Implementation and validation of an economic module for the epidemiological model Be-FAST to predict the costs generated by livestock diseases epidemics. Application to the Classical Swine Fever case in Spain.

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Abstract

Classical Swine Fever (CSF) is one of the most harmful livestock diseases for the economy of the swine sector worldwide. Specifically in Spain, the costs in the two last CSF outbreaks (1997 and 2001) have been estimated above 108 million euros. In this work, we aim to evaluate the economic impact of important livestock disease epidemics, and particularly the CSF in Spain. This study starts with a preliminary classification of the costs associated with CSF epidemics. In order to estimate the expected costs of a given epidemic in a considered area, a new economic module has been integrated into the epidemiological model Be-FAST, a time-spatial stochastic spread mathematical model for studying the transmission of diseases within and between farms. The input data for economic parameters have been obtained from entities related with the swine industry in Spain. The new Be-FAST module is tested by comparing the results obtained with historical data from CSF epidemics in Spain. The outcomes show that severe CSF epidemics also have a strong economic impact with around 80% of the costs related to animal culling, while costs associated with control measures are directly associated with the number of infected farms and the duration of the epidemic. The results presented in this work

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are expected to provide valuable information to decision makers, including animal health officials and insurance companies, and can be extended to other livestock diseases or used to predict the economic impact of future outbreaks.

Keywords: *epidemiological modelling, economic modelling, Be-FAST, classical swine fever, risk surveillance.*

1 Introduction

Classical Swine Fever (CSF) is a highly contagious disease that affects wild and domestic swine. It is considered as one of the diseases that causes most economic damage to the worldwide swine industry (see [7, 8, 9, 14]). Some examples of the economic consequences of CSF epidemics in Belgium and The Netherlands are shown in Table 1.

Outbreak costs in Europe				
	year	**outbr.**	**months**	**M€**
BE	1990	113	10	209
BE	1993	7	4	24
BE	1994	45	8	49
BE	1997	8	2	11
NE	1997	14	429	2313

Table 1: Historical data of CSF epidemics in Belgium, BE, and The Netherlands, NE with summarized data about year, number of outbreaks (outbr.), duration in months and estimated economic cost in M€ (see Saatkamp et. al. [8]).

Spain is the second largest producer of swines in the European Union and became CSF-free in 1988. However, two CSFV incursions occurred: The first one was in 1997/98 and affected the provinces of Lleida, Seville, Segovia and Saragossa; and the second one was in 2001/02 and affected the provinces of Lleida, Castellón, Valencia, Cuenca and Barcelona. Table 2 reports the estimated economic costs of both epidemics.

Outbreak costs in Spain				
year	**outbr.**	**months**	**culled animals**	**M€**
1997	99	16	609147	60
2001	48	11	378407	48

Table 2: Historical data of CSF epidemics in Spain with summarized data about year, number of outbreaks (outbr.), duration in months and estimated economic cost in M€ for animal compensation (see del Pozo [10]).

Generally, each CSF epidemic may exhibit a different behavior and economic consequences depending on the location, time period or type of holdings infected. In all cases, implementing strict control measures to stop the spread of this disease and eradicate it is necessary. For this reason, when a CSF epidemic is detected in Europe, the EU regulations require the following control measures (see M.A.P.A. report [11]): 1) Immediate cull of all swine that are found in the infected farms and destruction of the carcasses; 2) restriction of movements related to swine industry (e.g., animals, vehicles and persons) in the areas of declared CSF outbreaks; 3) strict measures of biosecurity as disinfection of holdings, material and transport vehicles that could be contaminated; 4) tracing and observation to determine the source of infection and the pattern of diffusion of the CSF: A particular attention is paid to the visits of veterinary practitioners and transport vehicles for animals and materials; 5) zoning around infected holding improving the detection time of infected farms in the neighbourhood and controlling the movements of vehicles within this zone that suppose a risk of further transmission of the disease.
All these control measures generate an economic cost which is supported by authorities and other entities of the swine industry. The study of the potential spread patterns of CSF into an area may help to identify risk zones to improve the prevention and management of future outbreaks. In the present work, we consider the time-spatial stochastic epidemiological model called Be-FAST (*Between-Farm-Animal Spatial Transmission*, see [1, 2, 3, 4, 5]). This model has been developed at the University Complutense of Madrid by the MOMAT (`www.mat.ucm.es/momat`) and VISAVET (`www.sanidadanimal.info`) research groups. The main objectives of Be-FAST focus on the next four points considered for a particular livestock disease (e.g. CSF, African Swine Fever or Foot and Mouth Disease) and area (e.g., region, province, country): 1) To evaluate the spatial risk of disease spread between farms in a considered area; 2) to identify the disease diffusion pattern; 3) to predict the amplitude and duration of particular outbreaks; and 4) to evaluate the efficiency of applied control measures. As it is out of the scope of this paper we only describe briefly the main processes considered in Be-FAST, more details can be found in [1, 2, 3].
Be-FAST is based on a Monte-Carlo algorithm that generates $M \in \mathbb{N}$ scenarios of possible epidemic evolutions. More precisely, considering an input database given by the user containing some information about farms and their commercial network, at the beginning of each scenario (that is, at time $t = 1$) every farm is in a susceptible state (i.e., free of disease) except a predefined number of randomly selected focus, which are assumed to have a predefined number of infected animals. During a period of time $[1, T]$, being $T \in \mathbb{N}$ the number of maximum days of simulation, the disease spreads *within-farm* through a SI model, and *between-farm* through an Individual-Based model (with the farms playing the role of individuals). Furthermore, the process of detection by the authorities of contaminated farms is made every day of the simulation. When a farm is detected, control measures 1)-6) described previously are activated. If at the end of a day the epidemic is over, that is no infections, the current simulation finishes and a next one starts. At the end of the last simulation sev-

eral outputs are computed (e.g., main epidemic amplitude and duration, risk of infection of each farm, etc.). Figure 1 shows a diagram with the main structure of Be-FAST.

