arriving at the same time might require structural modifications to the facilities. Lastly, all sows will receive a MLV **vaccination** once (assumed costs in Table 4). Costs saved occur because of **lower prices for younger gilts** (applied price discount in Table 4). Extra revenue incurs for the slaughter of drop-out gilts (for details on calculations see S1).

2.6.2.3. Mass vaccination of sows (MS). The strategy is supposed to become effective approximately two to three weeks after the second vaccination, when immunity has fully developed in sows and will be transferred to new-born piglets. The first new batch will consequently be weaned at around day 72, go to fattening around day 107 and be sold to slaughter at day 239. The calculation of the number of batches is conducted in the same way as shown for strategy 1) and 2) in S2, and in our farm scenario 2, this means 43 new batches weaned, 37 new nursery batches and 19 new fattening batches sold for slaughter.

Extra costs comprise the **basic immunization** and a second vaccination of all sows (cost per dose see Table 4, calculations see S1).

2.6.2.4. Mass vaccination of sows and vaccination of piglets (MS + piglets). The strategy is supposed to become effective once all batches of nursery pigs present at the farm are vaccinated pigs, i.e. at around day 53. In scenario 2, the number of new batches weaned will be 45, new nursery batches 39 and new batches sold for slaughter 22.

Extra costs, if the herd does not vaccinate any animals, are composed of twice the **vaccination of sows** as described above and the **vaccination of suckling pigs** (price see Table 4); otherwise only the vaccination costs for piglets (calculations see S1).

2.6.2.5. Improvement of (internal) biosecurity and management (BSM). Since measures take place in all farm parts simultaneously, contrary to all previous strategies they are assumed to become effective roughly at the same point in time for all farm parts, at around 3 months, corresponding to the duration of one fattening period. This results in 40 new batches weaned, 41 new nursery batches and 41 new batches sold for slaughter in the first year in scenario 2.

Extra costs are the expenses related to **improvements in biosecurity and management** and are the same as costs in the final status (details on calculations in S1).

2.6.2.5.1. BSM in combination with the vaccination protocols (MS + BSM, MS + piglets + BSM). The change from old to new batches is as described for the vaccinations.

Extra costs comprise expenses for **BSM** as under 5) plus the costs for **vaccination** (3) and 4).

So, to sum up, for the elimination procedures, most costs incur during the transition period and only the costs for permanently increasing biosecurity incur throughout the whole period of observation after completing the intervention. In contrast, for the vaccination strategies and the strategies relying on improvement of biosecurity costs incur on a regular basis throughout the whole period of observation.

2.7. Calculation of the expected value

With the results from partial budget analyses for transition period and final status, investment appraisals are performed to calculate the net present value, which is the total benefit or loss from the intervention, for each intervention strategy over an observation period of 5 years, at an annual discount rate of 3% (Alarcon et al., 2013). This net present value is then multiplied by the probability of success and represents the expected value (EV) for each intervention strategy (Eq. (3)):

$$EV_i = \left[(NVPBA_i)_{year0} + \sum_{n=1}^{Transitionperiod} ((NVPBA_i)_n/(1-r)^n) + \sum_{n=1}^{Finalperiod} ((NVPBA_i)/(1-r)^n)) \right] {*}P_{success} \qquad (3)$$

Where:

- EV_i is the expected value of the intervention *i* and reflects the total benefit or losses of the intervention in the 5 year period investigated.
- $(NVPBA_i)_{year0}$ refers to the net value of the partial budget analysis at day 1 of the intervention *i*. It therefore indicates the sum of extra cost and benefit obtained at the start of the model; or the quantity of cash needed (or benefit obtained) on day 1 to implement the intervention.
- *n* is the year, the *transition period* lasts 1 or 2 years, the *final period*

last 3 or 4 years

- $((NVPBA_i)_n/(1-r)^n)$ refers to the net value of the partial budget analysis done in year *n* of the intervention, accounting for an annual discount rate (*r*). It indicates the value of extra costs and benefits associated to the implementation of the intervention and obtained during year *n* of the transition period.
- $P_{success}$ is the probability (%) that an intervention strategy is successful in improving the farm situation as anticipated (different from 100% only for 2) C&R).

