Animal 20 (2026) 101786

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

An integrated individual-based model of transmission, clinical outcomes, and economic impact of *Mycoplasma hyopneumoniae* infection in a commercial pig fattening unit

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ARTICLE INFO

Article history:
Received 15 December 2025
Revised 12 February 2026
Accepted 12 February 2026
Available online 18 February 2026

Keywords:
Bio-economic modelling
Clinical signs
Enzootic pneumonia
Production performance
Swine

ABSTRACT

Mycoplasma (***M.***) *hyopneumoniae* remains a major economic and health challenge for pig production worldwide, causing lung lesions and coughing that reduce production performance and farm profitability. However, the interplay between transmission, clinical outcomes, and economic consequences has not yet been fully characterised. To address this gap, a stochastic, individual-based bio-economic simulation model was developed using the EMULSION modelling framework. The model integrates infection dynamics, the development of lung lesions and coughing, and their subsequent effects on production performance and economic outcomes. Pigs were grouped within pens to represent within- and between-pen transmission. Production losses and additional labour requirements were translated into economic outcomes using a partial-budgeting approach. Model parameters were derived from scientific literature, representative industry reports and expert elicitation. Sensitivity analyses explored alternative distributions or values for key epidemiological parameters and assessed the effect of ± 20% variation in all input variables on biological and economic outputs. Simulations indicated that infection spread rapidly, reaching all pigs within 4–8 weeks, with peak prevalence approximately four weeks after fattening unit entry. Lung lesions followed a similar pattern, persisting at high prevalence for around two months, and a median of 14% of pigs still had unresolved lesions at slaughter. Coughing lagged about one week behind the rise in infection prevalence, reflecting the delay between infection and clinical signs. Median economic losses were €6 per pig, with reduced feed efficiency accounting for 73% of total losses. Sensitivity analyses identified between-pen transmission and initial prevalence as the most influential drivers of infection progression and profitability. The findings highlight key knowledge gaps, including the prevalence, infectiousness, and production impact of subclinical infections, as well as the need for longitudinal field data on lesion progression and between-pen transmission, to refine model assumptions and better align simulations with observations in practice. The modelling framework presented here provides a novel, integrated understanding of the biological and economic consequences of *M. hyopneumoniae* infection and a foundation for evaluating future control strategies.

Implications

Mycoplasma hyopneumoniae remains one of the most economically important respiratory pathogens in pig production, yet its impacts are difficult to quantify due to variability in transmission, clinical manifestation and production losses across batches. The

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https://doi.org/10.1016/j.animal.2026.101786
1751-7311/

model developed in this study integrates these processes within a fattening compartment and shows that infection can cause substantial economic losses, primarily through reduced feed efficiency. Between-pen transmission emerged as a key driver of both disease spread and profitability. These findings can help farmers and veterinarians to better understand the mechanisms underlying economic losses and prioritise control strategies that improve herd health and productivity.

Introduction

*Mycoplasma (**M.**) hyopneumoniae*, the etiologic agent of enzootic pneumonia, remains a major economic and health challenge for swine production globally. Despite residual maternal immunity or vaccine-derived protection (Biebaut et al., 2023), piglets from positive farms arrive at fattening facilities with variable colonisation prevalence (Vangroenweghe et al., 2015). During the production cycle, transmission of *M. hyopneumoniae* can occur via direct nasal contact or airborne spread (Fano et al., 2005), while transmission through fomites appears minimal (Batista et al., 2004).

Upon infection, *M. hyopneumoniae* can cause a range of clinical manifestations. While some pigs develop severe respiratory signs, often exacerbated by coinfection with other respiratory pathogens or even with other *M. hyopneumoniae* strains (Palzer et al., 2008; Michiels et al., 2017), others remain subclinically infected, silently contributing to transmission as carriers (Regula et al., 2000; Fano et al., 2005). A persistent dry, non-productive cough resulting from lung lesions is the most common clinical manifestation and may last for weeks to months (Garcia-Morante et al., 2022). Notably, lung damage may also occur without clinical signs, while still affecting production performance (Regula et al., 2000). Depending on the timing of infection, lung lesions may be resolved by the time of slaughter (Pessoa et al., 2021). These characteristics underline the variability and complexity of *M. hyopneumoniae* infections, which contributes to the incomplete understanding of its impact.

Few studies have reported on the economic losses due to *M. hyopneumoniae* infection (Boeters et al., 2023). One study (Calderon Diaz et al., 2020) explicitly reported that a positive status for *M. hyopneumoniae* resulted in a reduction in profit of €5 per fattening pig produced. Three other studies (Byrt et al., 1985; Christensen, 1995; Ferraz et al., 2020) have estimated financial losses specifically attributable to cranio-ventral lung consolidation caused by the infection, with adjusted costs (inflation-corrected and converted to euros by Boeters et al., 2023) ranging from €1.50 to €7.50 per pig. However, one needs to bear in mind that the full financial burden is not captured when only focusing on lung lesions, as it overlooks subclinical infections as well as recovered and milder cases. Therefore, integrating data on clinical manifestation and production performance is essential to obtain a more comprehensive understanding of the economic impact of *M. hyopneumoniae* infection.

Since collecting high-quality longitudinal disease and economic data is challenging, modelling and simulation approaches can offer valuable insights by integrating diverse data sources and projecting outcomes under realistic farm conditions. However, to date, only one modelling study has been conducted for *M. hyopneumoniae* infections (Nathues et al., 2016). While this study explored disease dynamics and compared prevention strategies, it did not model the development of clinical signs or evaluate the economic losses due to infection. Furthermore, its compartmental modelling approach lacked the granularity to simulate within- and between-pen disease dynamics. Such detail is essential when studying pathogens whose transmission is influenced by the physical arrangement of pens and barriers within barns (Fano et al., 2005; Cobanovic et al., 2019). Therefore, we developed an individual-based bio-economic simulation model that integrates *M. hyopneumoniae* transmission dynamics, the development of lung lesions and coughing, the effects of infection on production performance, and the resulting economic losses in commercial pig fattening units, while explicitly accounting for both within-pen and between-pen transmission pathways.