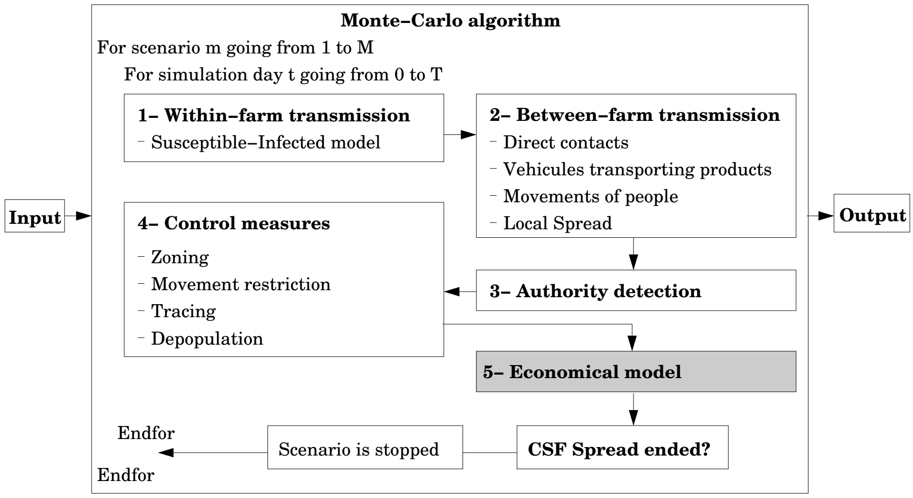

Figure 1: Main structure of the Be-FAST detailed in previous references about the model [1, 2, 3, 4, 5].

The main goals of this work are to develop an economic model to evaluate various economic costs of simulated livestock disease outbreaks, to include this model as a module of Be-FAST and to validate it by using historical data. For this reason, as suggested by Saatkamp et. al. [8], we have classified the costs in four categories (explained in Section 2): 1) Payable costs; 2) transferred costs; 3) calculated costs; and 4) indirect costs. At the end of a Be-FAST simulation, various statistical economic indicators are computed (e.g., maximum and mean epidemic losses, repartition of the classified costs, etc.). The main idea is to provide a tool useful for authorities and insurance companies in order, for instance, to estimate initial budget to fight against considered disease located in an specific area. We considered economic data from some real epidemics and compared them with the costs estimated by the model. This study is of high interest for public authorities and insurance companies to predict the evolution of each type of costs during the epidemic. We are also interested in studying the model behaviour according to the sanitary impact and duration of the epidemics and the relationship with the economic impact. We simulate different scenarios and study the evolution of each type of costs. Finally, the results are compare with literature about previous outbreaks in Spain (see [6, 10]) and other countries (see [9]). As said previously, we point out that, although the proposed methodology is developed within the particular CSF and Spanish frameworks, it can be easily extended to any other livestock disease by using the adequate parameter estimations.

This paper is organized as follows: In Section 2 we describe, from a general point of view, the economic model used to evaluate the different costs generated by a given disease outbreak in a considered area. Section 3 details the considered parameters used for studying the specific CSF cases in Spain. In Section 4, we present various numerical experiments used to check the behaviour of our economic model. Furthermore, to validate our model, we compare obtained results with economic estimations of the last Spanish CSF epidemics.

2 Economic model

The economic module is computed at the end of each simulation day, as we can see on the diagram representing the general Be-FAST structure shown in Figure 1, in order to evaluate the daily cost of the considered livestock disease epidemics in a specific area until its eradication. In the current section, we explain the costs involved in an epidemic and its computation in Be-FAST.
The cost classification used in the model is the same as the one proposed by H.W. Saatkamp et al. [8]: 1) Payable costs (C_{p}), which are the costs paid directly by the authorities to control and eradicate the epidemic; 2) Transferred costs (C_{t}), which are the costs paid by the authorities to compensate others entities (such as farmers); 3) Calculated costs (C_{c}), which are the losses generated in the livestock sector until the eradication of the epidemic (such as transportation companies); and 4) Indirect costs, caused to the livestock trade by the devaluation of the meat price.