Furthermore, in addition to the expected value, payback period, interest rate of return (IRR) and benefit-cost ratio (BCR) were estimated for each intervention. The payback period indicates the numbers of years until the costs of an intervention are covered by their benefits, based on the annual cash flow after the intervention. The IRR indicates the interest rate at which the cash flow of an intervention does not generate any benefit or losses. The BCR indicates how much benefit is obtained per one euro expended on the intervention. Lastly, the relative rank of each intervention according to the expected value is indicated for each disease/farm scenario.

2.8. Stochasticity, sensitivity analysis and model validation

To allow for variability and/or uncertainty in the model, stochasticity was included 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. To determine the impact of input parameters on the final outputs, a sensitivity analysis was conducted, based on the example of farm scenario 1: For strategy 1)–5) separately, disease parameters, general farm costs and the costs and parameters listed in Tables 3 and 4 were varied from their 1st to 99th percentile (variables with stochastic distributions) or from −10% to +10% of their current value (static variables). Subsequently, the changes in the EV's were recorded. Additionally, the impact of the assumed values for degree of improvement in disease and performance parameters on model outcomes was assessed: Here, since it was assumed that the general tendency in terms of impact on EV would be the same for all intervention strategies, strategy 4) MS + piglets was chosen as representative example. Improvement parameters were again varied from their 1st to 99th percentile and changes in EV recorded (presented as tornado graph, Supplementary material S3). The model and its results were validated via extensive review by three experts with vast PRRSV control and elimination field experience.

3. Results

The results of partial budget analyses of the transition phase for the seven different intervention strategies and five different farm and disease scenarios are shown in

Table 5 The same table also indicates the annual gross margin to be expected for each strategy after its completion. The net value (NVPBA) during the transition phase was negative for D/R in all five scenarios. For all other intervention strategies, net values during transition were positive. The estimated gross margins, denoted by revenue minus variable costs, were highest for the elimination strategies, regardless of the scenario. The median expected values (EV) over five years for the different scenarios and each strategy are presented in Figs. 1–5 and Table 6, the latter also indicating payback period, IRR, BCR and rank.

In scenario 1, a farrow-to-finish herd slightly affected in all farm parts, MS+ piglets exhibited the highest EV: the median was € 721′745, and in 90% of the simulations, the result was between € 604′121 and € 847′150 (5%ile and 95%ile). The lowest, i.e. a negative EV, had D/R (Fig. 1). This was further shown by the entirely negative cash flow over all five years for D/R, whereas the vaccination strategies and BSM yielded positive cash flows from the first year onwards (Fig. 6). If the same farrow-to-finish herd was moderately affected in all farm parts, like in scenario 2, EVs were generally higher and 2) C&R became the intervention strategy with the highest EV, followed by 4) sow and piglet vaccination (Fig. 2, Table 6). If (scenario 3) the farrow-to-finish herd already did sow mass vaccination but was moderately affected in nursery and fattening, the EV's were overall lower than in the previous examples. The highest EV yielded C&R, followed by MS + piglets, whereas the strategy with the lowest median EV, D/R, yielded almost no positive cash-flow, the 90% including interval covering negative values (Fig. 4, Table 6). In the case of a herd that does not have fattening pigs like the breeding herd in scenario 4, which is moderately affected in breeding only, MS yielded the highest median EV. The next highest value was estimated for BSM, whereas elimination strategies had the lowest EV's (Fig. 4 and Table 6). If the breeding herd was already vaccinating sows but was still slightly affected in breeding and nursery almost equally high EV's were estimated for MS + piglets and BSM (Fig. 5, Table 6).

In all scenarios, the 90% prediction intervals were generally larger for elimination strategies than for the other strategies. The BCR's were in most cases higher in the breeding than in the farrow-to-finish herd scenarios and highest for vaccination strategies. Combinations of BSM and vaccination usually obtained lower median EV's than vaccinations or BSM alone. The cost variables that caused the largest variation in EV, if varied themselves, were the additional biosecurity costs for the elimination strategies, and the received price per kg live weight of a slaughter pig for the other strategies, the latter being the second most important also for eliminations. In addition, feed costs had an important impact in most strategies (supplementary material S3). In terms of improvement in disease and performance parameters, (1) the assumed reduction in weaners' mortality, (2) the assumed increase in the number of piglets born alive per sow per litter, and the assumed decrease in fatteners' mortality had the largest impact on EV's at their current ranges. This can be seen in the sensitivity tornado in S3 for MS + piglets (the broader the bar, the larger the impact of each variable).