Material and methods

Model design

We developed a discrete-time (time step of one day), stochastic, individual-based model, using the epidemiological mechanistic modelling framework EMULSION (Picault et al., 2019) with the organisational multilevel agent-based system developed and described by Sicard et al. (2021); version 1.2b6. Each scenario and sensitivity analysis, as described subsequently, was run 100 times using high-performance computing resources to meet computational demands. Our model simulated the infection dynamics of *M. hyopneumoniae*, the development of lung lesions and non-productive dry coughing, and production performance for individual fattening pigs. These processes were modelled as "state machines", and an overview of all included state machines and their interconnections is provided in Fig. 1. In the model, pigs were assigned to pens within a compartment, allowing us to differentiate between within-pen and between-pen transmission. In the following sections, we describe each state machine in detail, along with the parameters used. We simulated the economic losses due to an *M. hyopneumoniae* outbreak in the absence of any preventive or control interventions (e.g. antibiotic treatment or vaccination). For each scenario, we also simulated an infection-free batch to serve as a reference to estimate the impact of an *M. hyopneumoniae* outbreak.

Simulated farm

The simulated unit represented a compartment of a commercial fattening farm dedicated exclusively to rearing pigs for slaughter. One hundred and eighty pigs entered the facility with an average live BW of 25 kg (SD: 2 kg) and were reared in a single compartment until reaching at least 120 kg live weight. In this context, a compartment was defined as a fully enclosed room of 144 m^2 in which all pigs shared the same airspace. The pigs were housed in 12 pens within this compartment (Fig. 2). Although such compartments are usually part of a larger multicompartment building, only a single compartment was modelled for simplicity. The farm followed an all-in/all-out management system at the compartment level. All pigs were assumed to originate from a single multiplier herd that was endemically infected with *M. hyopneumoniae*. After placement, pigs remained in the same compartment and pens throughout the fattening period. A proportion of pigs could be sent to slaughter early upon reaching market weight, but no new or younger pigs were introduced.

Infection dynamics

To model infection dynamics, we developed a state machine comprising 5 states: susceptible (**S**), exposed (**E**), acutely infected (**Ia**), chronically infected (**Ic**) and recovered from infection ($\mathbf{R_I}$). Definitions and diagnostic characteristics (clinical signs, PCR and serological status) of each state are provided in Supplementary Table S1, and all input parameters are provided in Table 1. Mortality was excluded from the model, as an *M. hyopneumoniae* infection without co-infection with other respiratory pathogens is generally considered to have a negligible impact on mortality in a herd (Sibila et al., 2009).

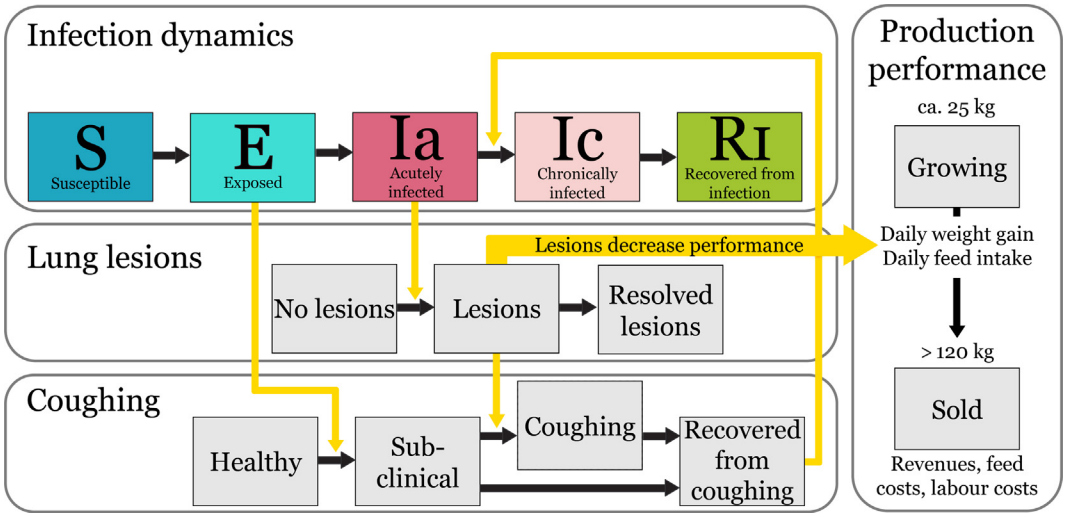

Fig. 1. Overview of the four interconnected state machines used in the model: infection dynamics, development of lung lesions and coughing, and production performance. Yellow arrows represent interdependencies: indicated transitions within a state machine are only possible if the individual pig is concurrently in the state from which the yellow arrow originates.

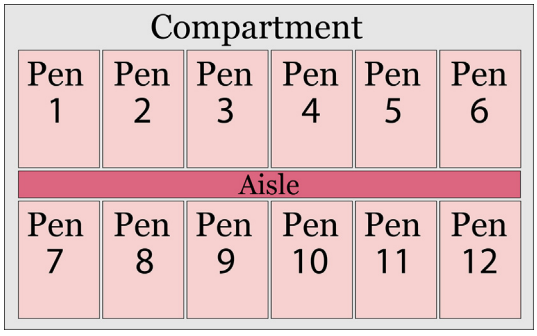

Fig. 2. Layout of the simulated compartment, representing a room where all pigs shared the same airspace. The compartment contained twelve pens arranged in two rows, separated by a central aisle.

The initial prevalence (π_0) of *M. hyopneumoniae* among piglets entering the fattening farm was parameterised based on field data reported by Vangroenweghe et al. (2015), using results from 47 *M. hyopneumoniae*-positive Dutch and Belgian farms. We assumed the infected individuals were evenly distributed among the E (p_E) and Ia states ($1 - p_E$) at the start of the simulation. The transition from state S to E was governed by the force of infection (λ), which represents the rate at which susceptible individuals become effectively exposed to *M. hyopneumoniae*. The force of infection depends on the transmission rate (β; defined as the average number of effective contacts per infected individual per day leading to new exposures) and the number of infected pigs within the same pen or in other pens in the compartment. We derived β from Betlach et al. (2020), who estimated frequency-dependent transmission rates (number of new infections per week) in a population of 30 pigs. Given that *M. hyopneumoniae* is transmitted via the respiratory route in pigs, we assumed density-dependent transmission for our model. Thus, we converted this frequency-dependent rate to a density-dependent transmission rate per day (β_{Ia}) by dividing by the time-period of 7 days and the reference population size of 30.