2.1 Payable costs

The human and material resources needed to apply the control measures presented previously in Section 1 are considered as payable costs since these resources should be paid directly by the authorities. In this category, we include the following costs:

- $C_{\mathrm{p,zn}}(i,t) \in \mathbb{R}$ denotes the daily costs related to zoning around a detected farm i at day t. The establishment of protection areas requires administrative and security resources (as, for instance, security officers) for controlling restricted activities. We consider:

$$C_{\mathrm{p,zn}}(i,t) = N_{\mathrm{zn}}(i,t) \cdot MC_{\mathrm{p,zn}}, \tag{1}$$

  where $N_{\mathrm{zn}}(i,t) \in \mathbb{N}$ is the number of farms included in the zone around farm i at day t and not already included in another protection zone; and $MC_{\mathrm{p,zn}} \in \mathbb{R}$ is the daily mean cost estimated for controlling one farm one day.

- $C_{\mathrm{p,cul}}(i,t) \in \mathbb{R}$ denotes the cost of culling and disinfecting farm i at day t. It includes the human and material resources and the cleaning products needed during this process. It is computed as:

$$C_{\mathrm{p,cul}}(i,t) = N_{\mathrm{ani}}(i,t) \cdot MC_{\mathrm{p,cul}}, \tag{2}$$

where $N_{\mathrm{ani}}(i,t) \in \mathbb{N}$ is the number of animals at farm i at day t; and $MC_{\mathrm{p,cul}} \in \mathbb{R}$ is the mean cost of culling and disinfecting the farm estimated for one animal.

- $C_{\mathrm{p,sm}}(i,t) \in \mathbb{R}$ denotes the cost of testing possible infection at farm i at day t. This cost involves sampling, laboratory analysis and employee salary. In order to detect an infected farm i at day t, it is necessary to collect and analyse random samples of size $N_{\mathrm{sm}}(i,t) \in \mathbb{N}$, calculated by the following formula extracted from Casal i Fàbrega et. al. [19]:

$$N_{\mathrm{sm}}(i,t) = (1 - (1-a)^{1/D}) \cdot (N_{\mathrm{ani}}(i,t) - \frac{D-1}{2}), \quad (3)$$

where $D > 0$ is the expected number of infected animals in the herd; and a is a required confidence level.

Therefore, $C_{\mathrm{p,sm}}(i,t)$ is calculated as:

$$C_{\mathrm{p,sm}}(i,t) = N_{\mathrm{sm}}(i,t) \cdot MC_{\mathrm{p,sm}}, \quad (4)$$

where $MC_{\mathrm{p,sm}} \in \mathbb{R}$ is the mean cost of testing one sample.

Considering previous costs, the total payable cost in one Monte-Carlo simulation is given by:

$$C_{\mathrm{p}} = \sum_{t=1}^{T} \left(\sum_{i \in \Theta_{\mathrm{zn}}(t)} C_{\mathrm{p,zn}}(i,t) + \sum_{i \in \Theta_{\mathrm{cul}}(t)} C_{\mathrm{p,cul}}(i,t) + \sum_{i \in \Theta_{\mathrm{sm}}(t)} C_{\mathrm{p,sm}}(i,t) \right), \quad (5)$$

where $\Theta_{\mathrm{cz}}(t)$ denotes the set of farms for which protection zones are applied at day t; $\Theta_{\mathrm{cul}}(t)$ the set of farms culled at day t; and $\Theta_{\mathrm{sm}}(t)$ the set of farms checked for infection at day t.

2.2 Transferred costs

After a culling, the authorities must usually compensate the affected livestock producers. These costs are called transferred costs and are denoted by $C_{\mathrm{t}} \in \mathbb{R}$. These expenses are strictly controlled and regulated by the authorities through a census of the culled animals per outbreak and it´s expected that they have an important economic impact (see Saatkamp et. al. [8]). This cost is evaluated by considering

$$C_{\mathrm{t}} = \sum_{t=1}^{T} \sum_{i \in \Theta_{\mathrm{cul}}(t)} N_{\mathrm{ani}}(i,t) \cdot MC_{\mathrm{t,cul}}(i), \quad (6)$$

where $MC_{\mathrm{t,cul}}(i) \in \mathbb{R}$ represents the compensation per animal depending on production type of farm i (fattening, farrowing, farrow-to-finish).

2.3 Calculated costs

The losses supported by livestock companies until the end of the epidemic represent the most difficult to estimate (see Saatkamp et. al. [8]). For this work we have considered the followings:

- $C_{\mathrm{c,ds}}(i,t) \in \mathbb{R}$ denotes the daily cost generated by removing or destroying food and material as disposal in a new farm i at day t under quarantine. We assume that this cost is proportional to the number of animals per farm and it is calculated as

  $$C_{\mathrm{c,ds}}(i,t) = N_{\mathrm{ani}}(i,t) \cdot MC_{\mathrm{c,ds}}(i), \tag{7}$$

  where $MC_{\mathrm{c,ds}}(i) \in \mathbb{R}$ is the daily mean cost per animal at farm i due to the disposal which depends on the production type of farm i (fattening, farrowing, farrow-to-finish).

- $C_{\mathrm{c,np}}(i,t) \in \mathbb{R}$ denotes the daily losses caused in farms without animals due to culling control measure. During quarantine, from detection to repopulation, the farms are under a non-production status in which there are no benefits for livestock producers. It´s calculated as

  $$C_{\mathrm{c,np}}(i,t) = N_{\mathrm{ani}}(i,t) \cdot MC_{\mathrm{c,np}}, \tag{8}$$

  where $MC_{\mathrm{c,np}} \in \mathbb{R}$ is the mean daily cost caused by non-production per day estimated for one animal.