4. Discussion

The study aimed to evaluate the economic efficiency of seven common PRRSV intervention strategies for five different farm and disease situations over a period of five years, using an economic simulation model. The two most commonly applied elimination strategies, D/R and C&R were considered. The costly test & removal strategy is rarely applied for PRRSV control and was therefore not considered in this manuscript. Furthermore, although various different vaccination protocols are in use, herein we focused on protocols based on 3-monthly mass vaccination of sows. Costs for other schemes ("6/60": vaccination of each sow six days after every farrowing and at day 60 of every gestation; included in the calculation tool) did not differ substantially.

Simulation models have been successfully used to address various aspects of PRRSV infection and epidemiology: A stochastic transmission model developed by Rovira et al. (2007) simulated the time to detection of a PRRSV outbreak in a boar stud with different monitoring protocols. Other within-herd transmission models examined the patterns of on-farm persistence and fade-out (Evans et al., 2010) or control strategies against PRRSV (Jeong et al., 2014). Farm-level models were built to model contact structures and between-herd transmission (Amirpour Haredasht et al., 2017; Lee et al., 2017; Thakur et al., 2015a,b), as well as ways to prevent airborne transmission (Dee et al., 2010), or to evaluate different regional surveillance strategies (Arruda et al., 2017). There are even mathematical models simulating the interactions between PPRSV and immunological structures and processes within a pig's body (Go et al., 2014). However, to the author's knowledge, the model presented herein is the first simulation tool to assess the

Table 5
Median partial budgets of the transition period (first year after start of the intervention, for D/R also second year) and median annual gross margins of the final status (from second (D/R third) year after start of the intervention) for seven different intervention strategies and five different farm and disease scenarios (negative values in italic).

Scenario					
Intervention	1	2	3	4	5
Partial budget transition (median)					
1. D/R 1st year	*€ −195.673,02*	*€ −128.264,96*	*€ −186.349,00*	*€ −122.061,06*	*€ −152.072,80*
1. D/R 2nd year	*€ −285.536,62*	*€ −144.712,51*	*€ −246.544,35*	€ 91.678,88	€ 68.714,07
2. C&R	€ 39.023,88	€ 34.752,61	€ 30.548,92	€ 68.594,13	€ 61.381,87
3. MS	€ 131.193,88	€ 117.472,94	not applicable	€ 126.951,57	not applicable
4. MS + piglets	€ 141.940,45	€ 137.274,08	€ 96.428,28	€ 112.003,61	€ 96.493,15
5. BSM	€ 196.846,43	€ 213.324,50	€ 123.186,59	€ 117.575,42	€ 96.930,88
6. MS + BSM	€ 77.313,26	€ 73.123,67	€ 0,00	€ 104.531,21	€ 0,00
7. MS + piglets + BSM	€ 74.051,79	€ 83.321,29	€ 35.467,83	€ 89.650,16	€ 73.247,87
Gross margin final status (median)					
1. D/R; 2. C&R	€ 734.831,46	€ 750.780,41	€ 727.880,50	€ 339.601,03	€ 364.117,07
3. MS	€ 657.097,76	€ 556.110,07	not applicable	€ 326.833,82	not applicable
4. MS + piglets	€ 670.706,80	€ 577.425,04	€ 567.205,72	€ 304.152,59	€ 324.575,36
5. BSM	€ 692.549,61	€ 597.380,71	€ 584.701,86	€ 329.854,59	€ 343.431,32
6. MS + BSM	€ 694.544,47	€ 619.936,38	not applicable	€ 333.942,33	not applicable
7. MS + piglets + BSM	€ 686.671,48	€ 625.879,75	€ 604.490,18	€ 311.011,47	€ 331.767,83

economic efficiency of intervention strategies in an endemically PRRSV-infected herd.