M. hyopneumoniae transmission rates have been primarily estimated during the acute phase of infection. To our knowledge, no studies exclusively described transmission during the chronic phase, but a lower risk of pathogen spread due to reduced shedding during this phase was hypothesised (Betlach et al., 2021). Consequently, we assumed that chronically infected pigs transmit the bacteria at half the rate of acutely infected ones, although true infectiousness during this stage remains uncertain. We also

Table 1
Parameters used in modelling infection dynamics, and the development of coughing and lung lesions in fattening pigs.

Parameter	Description	Value[1]	References
π_0	Initial prevalence (at time t = 0)	Triangular (0.23, 0.368, 0.506)	Vangroenweghe et al., 2015
p_E	Proportion of infected pigs that arrive as exposed	0.5	Expert opinion
β_{Ia}	Transmission rate per acutely infected pig per day	0.0015	Betlach et al., 2020
β_{Ic}	Transmission rate per chronically infected pig per day	0.5* β_{Ia}	Expert opinion
δ	Reduction factor for between-pen transmission	0.5	Fano et al., 2005
D_{latent}	Duration of the latent period (days)	Uniform (3,7)	Marois et al., 2007; Silva et al., 2022
$D_{chronic}$	Duration of the chronically infected state (days)	Uniform (46,186)	Sørensen et al., 1997; Pieters et al., 2009
$p_{lesions}$	Proportion of pigs developing lesions	Triangular (0.71,1, 1)	Garcia-Morante et al., 2017
$O_{lesions}$	Onset period of developing lesions (days)	Uniform (7, 14)	Garcia-Morante et al., 2017
$D_{lesions}$	Duration of lung lesions (days)	Uniform (63, 105)	Garcia-Morante et al., 2017
p_{cough}	Proportion of pigs developing cough	Triangular (0.89, 1, 1)	Lorenzo et al., 2006; Le Carrou et al., 2006; Almeida et al., 2021
O_{cough}	Onset period of coughing (days)	Triangular (6, 10, 31)	Supplementary Table S2.
D_{cough}	Duration of coughing (days)	Triangular (8, 50, 77)	Supplementary Table S2.

[1] Uniform (Min, Max), Triangular (Min, Most likely, Max).

Table 2
Parameters, costs and formulas used to model production performance in fattening pigs and to estimate economic outcomes.

Parameter	Description	Value/formula[1]	Source
EW	Entry weight (in kg) of a pig at t = 0	Normal (25, 2)	Unpublished data
DG	Daily weight gain (in kg) for an individual pig	Normal (0.923, 0.025)	Unpublished data
FCR	Feed conversion ratio	Normal (2.51, 0.13)	Unpublished data
FI	Feed intake (in kg) in a day for an individual pig	DG * FCR	–
F_{DG}	Factor to reduce daily gain in case of lesions	Uniform (0.83, 1)	Maes et al., 2023
F_{FCR}	Factor to increase feed conversion ratio in case of lesions	Uniform (1, 1.14)	Maes et al., 2023
DP	Dressing percentage	80%	Unpublished data
$Pr_{slaughter}$	Slaughter pig price per kg carcass weight	€1.98	Agrimatie, 2025
Pr_{feed}	Feed price per 100 kg	€32.67	Agrimatie, 2025
Pr_{labour}	Labour cost per hour	€27.90	Hoste and Benus, 2023
T_{pigday}	Time spent on pig care per day	0.2 min per pig	Dolman et al., 2012

[1] Uniform (Min, Max), Normal (Mean, SD).

assumed that transmission is strongest within the same pen, and weaker between pens (Fano et al., 2005; Table 2).

The force of infection (λ) was calculated accordingly:

$$\lambda = \beta_{Ia} \cdot Ia_{own\ pen} + \beta_{Ic} \cdot Ic_{own\ pen} + \delta \cdot (\beta_{Ia} \cdot Ia_{other\ pens} + \beta_{Ic} \cdot Ic_{other\ pens}) \quad (1)$$

where,

β_{Ia}: Transmission rate per Ia pig per day; β_{Ic}: Transmission rate per Ic pig per day; $Ia_{own\ pen}$ /$Ia_{other\ pens}$: Number of Ia individuals in the pig's own pen and in other pens, respectively; $Ic_{own\ pen}$ /$Ic_{other\ pens}$: Number of Ic individuals in the pig's own pen and in other pens, respectively; δ : Reduction factor applied to the contribution of infected individuals located in other pens to the force of infection.

A pig in state E transitioned to state Ia after a latent period (D_{latent}). The transition from the Ia state to the Ic state was considered to take place when coughing ended (following D_{cough}; Pieters et al., 2009). As the duration of the subclinical phase is unknown, we assumed the duration of the Ia state in subclinical pigs was the same as in pigs showing clinical signs. In the Ic state, pigs seroconverted and did not cough but continued shedding the pathogen and may still have had unresolved lung lesions. Finally, after the Ic state (following $D_{chronic}$), pigs transitioned to the final, R_I state. In this state, pigs were considered to be PCR-negative and assumed to have developed specific immunity to *M. hyopneumoniae*, preventing re-infection of those pigs.

Development of lung lesions and coughing

The lung lesions state machine comprised three states: No lesions, Lesions, and Resolved lesions. All input parameters for the lung lesions state machine can be found in Table 1. Following infection, a proportion of pigs ($p_{lesions}$) developed lung lesions over a defined onset period ($O_{lesions}$). The corresponding daily probability of developing lesions was calculated as ($p_{dailylesions}$):

$$p_{dailylesions} = 1 - (1 - p_{lesions})^{1/O_{lesions}} \quad (2)$$

For pigs that were already in the Ia state at the start of the simulation, we assumed that the same proportion ($p_{lesions}$) had lesions at simulation onset. Once a pig had developed lung lesions, it entered the Lesions state, where it remained for the duration of lesions ($D_{lesions}$). During this state, the pig could develop clinical signs, as will be described below. After the duration of lesions, pigs transitioned to the final Resolved lesions state.