- $C_{\mathrm{c,tr}}(i,t) \in \mathbb{R}$, $C_{\mathrm{c,su}}(i,t) \in \mathbb{R}$ and $C_{\mathrm{c,vt}}(i,t) \in \mathbb{R}$ denote the daily losses caused by the blockading of a farm i in a protection zone for livestock transportation companies, animal products transportation companies and veterinary services, respectively. They are computed as:

  $$C_{\mathrm{c,tr}}(i,t) = N_{\mathrm{tr}}(i,t) \cdot MC_{\mathrm{c,tr}}, \tag{9}$$

  where $N_{\mathrm{tr}}(i,t) \in \mathbb{N}$ is the number of animals transported and blocked at farm i at considered day t; and $MC_{\mathrm{c,tr}} \in \mathbb{R}$ is the mean cost caused per movement.

  $$C_{\mathrm{c,su}}(i,t) = N_{\mathrm{su}}(i,t) \cdot MC_{\mathrm{c,su}}, \tag{10}$$

  where $N_{\mathrm{su}}(i,t) \in \mathbb{N}$ is the number of movements of vehicles transporting products blocked at farm i at day t; and $MC_{\mathrm{c,su}} \in \mathbb{R}$ is the mean cost caused by blockading one supply movement.

  $$C_{\mathrm{c,vt}}(i,t) = N_{\mathrm{vt}}(i,t) \cdot MC_{\mathrm{c,vt}}, \tag{11}$$

  where $N_{\mathrm{vt}}(i,t) \in \mathbb{N}$ is the number of veterinarian services blocked at farm i at day t; and $MC_{\mathrm{c,vt}} \in \mathbb{R}$ is the mean cost caused by blockading one veterinarian movement.

The total calculated cost of a whole simulation is given by:

$$\begin{aligned} C_{\mathrm{c}} = \textstyle\sum_{t=1}^{T} \Big(\sum_{i\in\Theta_{\mathrm{qt}}(t)} \big(C_{\mathrm{c,ds}}(i,t) &+ \textstyle\sum_{i\in\Theta_{\mathrm{zn}}(t)} C_{\mathrm{c,np}}(i,t) \\ &+ C_{\mathrm{c,tr}}(i,t) + C_{\mathrm{c,su}}(i,t) + C_{\mathrm{c,vt}}(i)\big)\Big). \end{aligned} \tag{12}$$

2.4 Indirect Costs

From the detection of the considered CSF outbreak until its eradication, the livestock market and its derivatives are affected by a depreciation of the meat price due to social alarm or trade restrictions. The consequence generally consists in the loss of the expected benefits for all the implied partners. Theses losses are categorized as indirect costs, denoted by $C_{\mathrm{i}}(t)$ and computed daily as

$$C_{\mathrm{i}}(t) = (MP_{obs}(t) - MP_{pre}(t)) \cdot MC_{\mathrm{i,tr}}(t) \cdot MC_{\mathrm{i,wg}}, \tag{13}$$

where $MC_{\mathrm{i,tr}}(t)$ is the number of animals traded at day t; $MC_{\mathrm{i,wg}} \in \mathbb{R}$ is the mean weight of an animal; $MP_{obs}(t)$ is the daily evolution of the meat price observed in case of epidemic and $MP_{pre}(t) \in \mathbb{R}$ is the daily evolution of meat price predicted in case of no epidemic.
Thus, the total indirect costs are computed as:

$$C_{\mathrm{i}} = \sum_{t=1}^{T} C_{\mathrm{i}}(t) \tag{14}$$

2.5 Total Costs

Finally, Be-FAST estimates the total costs as the sum of direct and indirect costs:

$$C_{\mathrm{total}} = C_{\mathrm{d}} + C_{\mathrm{i}}, \tag{15}$$

where $C_{\mathrm{d}} = C_{\mathrm{p}} + C_{\mathrm{t}} + C_{\mathrm{c}}$ is called direct cost.

3 Evaluation of the model parameters for the CSF case in Segovia

The parameters of the economic model, described in Section 2, have been adapted for the specific case of CSF outbreaks in the Spanish province of Segovia. The election of disease and region is based on trying to replicate previous experiments done with Be-FAST (see [1, 2, 3]) with an additional novel economic point of view. The values of the parameters used by this model are summarized in Tables 3 and 4. In the next paragraphs, we briefly describe how these value are estimated.

- $MC_{\mathrm{p,zn}}$: We assume that each farm in a protection zone needs to be controlled by 2 employees daily. The estimated value for this parameter is calculated by averaging the daily gross salary of 2 security officers for a day of work.

- $MC_{\mathrm{p,cul}}$: The culling process is done in one day and includes the costs of employees for culling and cleaning carcasses. The disinfection task is done two times (see the M.A.P.A. report in [11]), one just after the culling process and other one seven days after. The estimated value for this parameter is calculated by averaging the gross salary of an employee for a working day and by adding the average cost of the chemical products used during the cleaning described in the M.A.P.A. report [11].

- $MC_{\mathrm{p,sm}}$: The expenses associated with the sampling process and the laboratory analysis is obtained from another swine disease control program which follows a similar protocol of testing and has similar costs (see Control program for eradication of the Aujeszky in Spain [13]).