The expected values, indicating the extra amount of money generated by the different intervention strategies, varied considerably between, and also within the different disease and farm scenarios. They were generally higher in more severely affected scenarios than in less severely affected scenarios. In the presented scenarios and with the prices used, vaccination strategies were more profitable if the farm was only slightly affected, whereas elimination strategies became more beneficial if the farm was more severely affected. The reason is that elimination strategies were more costly than other strategies, so that financial efforts were outweighed only if the expected improvement in performance was high enough, as could be expected for more severely affected farms. Among the elimination strategies, C&R always had the highest EV, whereas D/R in some scenarios did not yield any significant benefit within five years. The reason for this finding is that D/R, albeit being the most effective measure, is at the same time the most costly strategy of all, as could be concluded from the negative partial budgets during transition, the long payback periods and negative cash flow. Nevertheless, these calculations apply for the “traditional” D/R scheme considered herein, where unbred gilts are purchased, leading to a long time period without production. Modified schemes with external raising and mating of replacement gilts could shorten the time period without production and associated costs. This would make the strategy D/R more attractive from an economical perspective, and such a modified scheme could be considered in the continued development of the model/tool. In contrast, C&R is a relatively cheap strategy. This is in line with calculations for US breeding herds, in which the payback period for C&R was often between half a year and one year, whereas for D/R it ranged from 1.5 to more than five years (Holtkamp et al., 2012). This makes C&R an interesting option, provided that it is successful and feasible from a practical point of view. In most reports of successful elimination via C&R, it was applied to breeding herds or herds with segregated off-site production with no growing pigs present (Desrosiers and Boutin, 2002; Linhares et al., 2014). It might be less easily attainable in farrow-to-finish farms, although examples of successful elimination exist (Štukelj et al., 2015). Furthermore, before considering this strategy, it needs to be checked whether the space capacity on the farm allows for such a strategy.

When interpreting results it should be considered that EV’s reflect the farm’s benefits, provided that the farm conditions remain the same for the whole observation period. This is not only confined to general farm settings like prices; and especially feed prices and slaughter prices, which had a very high impact on the outcome, have been subject to strong fluctuation in the past (Rocadembosch et al., 2016). It also relates to the PRRSV status of the herd, implying that after elimination strategies a herd remains PRRSV-negative. This is a strong assumption, especially in pig dense areas like The Netherlands or north-western Germany, where the risk of re-infection is considered high (Fahrion et al., 2014). This problem of densely pig-populated areas was

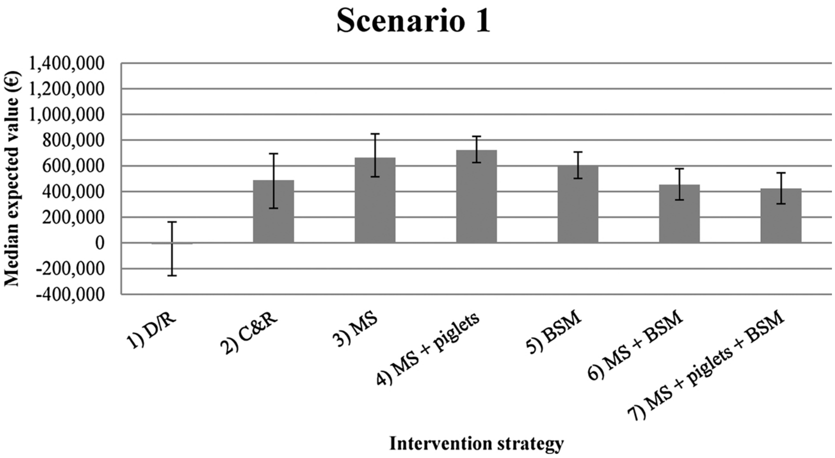

Fig. 1. Median expected value per intervention scenario for scenario 1, farrow-to-finish herd, no previous vaccination, slightly affected in all farm parts, no virus detected.

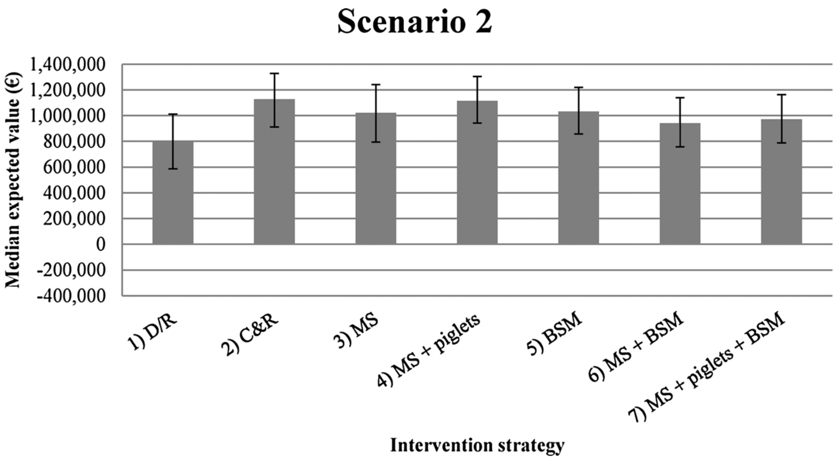

Fig. 2. Median expected value per intervention scenario for scenario 2, farrow-to-finish herd, no previous vaccination, moderately affected in all farm parts, virus detected.

