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Simulating the mechanics behind sub-optimal mobility and the associated economic losses in dairy production

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ABSTRACT

Hoof disorders and sub-optimal mobility (SOM) are economically important health issues in dairy farming. Although the dynamics of hoof disorders have an important effect on cow mobility, they have not been considered in previous simulation models that estimate the economic loss of SOM. Furthermore, these models do not consider the varying severities of SOM. The objective of this study was to develop a novel bio-economic simulation model to simulate the dynamics of 8 hoof disorders: digital dermatitis (DD), interdigital hyperplasia (HYP), interdigital dermatitis/heel-horn erosion (IDHE), interdigital phlegmon (IP), overgrown hoof (OH), sole haemorrhage (SH), sole ulcer (SU) and white-line disease (WLD), their role in SOM, and estimate the economic loss of SOM in a herd of 125 dairy cows. A Reed-Frost model was used for DD and a Greenwood model for the other 7 hoof disorders. Economic analysis was conducted per mobility score according to a 5-point mobility scoring method (1 = perfect mobility; 5 = severely impaired mobility) by comparing a scenario with SOM and one without SOM. Parameters used in the model were based on literature and expert opinion and deemed credible during model validation rounds. Results showed that the mean cumulative incidence for maximum mobility scores 2–5 SOM episodes were respectively 34, 16, 7 and <1 episodes per 100 cows per pasture period and 39, 19, 8, <1 episodes per 100 cows per housing period. The mean total annual economic loss due to SOM resulting from the hoof disorders under study was €15,342: €122 per cow per year. The economic analysis uncovered direct economic losses that could be directly linked to SOM episodes and indirect economic losses that could not be directly linked to SOM episodes but arose due to the presence of SOM. The mean total annual direct economic loss for maximum mobility score 2–5 SOM episodes was €1129, €3098, €4354 and €480, respectively. The mean total annual indirect economic loss varied considerably between the 5th and 95th percentiles: € − 6174 and €19,499, and had a mean of €6281. This loss was composed of additional indirect culling due to SOM (∼65%) and changes in the overall herd milk production (∼35%) because of additional younger replacement heifers entering the herd due to increased culling rates. The bio-economic model presented novel results with respect to indirect economic losses arising due to SOM. The results can be used to stimulate farmer awareness and promote better SOM management.

1. Introduction

Hoof disorders are a costly health issue in dairy production (Dolecheck and Bewley, 2018). These costs vary within and between hoof disorders depending on their respective severity, duration and recurrence. For example, the cost of a digital dermatitis case varied between €45 and €342 and for a sole ulcer case between €152 and €817 (Willshire et al., 2009; Cha et al., 2010; Charfeddine and Pérez-Cabal, 2017; Dolecheck et al., 2019). These costs can result in high economic losses for dairy producers, especially when the overall prevalence of hoof disorders can be as high as 81% (Somers et al., 2003). Bruijnis et al. (2010) found that hoof disorders are responsible for an annual economic loss of €76 per average cow for a dairy farm with a hoof disorder prevalence similar to Somers et al. (2003). Many of these costs arise

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potentially unbeknownst to the farmer because farmers tend to underestimate the prevalence of hoof disorders (Bruijnis et al., 2013).

Farmers may underestimate the prevalence of hoof disorders because they primarily detect hoof disorders first by adverse changes in the mobility of a cow (Bruijnis et al., 2013). Moreover, hoof disorders are largely associated with mild sub-optimal mobility (SOM; Tadich et al., 2010; O'Connor et al., 2019), which farmers are less sensitive in detecting (Alawneh et al., 2012a).

Due to the association between SOM and hoof disorders, it is expected that SOM, as an effect of underlying hoof disorders, will result in economic losses. This is confirmed with episodes of SOM reported to cost between €159 and €457 (Ettema and Østergaard, 2006; Guard, 2008; Liang et al., 2017). However, these studies focus on severe forms of SOM, omitting the potential economic losses associated with milder forms of SOM.

Mild SOM has not often been included in studies estimating the economic losses associated with SOM. Studies that include mild forms of SOM do so by usually employing a mobility scoring method. A mobility scoring method helps define a cow with SOM according to varying levels in severity of SOM based on the number of scores in the method (Schlageter-Tello et al., 2014). However, in doing so, the definition of a cow with SOM is generalised whereby a cow with a mobility score above a predefined mobility score threshold is defined as SOM. This generalisation reduces the ability of the method to help better identify which forms of SOM are of greater economic importance. For instance, Ettema et al. (2010) show the economic impact for SOM as defined by cows with mobility score ≥3 according to a 5-point mobility scoring method, but the economic impact for SOM respective of mobility scores 3–5 are not reported. In addition, omitting lower mobility scores (i.e. 2) from the definition of SOM may also lead to an underestimation of costs.