- For the equation 3, in the case of CSF, we consider a prevalence of disease in $D = 10\%$ and a confidence interval of $a = 95\%$ (see, Casal i Fàbrega [19]).

- $MC_{\mathrm{t,cul}}(i)$: The estimated price per animal is taken from an official Spanish report (see B.O.E. [12]), which provides an average cost per animal according to the category of the farm (i.e., fattening, farrowing or farrow-to-finish).

- $MC_{\mathrm{c,ds}}(i)$: The daily cost of food needed for one swine is obtained from the expertise opinion of several companies specialized in swine feeding. Therefore, the cost is estimated as seven times the cost of the daily food needed for one swine ($i \in \{$fattening, farrowing, farrow-to-finish$\}$).

- $MC_{\mathrm{c,np}}$, $MC_{\mathrm{c,tr}}$, $MC_{\mathrm{c,su}}$ and $MC_{\mathrm{c,vt}}$: The estimated costs associated to each blocked movement or service is obtained, again, by expert opinion and by collecting information from active companies and professionals involved in the livestock sector.

- $MC_{\mathrm{i,tr}}(t)$: This value is averaged from the traded swine database at day t.

- $MC_{\mathrm{i,wg}}$: This value represents the average weight of one animal and is obtained from an official Spanish report (see B.O.E. [12]).

- $MP_{obs}(t)$ and $MP_{pre}(t) \in \mathbb{R}$: Mercolleida is the official institution in charge of defining and evaluating the weekly value of the price of swine per kilogram (€/kg) in Spain. We analysed the historical evolution of the market prices (€/kg) during the last epidemic (2001/02) in Spain by collecting data spanning from two years before and after the epidemic from Mercolleida database (`www.mercolleida.com`) (he añadido esto). The epidemic started in June 2001 and lasted for 11 months (see del Pozo [7]). $MP_{obs}(t)$ denotes the observed evolution of prices during the Spanish epidemic while $MP_{pre}(t)$ denotes the predicted evolution of prices during the same period of time under the assumption of no epidemic. $MP_{pre}(t)$ was estimated by using historical data before and after the real epidemic of the swine market from Mercolleida database (`www.mercolleida.com`) through the followings backwards operators

Direct costs parameter list					
Parameter	$MC_{\text{p,zn}}$	$MC_{\text{p,cul}}$	$MC_{\text{p,sm}}$	$MC_{\text{i,wg}}$	$MC_{\text{t,cul}}(i)$
Value(s)	195.00	1.53	5.80	90.00	{262, 320, 169}*
Units	€$^{\text{d,f}}$	€$^{\text{a}}$	€$^{\text{t}}$	kg$^{\text{a}}$	€$^{\text{a}}$
Reference	exo	[5]	[9]	[9, 19]	[10]
Parameter	$MC_{\text{c,np}}$	$MC_{\text{c,tr}}$	$MC_{\text{c,su}}$	$MC_{\text{c,vt}}$	$MC_{\text{c,ds}}(i)$
Value(s)	0.25	1.53	130.00	62.50	{2.30, 2.30, 1.43}*
Units	$e^{\text{d,a}}$	e^{a}	e^{m}	e^{m}	$e^{\text{d,a}}$
Reference	exo	exo	exo	exo	[5]

* : fattening, farrowing, farrow-to-finish

d: per day; f: per farm; a: per animal, m: per movement, t: per test

exo: expert opinion from companies, professionals and experts

Table 3: Value of the parameters of the economic model presented in Section 2 used for the numerical experiments.

$$\nabla MP_{obs}(t) = \frac{MP_{obs}(t)}{MP_{obs}(t-1)}, \tag{16}$$

$$\nabla MP_{his}(t) = \frac{MP_{his}(t)}{MP_{his}(t-1)}, \tag{17}$$

where $\nabla MP_{obs}(t)$ denotes the daily increment of swine price during the epidemic period at day t (€/kg.day), $MP_{his}(t)$ denotes the mean historical value of the swine price (€/kg) 2 years before and 2 years after the epidemic at the same day t of the year as $REA(t)$ and $\nabla MP_{his}(t)$ denotes the mean historical daily increment of swine price (€/kg) at the same day t of the year. The computation of $MP_{obs}(t)$ and $MP_{pre}(t)$ is given by

$$MP_{obs}(t) = MP_{obs}(t-1) \cdot \nabla MP_{obs}(t), \tag{18}$$

$$MP_{pre}(t) = MP_{pre}(t-1) \cdot \nabla MP_{his}(t). \tag{19}$$

The initial value of meat price at the beginning of the 2001/02 epidemic in Spain was 1.45 €/kg (Mercolleida). Assuming the same initial value for $MP_{pre}(t)$ at day $t = 1$, the daily evolution of both index, displayed in Figure 2, shows values for $MP_{obs}(t)$ generally below $MP_{pre}(t)$. Furthermore, during the first weeks and the last weeks of the graphic, both lines exhibit parallel evolution while they show a funnel-shape behavior during the middle of the epidemic. The differences are summarized in the following time-slots:

– First period (before week 15): The distances between $MP_{obs}(t)$ and $MP_{pre}(t)$ are around 0 while the standard deviation is $7 \cdot 10^{-3}$ (€/kg).