confirmed by a US-study, in which 40% of 33 observed breeding herds became PRRSV-positive within the first year after being established PRRSV-free (Holtkamp et al., 2010). In this model, however, we decided not to consider this risk of re-infection, since it would have further inflated the complexity of the model. Furthermore, it would have required substantiated estimates of the annual probability of re-introduction, which is as such very much dependent on various herd individual but also regional factors. Thus, to make the model useable for all different farms and regions, we would have had to use an extremely broad-ranged probability distribution, rendering the resulting estimate almost uninformative. Another observation from the calculated scenarios is that prediction intervals for elimination strategies were usually larger than for the others, indicating a higher degree of uncertainty in the estimation. In scenario 2, although C&R had a higher median EV, the 5%ile was higher for MS + piglets or BSM.

Summarizing the above, the most appropriate intervention for a farm depends on the farmer's willingness to invest into PRRSV control and the return on investment and level of risk which is acceptable to his/him: elimination strategies should only be considered for farms with a sufficiently comfortable financial background, which can bear higher degrees of uncertainty and the relatively high costs at the beginning of the intervention. Otherwise, vaccination strategies are a more predictable alternative in their long-term benefits. Certainly, their effect on disease and performance depends on many factors, to mention only the PRRSV strain circulating in the farm, type of vaccine or presence of co-infections. These specific influences could not be accounted for, because this would have made the model too complex, or no data were available. However, this variation was covered by including stochasticity in the model, to account for uncertainty or variability. One of the advantages of vaccinations is that they do not require huge expenses at the beginning of the intervention, because costs incur on a regular basis. Moreover, the risk of re-infection does not play such an important role, or more explicitly, vaccinations are especially economic in cases of frequent re-infection with field virus (Linhares et al., 2015).

In most scenarios, combined vaccination of sows and piglets held advantage over sow vaccination alone. Even if sows had already been vaccinated, additional piglet vaccination yielded an additional financial benefit. Only in one scenario where just the breeding part was affected, sow vaccination alone was more beneficial compared to sow and piglet vaccination. This seems reasonable, as in a herd with PRRSV problems only in sows, targeting these sows directly is likely to lead to the most prominent improvement. The strategy of BSM yielded EV's that were often similar to those of vaccinations, but was never ranked top. One reason for this was certainly that we assumed quite high costs for this strategy in the presented scenarios, so that the expected improvement did not outweigh these costs. The results might be different with lower assumed costs (as underpinned by sensitivity analysis where they had an important impact on the outcome). For the same reason, combined strategies of BSM and vaccinations did not yield a high EV either. It can be argued that the way how BSM was modelled was fairly crude, because no distinction between individual measures was made. Here again, the reason was that it would have caused an excess in complexity of the model; and since information found on the expected improvement in disease and performance of individual measures was scarce, it

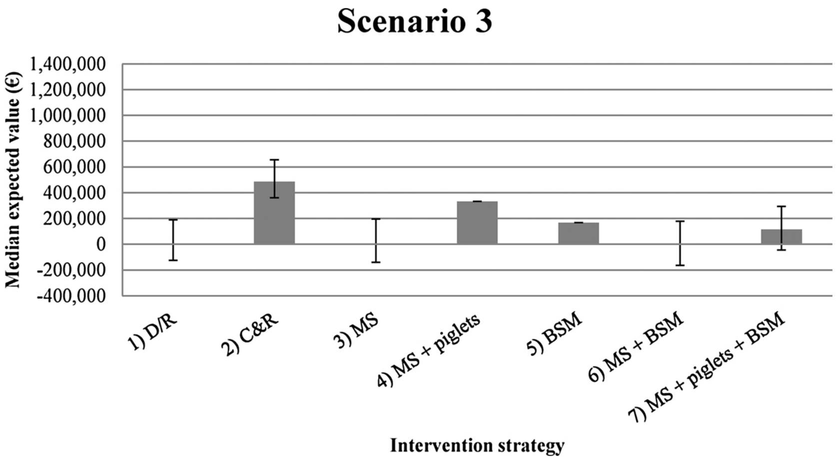

Fig. 3. Median expected value per intervention scenario for scenario 3, farrow-to-finish herd, previously sow mass vaccination every three months, moderately affected in nursery and fattening, virus detected.