The coughing state machine consisted of four states: Healthy (non-exposed), Subclinical, Coughing and Recovered from coughing. A summary of relevant literature on the development of coughing in pigs is provided in Supplementary Table S2, and all final input parameters used in the coughing state machine are provided in Table 1. Pigs remained in the Healthy state for as long as they were susceptible. Upon exposure to *M. hyopneumoniae*, they transitioned to the Subclinical state. Under natural conditions, a proportion of infected pigs may remain subclinical, but this proportion is not well characterised in the literature. Therefore, we estimated it indirectly using data from inoculation studies that reported the proportion of pigs coughing. The complement of this proportion (i.e., pigs that did not cough) was used to approximate the subclinical fraction in our model. To reflect that coughing primarily occurs during the early phase of infection, we again introduced an onset period for coughing (O_{cough}). Pigs could only transition from the Subclinical to the Coughing state during this period and remained Subclinical otherwise. The daily probability of developing a cough ($p_{dailycough}$) was calculated by:

$$p_{dailycough} = 1 - (1 - p_{cough})^{\frac{1}{O_{cough}}} \quad (3)$$

Once a pig began coughing, it entered the Coughing state, where it remained for the duration of coughing (D_{cough}). As the duration of the Subclinical state is unknown, we assumed it to be equal to the duration of the Coughing state. After this period, pigs in either the Coughing or Subclinical state shifted to the Recovered from coughing state, where they stayed for the remainder of the production cycle. In addition, this shift from Coughing or Subclinical to Recovered from coughing defined the point at which pigs transitioned from the Ia to Ic state within the infection dynamics state machine.

Production performance

The final state machine in the model described production performance and included two states: Growing and Sold. Once all pigs were randomly assigned to pens within the compartment, they entered the Growing state, which spanned the entire fattening phase. Pigs remained in this state until they were ultimately sent to slaughter, at which point they transitioned to the Sold state. All parameter values related to production performance are provided in Table 2.

Throughout the Growing state, the model tracked the weight and cumulative feed intake for each individual pig. At time step 0, the weight was initialised based on the entry weight, and cumulative feed intake was set to zero. At each subsequent time step, both values were incremented by the daily weight gain and feed intake, which could be negatively impacted by the presence of lung lesions. Lesions triggered adjustment factors for reduced daily growth (F_{DG}) and increased feed conversion ratio (F_{FCR}). Due to the absence of detailed data on growth curves and the specific effects of *M. hyopneumoniae* infection on growth at different ages, we assumed stochastic weight progression based on the average and SD of daily gain for pigs weighing between 25 and 125 kg. This assumption reflects the approximately linear growth trajectory

typically observed in pigs during this production phase (Zumbach et al., 2010; Revilla et al., 2022).

In the Netherlands, it is common practice to send a subset of pigs to slaughter one or two weeks before the rest of the batch once they have reached their target slaughter weight. These pigs are then transported together with pigs from other compartments. In our model, we defined three potential selling moments: at 105, 112 and 119 days after placement in the fattening unit. At 105 days, the model identified whether at least 10% of pigs were at a weight exceeding 120 kg. If so, these pigs were sold as early sellers. The remaining pigs were retained until day 112. At that point, all pigs that had reached the target weight (120 kg) were sold. If selling at this point would have left less than 10% of the original batch behind, all pigs were sold regardless of weight. Any remaining pigs were retained for at least one week more until all had reached the target weight, after which the final sale took place, involving the late sellers (day 119). The age at which pigs were sold was recorded, and the average time per pig from entry to slaughter was calculated. At the end of the production cycle, each pig's cumulative feed intake and live weight were recorded. These data were aggregated to calculate the total feed intake and the total live weight at slaughter. The live weight was then converted to carcass weight using a dressing percentage of 80%. To evaluate batch homogeneity, the SD of individual live weights within the batch was calculated.

Economic losses

Economic losses were estimated under average market conditions in the Netherlands from 2022 to 2024 (Table 2). We used a partial budgeting approach to quantify the net financial impact of an *M. hyopneumoniae* outbreak. Partial budgeting is well-suited for this type of analysis because it focuses specifically on the marginal changes in costs and revenues that result from a defined change in herd health status, without requiring a full enterprise budget. This allowed the direct comparison of outbreak and infection-free scenarios while isolating only those economic outcomes affected by the infection. This method accounts for four possible components: (i) additional revenues, (ii) reduced costs, (iii) reduced revenues, and (iv) additional costs.

For this analysis, we made the following assumptions:

- Change in revenues resulted solely from a change in the total slaughter weight;
- Additional costs stemmed from increased feed and labour costs. As no treatment was simulated, no additional veterinary costs were incurred.
- Outbreaks did not directly increase labour requirements. Instead, the increased labour costs resulted from the additional time required to care for pigs that remain on the farm longer due to the outbreak.

Under these assumptions, the economic losses due to an outbreak, relative to an infection-free scenario, were calculated as a change in margin over feed and labour costs:

$$\text{Economic losses} = -\Delta Revenues + \Delta Feed\ costs + \Delta Labour\ costs \quad (4)$$

where Δ represents the difference between the outbreak scenario and the respective infection-free scenario.

Sensitivity analysis

We conducted a series of sensitivity analyses to evaluate how robust the model outcomes were to uncertainty in both key epidemiological parameters and general input values. These analyses consisted of two components. First, we examined alternative distributions or values for key epidemiological parameters to assess how different assumptions regarding infection dynamics influence model behaviour. Second, we performed one-at-a-time sensitivity analyses in which all input parameters were varied by ± 20%, allowing us to quantify the impact of moderate parameter changes on both biological and economic outputs.

Adaptation of key epidemiological parameters

To account for variation in piglet-level infection prevalence across *M. hyopneumoniae*-positive farms, as reported by Vangroenweghe et al. (2015), we simulated low (1–10%) and high (50–70%) initial prevalence at arrival. This enabled us to evaluate how starting infection levels influenced subsequent disease dynamics and outcomes. We further explored uncertainty in several key assumptions related to infection dynamics. We varied the distribution of infected pigs at arrival—E versus Ia—by reducing the default proportion of pigs starting in the E state from 50 to 25 and 0%, thereby assessing how different initial infection states affect early transmission dynamics. To examine the potential contribution of Ic individuals, we tested alternative assumptions in which their infectiousness was reduced by half, made equal to that of Ia pigs, or removed entirely. Finally, the role of between-pen spread was evaluated by halving the between-pen transmission rate, setting it equal to the within-pen transmission rate, or assuming no between-pen transmission.