There are a number of studies concerning the economic losses associated with hoof disorders and SOM (Dolecheck and Bewley, 2018). Most of the studies reporting the economic loss of hoof disorders and SOM are conducted by simulation modelling. However, studies simulating the economic loss of hoof disorders do not simulate the effect of hoof disorders on cow mobility (Bruijnis et al., 2010; Dolecheck et al., 2019). Conversely, studies simulating the economic impact of SOM do not simulate hoof disorders as responsible mechanisms for SOM and the definitions of SOM related to severe forms (Ettema and Østergaard, 2006; Liang et al., 2017). An exception to the aforementioned studies simulating the economic loss of SOM is the study of Ettema et al. (2010) whereby hoof disorders are simulated as responsible mechanisms of SOM and milder forms of SOM are considered. However, Ettema et al. (2010) specify SOM in more general terms. More information is needed on the dynamics of SOM with hoof disorders acting as the responsible and the underlying mechanisms of SOM. Moreover, more precise information is needed on the economic losses due to different severities of SOM, including mild SOM.

We developed a novel stochastic bio-economic simulation model that creates a stronger link between SOM and hoof disorders whereby the hoof disorders act as the responsible mechanisms behind the dynamics of SOM. Adding to the literature concerning the economic losses due to SOM we present the direct economic losses due to SOM, for mild and severe forms, as well as the indirect economic losses due to SOM.

2. Materials and methods

2.1. Model overview

A dynamic, stochastic and mechanistic discrete-time step bio-economic model was developed in R version 3.6.1 – "Action of the toes" (R Core Team, 2019) to simulate the spread and occurrence of hoof disorders as responsible mechanisms of SOM in dairy cows as well as the management of SOM. A typical Dutch dairy production system of 125 milking cows was simulated. It was assumed that cows were housed in cubicles with slatted concrete floors during the Autumn and Winter months (housing period) and had access to pastures for >6 h a day in the Spring and Summer months (pasture period). The model simulated events in daily time-steps either at the hoof- or cow-level. Simulations at the hoof-level include hoof specific events (i.e. infection and treatment) whereas (re)production events (i.e. milking, calving, and culling) and mobility scoring are at the cow-level. A 5-point ordinal scale mobility scoring method was used to describe cow mobility (Sprecher et al., 1997). Per cow, per time-step and per mobility score the economic in- and outflows associated with SOM were computed. Based on these in- and outflows, the net partial economic results per year of the simulated farm were calculated. By comparing the net partial economic results of farms with and without hoof disorders, the total (direct and indirect) annual economic effect of SOM due to the hoof disorders under study could be estimated. The costs directly associated with SOM were also calculated per SOM per year.

2.2. Production dynamics

Cows were either lactating or dried-off, and spent a number of days in either period. The dry period length (DPL) was a fixed length, and the lactation length depends on a fixed minimum voluntary waiting period (VWP) before first service, stochastic estimates of oestrus detection and conception, and possible removal by culling decisions. A cow was prescribed a maximum number of days to conceive. If the cow did not conceive by this day she was culled for fertility reasons once her actual daily milk yield dropped below a fixed daily yield threshold. The decision to cull for fertility reasons was based on a cows production level relative to the herd. The decision to cull for general reasons depended on the removal of cows due to health disorders other than SOM[1] and mortality, and was calibrated so that the overall culling rate coincided with the ~30% for Dutch dairy farms (Nor et al., 2014). It was assumed that culling took place on the premise that a replacement heifer entered the milking herd on the following day a cow was culled. If a cow died, a replacement heifer entered the milking herd on a random day within a month after the cow died because those replacement events cannot be planned.