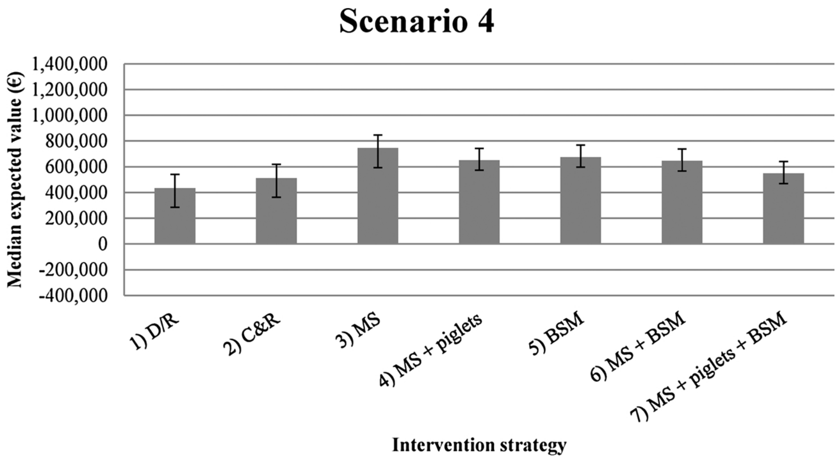

Fig. 4. Median expected value per intervention scenario for scenario 4, breeding herd, no previous vaccination, moderately affected in breeding part, virus detected.

would not have contributed to the accuracy of the model's estimates. Nevertheless, a good biosecurity is an important part in the control of PRRS as well as other infectious diseases.

In general, it must be pondered that the described results are valid for the indicated farm structures, prices etc. In other countries with different structures, outcomes might differ completely. Especially prices show a strong variation between countries, some like labour costs even between individual farms. In particular, prices for feed, pigs and labour had a high impact on the profitability of the strategies according to sensitivity analysis. This seems reasonable as these costs generally contribute the most to the farm budget (Linhares et al., 2015; Rocadembosch et al., 2016). Also, the presented scenarios are only a small and arbitrary selection of all possible constellations of farm type, farm parts affected or disease severity, and it was impractical to cover the whole range of possible scenarios, which might have yielded other results. Regarding herd stability, we could not stick to the strict interpretation of Holtkamp categorization. This is for practical reasons, because we assume that users, at the time of using the model, have in many cases not made sufficient diagnostics to substantiate a stable herd status. Thus, the fact that no virus has been detected in a herd is not a proof of its stability, but can only serve as a hint that PRRSV circulation in this herd was at somewhat lower levels. This does not preclude a slight clinical impact of the virus. Moreover, the model was specifically designed for PRRS, as changes in productivity and health parameters are used to model the impact of and losses due to PRRS. This implies that the obtained results are only informative if PRRSV is the (main) cause of disease in the farm, which should be confirmed *a priori* by laboratory diagnosis. Likewise, co-infections are not specifically accounted for in the model, because this again would unnecessarily inflate its complexity, but the potential need for their control should be given consideration in the weighing of interventions. An advantage of D/R is that other infectious agents present in the herd can be eliminated at the same time, and many BSM measures have a positive effect not only on PRRSV but also many other infectious diseases. Besides, due to the interaction of PRRSV with various pathogens (Zimmerman et al., 2012), its control as such can have a beneficial effect on the clinical presentation of other diseases.

A general limitation of all models is that in the face of insufficient data on model parameters, several assumptions have to be made. Since only little information could be found especially on the effect of vaccination or biosecurity measures on several disease and performance parameters, estimates from an expert poll were used. While so-derived data usually obtain a satisfactory reliability (Dorussen et al., 2005), the limited number of experts might be associated with some uncertainty. The use of stochasticity somewhat resolves this uncertainty. Besides input parameters, also the structure of the model itself is based on assumptions. For instance, the modelling of the transition phase (in particular the abrupt change from "old" to "new" status) is a strong simplification, as in real life improvement would happen more gradually. However, since the period of observation is long, this inaccuracy in the first months is deemed to be of minor relevance for the overall outcome. Nevertheless, to gain more certainty about input parameters and model outcomes, the model shall be validated in a field study.