One-at-a-time sensitivity analyses on all input parameters

In addition to the epidemiological scenarios above, all other model input parameters were subjected to one-at-a-time sensitivity analyses. Each input parameter—whether a point estimate or sampled from a distribution—was systematically varied by ± 20%, with probabilities constrained to the range 0–1, while all other parameters were held constant. For each parameter, biological and economic outputs were recalculated to assess the influence of moderate deviations from the baseline values.

Results

Infection dynamics and the development of lung lesions and coughing

Fig. 3 illustrates the temporal dynamics of infection, lung lesions, and coughing in pigs, based on 100 stochastic simulations. Infection spread rapidly through the population, reaching all pigs within 4–8 weeks after entry, with the highest prevalence observed approximately four weeks post entry. The development of lung lesions followed a similar trajectory, with a high prevalence persisting for around two months before gradually declining towards slaughter. At slaughter, a median of 14% of pigs still exhibited unresolved lung lesions (Table 3). Coughing lagged approximately one week behind the rise in infection prevalence, reflecting a delay between infection and onset of clinical signs.

Production performance and economic losses

Outcomes related to production performance and economic losses are provided in Table 3 as well. Under the default scenario, the median time from entry to slaughter on the fattening farm was 114 days, one week longer than in the infection-free scenario. The SD in slaughter weights within batches was comparable between the default and infection-free simulations. However, the range of variation indicated slightly greater within-group heterogeneity under infection (range: 1.7–2.4) compared with the infection-free baseline (range: 1.6–2.0).

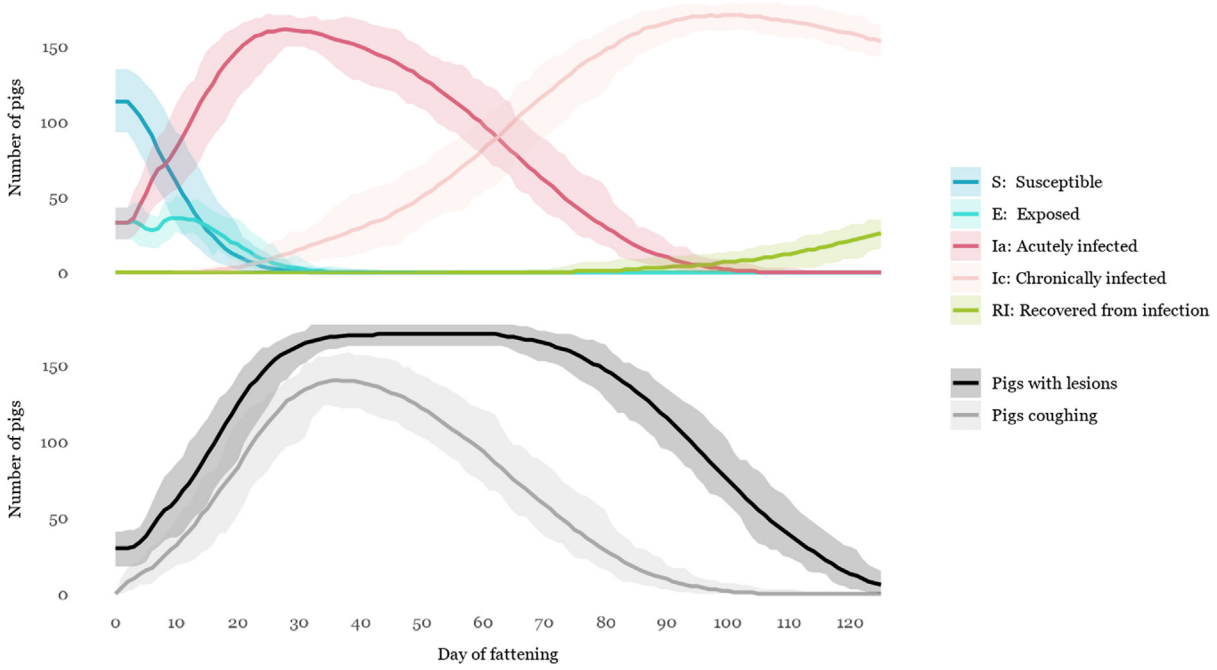

Fig. 3. Temporal evolution of pigs across infection dynamics, and lung lesion and coughing development. The figures summarise 100 repetitions of the default model, with the bold lines representing median values, and the shaded areas indicating the min–max ranges in outcomes per timestep.

Table 3
Summary of median outcomes at the batch-level (180 pigs) across 100 stochastic repetitions.

	Median value (min–max range) per scenario	
Outcomes	Default	Infection-free
Time until last pig became infected (days)	37 (28–57)	–
Peak of coughing (day)	36 (30–43)	–
Percentage of pigs with lung lesions at slaughter (%)	14 (6–23)	–
Average time per pig from entry to slaughter (days)	114 (114–115)	107 (106–108)
Average live weight at slaughter per pig (kg)	122.9 (122.4–123.8)	123.5 (123.2–123.8)
SD of individual weights at slaughter (kg)	1.9 (1.7–2.4)	1.8 (1.6–2.0)
Average feed consumption per pig (kg)	258.0 (256.5–260.1)	246.9 (245.5–248.6)
Total revenues per batch (€)	35 050 (34 887–35 307)	35 226 (35 133–35 301)
Total feed costs per batch (€)	15 172 (15 083–15 294)	14 520 (14 435–14 618)
Total labour costs per batch (€)	1 892 (1 881–1 907)	1 784 (1 773–1 796)
Loss in margin over feed and labour costs per pig due to infection (€)	5.91 (4.70–6.77)	–

The median reduction in margin over feed and labour costs due to infection was €5.91 per pig (range: €4.70–6.77). Fig. 4 illustrates the economic losses per pig, decomposed into their partial budget components. Increased feed costs represented the largest contributor to losses, with a median of €4.31 per pig (range: €3.90–4.84), followed by reduced revenues (€0.89; range: 0.08–1.53) and additional labour costs (€0.68; range: 0.64–0.74). These results highlight feed efficiency losses as the main driver of economic losses due to *M. hyopneumoniae* infection in the simulated production system.