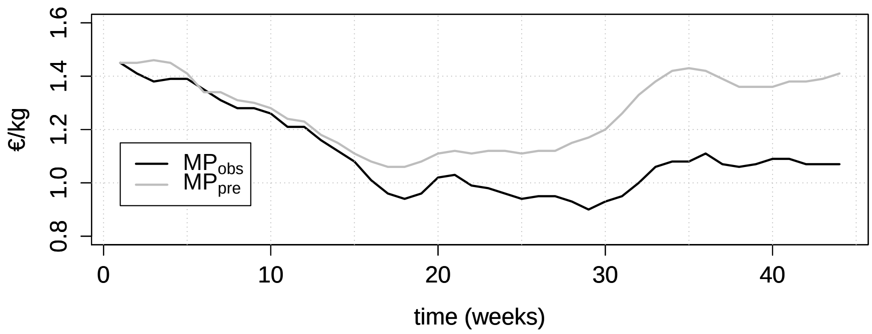

Figure 2: Evolution of observed swine price $MP_{obs}(t)$ (€/kg) and predicted swine price $MP_{pre}(t)$ (€/kg) during the period of the 2001/02 epidemic in Spain. The initial value taken for both index is 1.45 €/kg, corresponded to $MP_{obs}(1)$.

- Second period (between week 15 and 35): The distances between $MP_{obs}(t)$ and $MP_{pre}(t)$ increase progressively. The standard deviation reaches $37 \cdot 10^{-3}$ (€/kg).
- Third period (after week 35): The distances between $MP_{obs}(t)$ and $MP_{pre}(t)$ are around 0 while the standard deviation is $6.9 \cdot 10^{-3}$ (€/kg).

For this work, we have assumed a Normal distribution (K-S test, p-value $>$ 0.05) of $MP_{obs}(t)$ and $MP_{pre}(t)$ according to the three time-slots defined previously. The Table 4 shows the parameters of mean and standard deviation estimated for daily computation in the model of $MP_{obs}(t)$ and $MP_{pre}(t)$.

4 Numerical experiments

In this Section, we present and analyse the results given by our economical model when considering two numerical experiments based on data from the Spanish province of Segovia in 2005 and 2008. The objective of the 2008 experiment is to evaluate the behaviour of the model in a recent swine sector framework. The 2005 experiment aims to validate the model by comparing the outputs with past epidemics in Spain.

Indirect costs parameter list		
index	**phase**	**distribution**
$MP_{obs}(t)$	1st period	Normal$(0.981, 3.14 \cdot 10^{-3})$
$MP_{obs}(t)$	2nd period	Normal$(1.003, 3.34 \cdot 10^{-3})$
$MP_{obs}(t)$	3rd period	Normal$(1.013, 6.62 \cdot 10^{-3})$
$MP_{pre}(t)$	1st period	Normal$(0.979, 4.10 \cdot 10^{-3})$
$MP_{pre}(t)$	2nd period	Normal$(0.987, 13.42 \cdot 10^{-3})$
$MP_{pre}(t)$	3rd period	Normal$(1.012, 9.11 \cdot 10^{-3})$

Table 4: Estimated daily evolution of $MP_{obs}(t)$ and $MP_{pre}(t)$ according to the 3 time-slots defined in Section 3.

4.1 Model behaviour

This experiment was carried out with a database of Segovia in 2008 which consists in 1,400 farms, 1.108 million of animals and 10,046 movements of animals. The Be-FAST model was adapted to simulate the possible evolution of CSF outbreaks and their economic impact for different epidemic magnitudes. For each case, we compute 1000 Monte-Carlo simulations with a predetermined number of infected farms at the first day $t = 1$. Thus, we can estimate the expected sanitary and economic impacts from low up to severe outbreaks. We denote by F the number of first infected randomly chosen farms per case: $F \in \{1, 5, 10, 15, 20, 25, 50, 75, 100\}$. Table 5 summarizes the results obtained for these 9 cases according to the cost classification described in Section 2.

Case	F	D	CS	IF	C_{total}	C_{i}	C_{d}	C_{p}	C_{t}	C_{c}
1	1	54.5	1.9	2.42	0.91	0.36	0.55	0.06	0.42	0.06
2	5	76.9	8.3	10.49	3.18	0.84	2.34	0.22	1.84	0.27
3	10	82.8	15.9	19.58	5.18	0.86	4.43	0.38	3.52	0.52
4	15	87.6	23.6	28.72	7.41	0.87	6.53	0.53	5.23	0.77
5	20	89.4	30.3	36.67	9.34	0.98	8.35	0.65	6.71	0.98
6	25	90.3	36.6	44.59	11.10	1.00	10.01	0.76	8.13	1.19
7	50	91.5	69.4	82.34	20.00	1.19	18.80	1.19	15.36	2.25
8	75	90.7	100.7	119.18	28.02	1.19	27.06	1.43	22.36	3.27
9	100	94.7	132.1	156.56	36.55	1.38	35.16	1.56	29.32	4.28

Table 5: Results obtained by the economic model during the experiments described in Section 4.1. We present the following average values for 1000 simulations in the 9 considered cases: Number of initial infected farms, F; duration in days, D; number of culled swines in miles, CS; number of infected farms, IF; total costs in M€, C_{total}; indirect costs in M€, C_{i}; direct costs in M€, C_{d}; payable costs in M€, C_{p}; transferred costs in M€, C_{t}; and calculated costs in M€, C_{c}.