If these issues are considered, the model can serve as a valuable tool

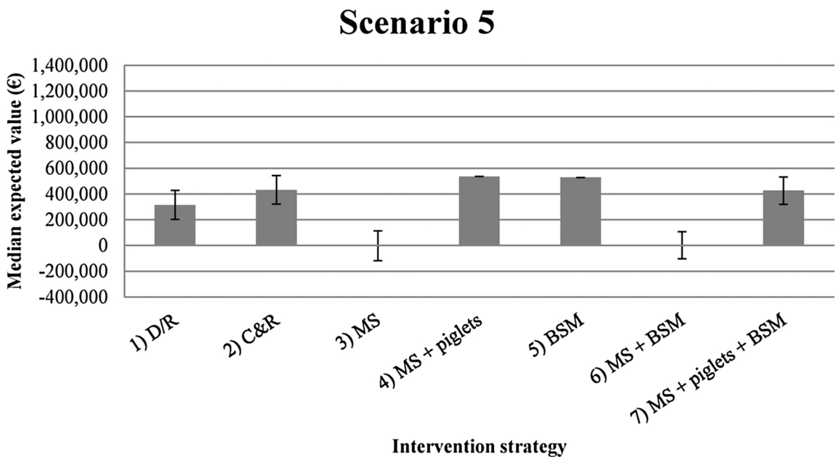

Fig. 5. Median expected value per intervention scenario for scenario 5, breeding herd, previously sow mass vaccination every three months, slightly affected in breeding and nursery, no virus detected.

Table 6
Summary of economic outputs for each intervention strategy and all scenarios, including the expected value (EV), the payback period, the interest rate of return (IRR), the benefit-cost ratio (BCR) and each strategy‘s rank based on its median EV (negative values in italic).

Scenario					
Intervention	1	2	4	4	5
1) D/R					
EV median	*€ −8′603*	€ 800′003	€ 6′829	€ 434′396	€ 313′165
EV 5%ile	*€ −254′799*	€ 570′383	*€ −233′750*	€ 322′052	€ 191′874
EV 95%ile	€ 164′673	€ 966′150	€ 164′527	€ 533′710	€ 419′506
Payback period	> 5years	3 years	5years	3 years	3 years
Median IRR	n.c.[a]	0.840	0.006	1.022	0.632
Median BCR	0.998	1.149	1.001	1.327	1.246
Rank	7	7	5	6	5
2) C&R					
EV median	€ 489′004	€ 1′126′807	€ 485′214	€ 511′951	€ 431′505
EV 5%ile	€ 270′389	€ 785′252	€ 266′604	€ 352′659	€ 289′776
EV 95%ile	€ 694′185	€ 1′396′677	€ 685′379	€ 652′384	€ 569′592
Payback period	< 1year	< 1year	< 1year	< 1year	< 1year
Median IRR	n.c.[a]	n.c.[a]	n.c.[a]	n.c.[a]	n.c.[a]
Median BCR	1.654	1.677	1.746	3.169	3.858
Rank	4	1	1	7	3
3) MS					
EV median	€ 664′111	€ 1′021′527	strategy not applicable	€ 746′463	strategy not applicable
EV 5%ile	€ 568′114	€ 832′760		€ 592′551	
EV 95%ile	€ 771′887	€ 1′212′381		€ 849′454	
Payback period	< 1year	< 1year		< 1year	
Median IRR	66.57	60.62		64.67	
Median BCR	1.876	1.668		4.864	
Rank	2	4		1	
4) MS + piglets					
EV median	€ 721′745	€ 1′114′649	€ 332′296	€ 650′271	€ 535′244
EV 5%ile	€ 604′121	€ 901′690	€ 200′459	€ 500′656	€ 425′314
EV 95%ile	€ 847′150	€ 1′326′905	€ 515′102	€ 756′133	€ 649′562
Payback period	< 1year	< 1year	< 1year	< 1year	< 1year
Median IRR	72.01	70.483	n.c.[a]	57.256	n.c.[a]
Median BCR	1.886	1.700	1.999	3.637	5.258
Rank	1	2	2	3	1
5) BSM					
EV median	€ 602′060	€ 1′032′336	€ 167′253	€ 674′879	€ 528′463
EV 5%ile	€ 465′349	€ 806′016	€ 27′430	€ 520′580	€ 410′700
EV 95%ile	€ 733′198	€ 1′252′563	€ 362′625	€ 775′536	€ 643′155
Payback period	< 1year	< 1year	< 1year	< 1year	< 1year
Median IRR	n.c.[a]	n.c.[a]	n.c.[a]	n.c.[a]	n.c.[a]
Median BCR	1.539	1.532	1.321	3.297	3.857
Rank	3	3	3	2	2
6) MS + BSM					
EV median	€ 453′116	€ 940′482	strategy not applicable	€ 645′134	strategy not applicable
EV 5%ile	€ 342′926	€ 767′134		€ 567′265	
EV 95%ile	€ 565′710	€ 1′130′422		€ 736′972	
Payback period	< 1year	< 1year		< 1year	
Median IRR	39.82	39.34		53.53	
Median BCR	1.390	1.452		2.877	
Rank	5	6		4	
7) MS + piglets + BSM					
EV median	€ 422′274	€ 970′174	€ 114′796	€ 547′718	€ 426′632
EV 5%ile	€ 309′028	€ 788′003	*€ −49′023*	€ 469′754	€ 322′368
EV 95%ile	€ 534′698	€ 1′169′939	€ 293′501	€ 640′047	€ 534′310
Payback period	< 1year	< 1year	< 1year	< 1year	< 1year
Median IRR	38.20	44.202	n.c.[a]	46.060	n.c.[a]
Median BCR	1.341	1.443	1.134	2.380	2.604
Rank	6	5	4	5	4