Sensitivity analysis

Fig. 4 additionally presents the sensitivity of economic outcomes to variations in key epidemiological input parameters, including the initial infection prevalence, the proportion of infected pigs that arrive as exposed, the contribution of chronically infected individuals to the force of infection and the between-pen transmission rate. Supplementary Figure S1 shows the infection dynamics for each of these sensitivity analyses. The results of the sensitivity analyses on all input parameters (± 20% variation) are shown in Fig. 5.

For each sensitivity analysis on the key epidemiological input parameters, the median margin over feed and labour costs remained within the range of the default model outcomes, except when between-pen transmission was set to zero (€3.40 per pig). Reducing between-pen transmission substantially slowed the spread of infection and increased the proportion of pigs with lung lesions at slaughter. Changes in initial prevalence also affected infection dynamics, primarily by shifting the timing of peak infection prevalence and coughing incidence. In contrast, varying the distribution of infected individuals at arrival—i.e. the proportion arriving as E versus Ia—and adjusting the transmission rate of Ic pigs had only small to negligible effects on both economic and epidemiological outcomes.

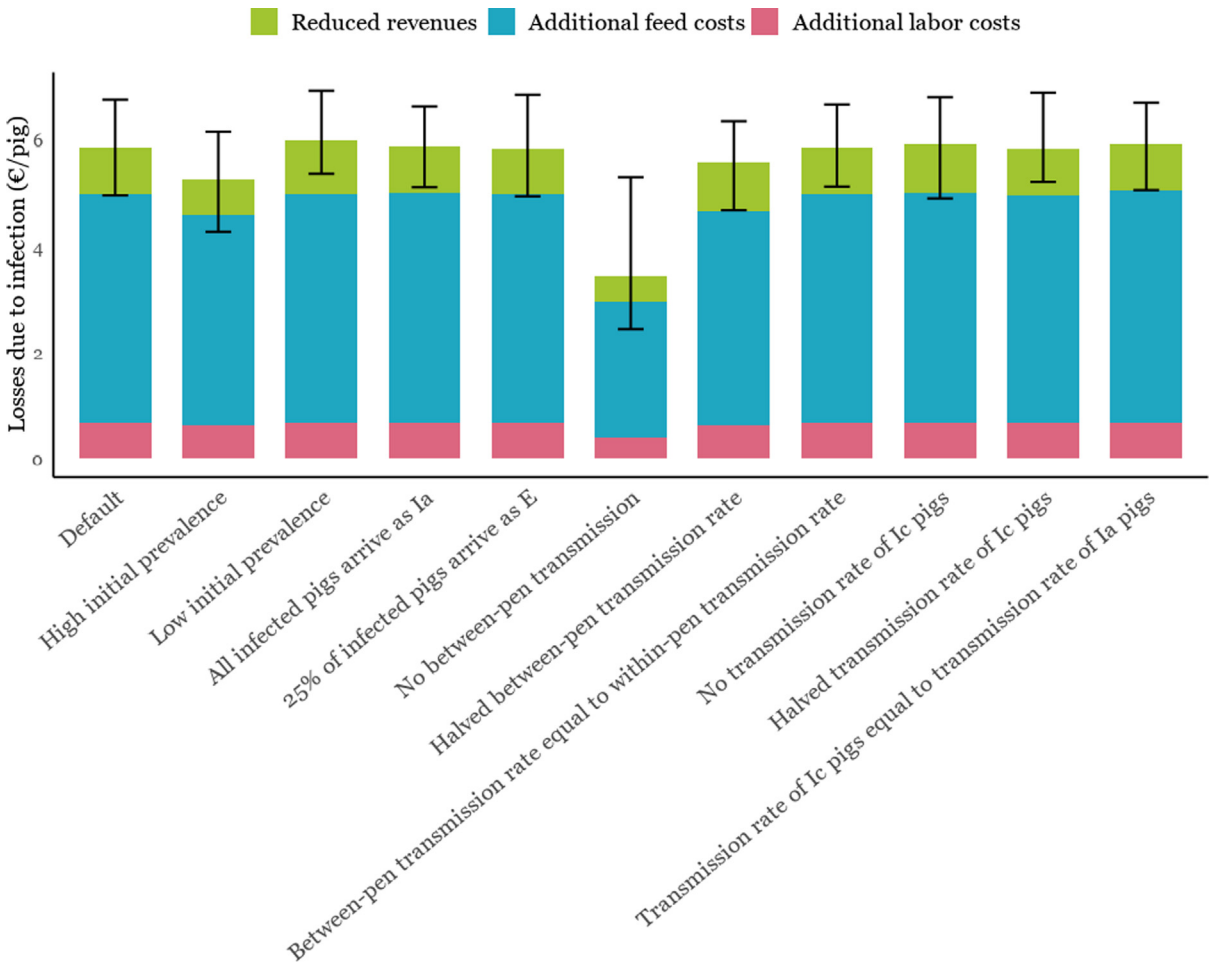

Fig. 4. Economic losses per pig under sensitivity analyses of key epidemiological assumptions. Abbreviations: E = exposed; Ia = acutely infected; Ic = chronically infected. Bars show the median losses per pig (in euros) for three economic components: reduced revenues (green), additional feed costs (blue), and additional labour costs (pink). Error bars represent the minimum–maximum range of the total economic losses (sum of all components).

Among the six biological and economic outcomes investigated, the percentage of pigs with lung lesions at slaughter was most affected in the one-at-a-time sensitivity analyses. When $D_{lesions}$, DG and F_{DG} were decreased by 20%, the median proportion of pigs with lung lesions at slaughter dropped to 0%, corresponding to a −100% change relative to the default value. Conversely, increasing $D_{lesions}$ by 20% led to a median of 78% of pigs with lung lesions at slaughter, which corresponds to a +560% increase relative to the default value. Expressed in absolute terms, this sensitivity analysis therefore resulted in a range from no detectable lung lesions to lesions in more than three-quarters of pigs at slaughter. Among all sensitivity analyses, variation in DG and F_{DG} produced the greatest changes in both the SD of individual weights at slaughter and the average time from entry to slaughter. For economic outcomes, the effects were mostly straightforward: labour costs varied proportionally with labour requirement and labour price, feed costs with feed price and feed conversion ratio, and revenues with dressing percentage and selling price. Additionally, changing the effect of infection on daily gain and feed conversion ratio affected labour costs and feed costs, respectively.