In Table 6, we present the percentage repartition of C_{p} , C_{t} and C_{c} in function of the total direct cost amount. We note that 77% up to 83% of the direct costs are transferred costs. Furthermore, as the direct costs increases, the payable costs decreases from 11% to 4%, meanwhile the calculated costs percentage is always around 11% in all cases.

Case	$C_{\mathrm{p}}(\%)$	$C_{\mathrm{t}}(\%)$	$C_{\mathrm{c}}(\%)$
1	11.61	77.10	11.29
2	9.44	78.97	11.58
3	8.62	79.64	11.74
4	8.19	80.03	11.78
5	7.87	80.34	11.79
6	7.62	80.54	11.85
7	6.33	81.68	11.98
8	5.28	82.63	12.09
9	4.45	83.38	12.17

Table 6: Percentages, computed from Table 5, in function of the total direct costs amount of: Payable costs, C_{p}; transferred costs, C_{t}; and calculated costs, C_{c}.

Table 7 shows the Spearman´s ρ correlation between each economic variable with D, CS and IF variables. We observe that all economic costs exhibit a correlated relationship with those variables. In particular, indirect costs present a strong correlation with the duration of the epidemic ($\rho = 0.996$). Furthermore, the payable costs exhibit a better correlation with the number of infected farms ($\rho = 0.959$). Finally, the transferred and calculated costs are more correlated with the number of animals culled ($\rho = 0.996$ and $\rho = 0.995$, respectively) than with other variables.

Spearman´s ρ	C_{i}	C_{p}	C_{t}	C_{c}
D	0.629	0.718	0.647	0.651
IF	0.462	0.959	0.901	0.900
CS	0.419	0.896	0.996	0.995

Table 7: Sperman´s ρ correlation, considering the significance at the 0.01 level, between the economic and the sanitary variables: Indirect costs, C_{i}; Payable costs, C_{p}; transferred costs, C_{t}; calculated costs, C_{c}; duration of the epidemic, D; culled swines, CS; and infected farms, IF.

Taking into account those correlations, some estimation formulas for each cost can be evaluated through the best fitted regression equations considering the parameters D, CS and IF. We obtain,

$$C_{\rm i}(D) = 0.998 - 0.031 \cdot D + 0.0003 \cdot D^2,^{(1)} \quad (20)$$

$$C_{\rm p}(IF, CS) = 0.032 + 0.013 \cdot IF + 0.001 \cdot CS,^{(2)} \quad (21)$$

$$C_{\rm t}(IF, CS, D) = -0.027 - 0.003 \cdot IF + 0.225 \cdot CS + 0.0005 \cdot D,^{(3)} \quad (22)$$

$$C_{\rm c}(IF, CS, D) = -0.016 + 0.0005 \cdot IF + 0.033 \cdot CS + 0.0003 \cdot D,^{(4)} \quad (23)$$

with $R^2 = 0.802^{(1)}, R^2 = 0.988^{(2)}, R^2 = 0.997^{(3)}$ and $R^2 = 0.996^{(4)}$.

4.2 Model validation

The model validation was carried out by considering historical data from the 1997-98 CSF epidemics occurring in Spain. As described in Table 2, this epidemic lasted around 480 days, had a total of 99 outbreaks and 609,147 animals were culled. This particular epidemic had a total economic losses of 89.5 M€, whereby 60 M€ were destined to animal culling compensations (transferred costs) [6]. It yields that 67% of the total costs are transferred costs and 33% are payable and calculated costs. As we observe in Table 2, the proportions between epidemic economic cost and the number of culled animals lead to mean values of 98.5 € and 126.8 € per animal as compensation for the 1997/98 and 2001/2002 epidemics, respectively. That implies an increment in time of the price per animal. The results of dividing $C_{\rm t}$ by CS, considering the results reported in Table 5, is around 221 € per animal as compensation for the 2008 simulated cases.

If we apply formulas (21) and (23) to calculate payable and calculated costs and assume 60 M€ for transferred costs, the estimated direct costs reach 81.52 M€, 8 M€ lower than the real value (i.e., an error of 9%). This result is quite reasonable, taking into account that other factors as the efficiency of control measures, the marketability of the region, the density of farms or the animal census may have an influence on the economic impact. However, we would like to improve the precision of the estimators (21) and (23) for this particular epidemic. We noted that, in 2006, an economic crisis in the swine industry have changed the animal census and reduced significantly the density of farms in Spain, specifically in Segovia (see d[10, 18]). Thus, we have repeated a new experiment, similar to the one described in Section 4.1, with a database of 2005 in Segovia (the older database available) which consist in 2,354 farms, 1.405 million of animals and 10,107 movements of animals. In addition, for this experiment, we set $MC_{\rm t,cul}(i) = 98.5$ € per animal, $\forall i$, as the result of dividing 60 M€ by 609,147 animals culled in 1997/98 epidemic. Rapid estimators for each cost can be calculated through the best fitted regression equations,