[a] n.c. = IRR is not always possible to calculate (e.g. if there are only benefits and no costs or vice versa).

in the decision-making process of farmers and veterinarians on the most suitable intervention strategy. Although many strategies are effective against PRRS, not all of them have been proven to be equally economically efficient in all cases, and until to date the long-term benefits of a strategy in a given farm situation were speculative. As Fraile (2012) reminded emphatically, a cost-benefit-analysis should be an integral part before implementing any control or eradication measure for livestock diseases. The present model gives quantitative estimates to project the long-term benefits of a strategy for a specific farm setting and thus enables a better informed decision. Although the model has been designed for PRRSV, due to its modular structure it can be adapted with little effort for the evaluation of other diseases.

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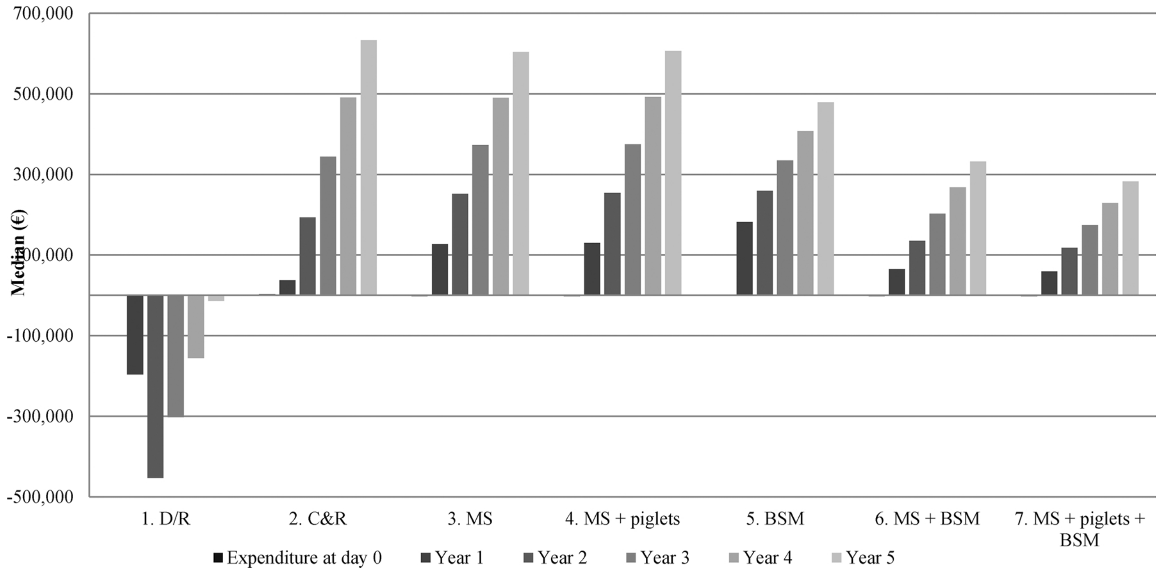

Fig. 6. Median cash flow for each intervention strategy: at day 0 of the intervention and in every year of the five-year observation period, indicated for the example of scenario 1000.

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Conflicts of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.prevetmed.2018.02.005.

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