Discussion

A stochastic individual-based model was developed to integrate *M. hyopneumoniae* transmission dynamics, the development of coughing and lung lesions, the effects of infection on production performance, and the resulting economic losses in commercial pig fattening units. To our knowledge, only one previous modelling study has simulated *M. hyopneumoniae* transmission (Nathues et al., 2016), focusing primarily on disease dynamics and the evaluation of preventive and control strategies. The present work expands upon this by introducing a simulation framework that integrates biological, clinical, and economic components of infection while accounting for pen-level structure and spatially dependent transmission rates. Its stochastic design captures the natural variability in infection processes and individual pig responses, providing a more realistic representation of herd-level dynamics.

The simulated infection patterns indicate that the period between three- and four-weeks post entry represents a critical window for mitigating transmission in fattening herds under the modelled conditions. However, this timing is specific to our scenario and may differ substantially under field conditions, where infection dynamics are influenced by factors such as herd structure, ventilation, and pen separation (Leon et al., 2001; Fano et al., 2005). Field studies have shown that infection often occurs weeks before clinical signs become apparent (Sørensen et al., 1997; Leon et al., 2001), which complicates timely detection based solely on coughing. In our simulations, coughing lagged approximately one week behind the rise in infection prevalence, but this delay can be even longer in practice, and a proportion of pigs may remain subclinical throughout the production cycle (Sørensen et al., 1997; Fano et al., 2005). These observations under-

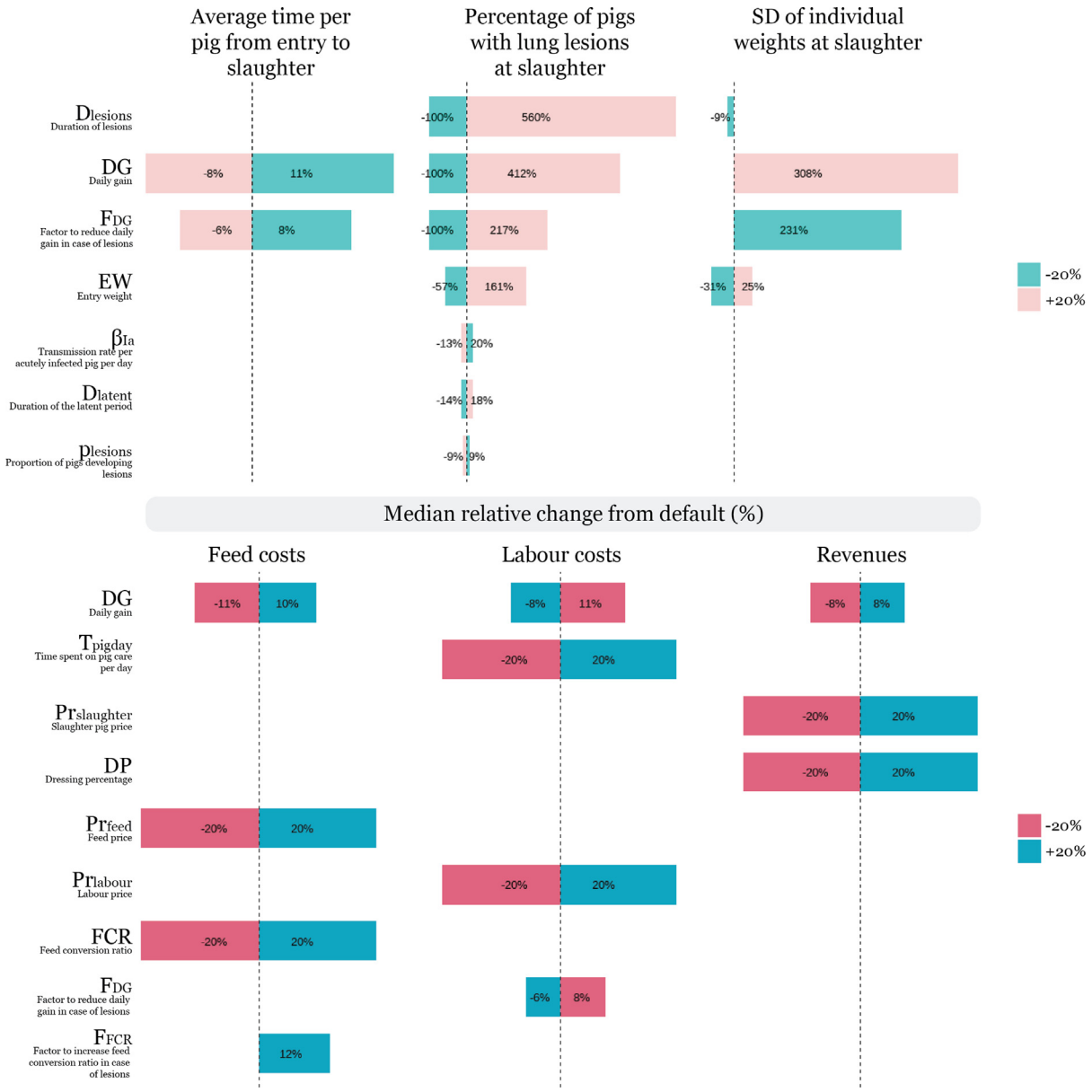

Fig. 5. Sensitivity analysis showing the effects of ± 20% changes in input parameters on (a) key biological outcomes: average time per pig from entry to slaughter on the fattening farm, percentage of pigs with lung lesions at slaughter, and SD of individual weights at slaughter; and (b) economic outcomes: feed costs, labour costs, and revenues. Only effects of 5% or larger are shown. The bars represent the median effect.

score the limitations of relying on clinical signs for early detection and highlight the value of complementary diagnostic approaches, such as PCR testing of tracheal secretions, which can identify infection during the preclinical phase (Clavijo et al., 2021; Silva et al., 2022). Incorporating such diagnostic strategies into modelling frameworks could provide additional advantages, enabling evaluation of intervention timing and cost-effectiveness under different surveillance scenarios.