$$C_{\rm i}(D) = -0.403 - 0.019 \cdot D + 0.0003 \cdot D^2,^{(1)} \quad (24)$$

$$C_{\rm p}(IF, CS, D) = 0.049 + 0.001 \cdot IF + 0.005 \cdot CS + 0.0002 \cdot D,^{(2)} \quad (25)$$

$$C_{\rm t}(CS) = 0.0985 \cdot CS,^{(3)} \quad (26)$$

$$C_{\mathrm{c}}(IF, CS, D) = 0.028 - 0.001 \cdot IF + 0.035 \cdot CS + 0.0004 \cdot D,^{(4)} \qquad (27)$$

with $R^2 = 0.921^{(1)}, R^2 = 0.804^{(2)}, R^2 = 1^{(3)}$ and $R^2 = 0.992^{(4)}$.
The equations (25)-(27) estimate the direct costs of 85.26 M€, for the considered epidemic. With this estimation, payable and calculated costs cover the 30% of the direct costs, and transferred costs the 70%. Both percentages are quite close to the real ones, which are 33% and 67%, respectively.
Finally, as a last validation technique, we can compare the results of the first experiment (i.e., with 2008 data) with those given in [9]. In this work, the authors have estimated the possible repercussions that CSF would have by considering different epidemic magnitudes in Finland and by using Monte-Carlo techniques. Table 8 summarizes their results.

Economic losses in Finland		
case	**normal epidemic**	**long epidemic**
Lowest decrease in exporting	1.4	5.4
Medium decrease in exporting	7.5	12.3
Highest decrease in exporting	13.2	19.2
Direct costs	0.5	1.6

Table 8: Economic losses, in M€ , presented in [11] for the case of Finland and for the cases: normal epidemics (1-5 infected farms), long epidemics (6-33 infected farms).

The authors distinguish two types of epidemics, denoted as normal and long, according to the number of infected farms (i.e., normal epidemic: 1-5 infected farms; and long epidemic: 6-33 infected farms). On the one hand, it has used a different technique for the simulation of indirect costs: Instead of examining the history of epidemic cases (the last CSF epidemic in Finland occurred in 1917), the work studies the supply and demand of swine meat inside the country. According to this data, the price of swine in the market varies. Our approach offers a different point of view in the calculation of indirect costs. Indeed, Spain is mainly an export country and the price of the meat is highly correlated to the export activity. Thus, the indirect costs between both works cannot be compared directly. The comparison of direct costs is more reasonable. As we can observe on Table 5, for normal epidemics (i.e., $F = 1$) the direct costs are around 0.55 M€, which is quite similar to the 0.5 M€reported on Table 8. In severe epidemics, this difference is higher as in Finland, the direct costs are estimated to be around 1.6 M€ whereas for Spain, considering the cases $F = 5, 10$, we obtain a mean costs value of 4.5 M€. However, it should be emphasised that the Finland swine industry and the Spanish one are quite different (see [6, 9, 10]).

4.3 Sensitivity analysis

An extensive sensitivity analysis of the Be-FAST non economic parameters was carried out in previous works (see [1, 2]). We note that in the model described here, perturbations on the economic parameters do not affect the epidemic magnitude outputs. Furthermore, the impact of changes in the epidemic parameters on the computed costs can be obtained directly from the analytical formulas given previously. In the studied case, $MC_{\mathrm{t,cul}}(i)$ deserves a particular interest due to high proportion on the final costs because reducing (or increasing) a 5% its value might reduce (or increase) up to 1.5% of the direct costs in mild epidemics and up to 1% in severe epidemics. Small disturbances on the rest of the parameters do not produce significant changes in the final costs.

5 Conclusions

In this paper, we have presented a spatio-temporal simulation model to estimate the economic costs associated to livestock disease epidemics. To validate the model, we have focused on the study of the economic impact of CSF in the Spanish province of Segovia. The results have been compared with real economic data from the last epidemics in Spain. Finally, we have analysed the behaviour of the costs depending on the magnitude and duration of the epidemics and we have compared the results obtained with similar studies found in the literature. An important contribution of this work is the classification of the economic costs, the evaluation of the values of the model parameters and the study of the behaviour of the those costs during an epidemic.
As expected, the evolution of the economic costs depend on the amplitude of the epidemics. More specifically, the direct costs are highly correlated with the duration and the number of farms affected during an epidemic. In particular, for the studied cases in Spain, the transferred costs represent the main percentage of the direct costs (around 80%) while the calculated and payable costs represent only around 5-15% of the direct costs. On the other hand, the indirect costs have a better correlation with the duration of the epidemic than with the number of infected farms or animals culled.
The model presented here can be easily adapted to any other livestock disease and region. All the parameters have been estimated with reliable real economic data obtained directly from experts, professionals and companies of the swine industry. Obtaining relevant information about economic values can be a challenging task due to the sensitive nature data and confidentiality issues.
In future works, we will apply the epidemiological and economic model presented here to design optimal control strategies of livestock diseases. The main objective should be to minimize the global economical impact of an epidemic. In particular, we will study the interest of implementing alternative control measures such as: Vaccinating, preventive culling, risk-based surveillance strategies for the reduction of both sanitary and economic impact of future epidemics.

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