Field studies also report higher lesion prevalence at slaughter than our model predicted (median 14%). According to Maes et al. (2023), cranioventral pulmonary consolidation (CVPC) prevalence in slaughter pigs typically ranges between 20 and 75%, depending on herd health status, vaccination, and coinfections. Pessoa et al. (2021) further showed that lung lesion prevalence correlates strongly with coughing scores and batch-level performance, reinforcing that slaughter checks remain a useful—though imperfect—indicator of respiratory health. The discrepancy with our results likely reflects two factors: (i) the relatively high initial prevalence and accelerated spread assumed in our simulations, and (ii) reliance on parameters derived from inoculation studies, which tend to overestimate bacterial load and shedding compared to natural infections (Fano et al., 2005). Sensitivity analyses confirmed that reducing initial prevalence or between-pen transmission slowed spread and increased lesion prevalence at slaughter, suggesting that housing design and pen-level separation may also play a larger role in field conditions than captured here. Importantly, lesion-based assessments underestimate the true economic impact because they fail to account for subclinical infections and resolved lesions, which still impair growth and feed efficiency during the fattening period. Our findings emphasise the need for longitudinal field data on subclinical cases, lesion dynamics, and between-pen transmission to refine model assumptions and improve alignment with patterns observed in the field.

In the simulated outbreak, *M. hyopneumoniae* infection caused a median loss of €5.91 per pig marketed (€5.20 when excluding labour costs). This aligns with the findings of Calderon Diaz et al. (2020), who reported a €0.10 reduction in revenue and a €4.20 increase in feed costs per sold fattening pig, which corresponds with a total loss of €5.30 after inflation correction. In the present analysis, feed-related inefficiencies were the dominant contributor to overall losses, accounting for approximately 73% of the total impact. Our results and sensitivity analyses emphasised that even an increase in feed price or decline in feed conversion efficiency can substantially reduce profitability under endemic infection conditions. Sensitivity analyses showed that the estimated economic losses were generally robust to changes in key epidemiological parameters. Median margins over feed and labour costs remained within the range of the default model outcomes, except when between-pen transmission was set to zero, which reduced the median loss to €3.40 per pig. This further emphasises that between-pen transmission is a key driver of both infection spread and associated economic losses, highlighting that interventions aimed at reducing between-pen transmission could provide the greatest financial benefit.

It is important to note that the current analysis focused on the short-term effects of a single outbreak within a compartment and did not account for transmission between compartments or longer-term consequences, such as changes in the number of production cycles or pigs marketed per year. Consequently, the estimated economic losses per pig reflect batch-level outcomes and may not directly translate to the farm level without additional assumptions or adjustments. Extrapolating these results to the entire farm would require assuming that all compartments perform similarly in terms of disease dynamics. Alternatively, the model could be extended to simulate multiple batches, allowing some to arrive with lower infection prevalence or completely uninfected (Vangroenweghe et al., 2015) and only become exposed to infection through indirect contact with other compartments during the production cycle. Incorporating these inter-compartment processes in future modelling work would provide a more comprehensive assessment of the economic burden at the farm level. Additionally, our model included only single-pathogen *M. hyopneumoniae* infections, whereas field observations typically capture more complex clinical presentations involving coinfections with pathogens such as *Pasteurella multocida*, *Actinobacillus pleuropneumoniae*, porcine reproductive and respiratory syndrome virus, swine influenza virus or porcine circovirus 2, which are known to exacerbate lung damage and production losses (Oh et al., 2022; Tonni et al., 2022). Future modelling efforts should incorporate coinfection effects, either through experimental studies or expert knowledge elicitation, to enhance realism and field applicability.

Although we simulated a Dutch pig fattening farm, the model's state machines describing infection dynamics and the development of lung lesions and coughing were parameterised using literature data, making them representative of a broader geographic context. Production performance parameters were derived from Dutch national statistics and databases but can easily be adapted to data from other countries. This is particularly advisable given that the sensitivity analysis showed daily gain and feed conversion ratio to be among the most influential parameters, especially affecting the proportion of pigs with lung lesions at slaughter and economic outcomes. The model's flexible structure allows straightforward adaptation to different production parameters, target finishing weights, or economic conditions. We also explored the impact of increasing or decreasing stocking density at both pen and compartment levels; these adjustments had negligible effects on the key outcomes (data not shown), indicating that the model is robust to moderate variations in housing density.

Lastly, we wish to emphasise that the full burden of *M. hyopneumoniae* extends beyond purely economic outcomes. The infection also drives substantial antimicrobial use (Mallioris et al., 2025), compromises pig health and welfare, and increases environmental impacts through higher feed requirements and associated resource use (van der Werf et al., 2005). Considering these dimensions is essential for a comprehensive understanding of the infection's true impact.

In short, the modelling framework presented here provided an integrated perspective on the biological and economic consequences of *M. hyopneumoniae* infection. The model can be further adapted to include multiple burdens, as well as to assess the cost-effectiveness of preventive and control measures.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2026.101786) can be found at the foot of the online page, in the Appendix section.

Ethics approval

Not applicable.

Data and model availability statement

The full model code that supports the study findings is publicly available at https://doi.org/10.5281/zenodo.17723929. Information can be made available from the authors upon request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (GPT-5) in order to improve readability and language. Additionally, the authors used Elicit to assist in the search for relevant literature during parameterisation and writing. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Declaration of interest

None of the authors have a conflict of interest.

Acknowledgements

We are grateful to Dr. Vianney Sicard for his assistance in implementing the organisational structure of the model, and to Dr. Tijs Tobias for his contributions to defining key model assumptions and the default farm structure. We also thank Léo Fritz for his support in executing the simulations on INRAE's high-performance computing (HPC) system. Finally, we acknowledge the INRAE MIGALE bioinformatics facility (DOI: 10.15454/1.5572390655343293E12) for providing access to their computing resources.

Financial support statement

This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101000494 (DECIDE).

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