Expected daily milk yield for lactating cows depend on cow specific parameters and was modelled by fitting a lactation curve to each cow with the following equation

$$M^{(\mathrm{emy})}_{i,p,t} = a_{i,p} + b_{i,p} \times M^{(\mathrm{dim})}_{i,t} + c \times \exp\left(- k \times M^{(\mathrm{dim})}_{i,t} \right) + M^{(\mathrm{rpl})}_{i} \times M^{(\mathrm{ady})}_{i,p,t} \quad (1)$$

where $M^{(\mathrm{emy})}_{i,p,t}$ is the expected daily milk yield for cow i in parity p in time time-step t, $M^{(\mathrm{dim})}_{i,t}$ is the day in milk, $M^{(\mathrm{ady})}_{i,p,t}$ is the average daily yield, and $a_{i,p}$, $b_{i,p}$, c, and k are factors responsible for the shape of the curve (Wilmink, 1987). Variation in cow lactations was achieved by assigning a cow specific production level relative to the mean herd production to each cow. This relative production level (RPL) is denoted by $M^{(\mathrm{rpl})}_{i}$ and was drawn from a normal distribution with a mean of 0 and a standard deviation of 0.1 (Kok et al., 2017).

Feed requirements, expressed in VEM (where 1 VEM = 1.65 kcal of NE_L), for each cow was modelled as a function of daily FPCM milk produced (kg) for lactating cows (van Es, 1978). Parity 1, 2 and ≥3 cows respectively have a fat content (%) of 4.48, 4.5 and 4.51, and a protein content (%) of 3.55, 3.59 and 3.51 (Kok et al., 2017). Higher feed requirements for parity 1 and 2 cows, and four pregnancy stages were included to account for different feed requirements during pregnancy (Remmelink et al., 2016).

Body weights were assigned to parity 1 cows on their first milking day by a normal distribution with a mean of 540 kg and a standard

[1] Comorbidity was not directly included in the simulation model. However, it was indirectly accounted for in the general culling decisions so that an overall culling rate was attainable.

deviation of 6 kg. Thereafter, cows gained 0.13 kg per day until the end of their second lactation (based on Kok et al. (2017)).

2.3. Hoof disorders

Eight hoof disorders were modelled; five non-infectious and three infectious. The non-infectious hoof disorders include interdigital hyperplasia (HYP), overgrown hoof (OH), sole haemorrhage (SH), sole ulcer (SU) and white line disease (WLD). The infectious disorders include digital dermatitis (DD), interdigital dermatitis and heel horn erosion (IDHE), and interdigital phlegmon (IP). Infections and the dynamics of these disorders were modelled at hoof-level. However, cow-level infection risk factors were accounted for allowing individual variation in susceptibility. Non-infectious hoof disorders were modelled as environmental infections with the Greenwood model (Becker, 1989). Infectious hoof disorders, IDHE and IP, were also modelled as environmental infections, because, to our knowledge, there is no information on the transmission dynamics of IDHE and IP. Only DD was modelled as a contagious hoof disorder with the Reed-Frost model (Becker, 1989).

It was assumed that a hoof can hold only one disorder at a time since the dynamism between multiple disorders on the same hoof is not clearly understood. Therefore, a cow could have a maximum of four hoof disorders (one for each hoof) at a time. Once a cow received a hoof disorder, a mobility score was assigned at hoof-level. A hoof will remain with a disorder until it has fully cured, either spontaneously or following a successful treatment.

In our model, the hooves of cow i were defined by a set of properties and are represented by the hoof matrix Ω with $j \times k$ elements,

$$\Omega_i = \begin{pmatrix} j=1,k=1 & j=1,k=2 & j=1,k=3 & j=1,k=4 \\ j=2,k=1 & j=2,k=2 & j=2,k=3 & j=2,k=4 \\ j=3,k=1 & j=3,k=2 & j=3,k=3 & j=3,k=4 \\ j=4,k=1 & j=4,k=2 & j=4,k=3 & j=4,k=4 \\ j=5,k=1 & j=5,k=2 & j=5,k=3 & j=5,k=4 \\ j=6,k=1 & j=6,k=2 & j=6,k=3 & j=6,k=4 \\ j=7,k=1 & j=7,k=2 & j=7,k=3 & j=7,k=4 \\ j=8,k=1 & j=8,k=2 & j=8,k=3 & j=8,k=4 \end{pmatrix} \tag{2}$$

where j is the property of hoof k for cow i. Front and hind hooves are $k = (1,2)$ and $k = (3,4)$, respectively. Property $j = 1$ represents the state of the hoof (susceptible = 0, infected = 1); property $j = 2$ represents the hoof disorder (DD, HYP, IDHE, IP, OH, SH, SU and WLD); $j = 3$ represents the mobility score (score 1, 2, 3, 4, and 5); $j = 4$ is the day of mobility score progression (respective of hoof disorder; uniform distribution); $j = 5$ is the treatment day (uniform distribution) after successful detection, and $j = 6$ is the day of mobility score regression after successful treatment (respective of hoof disorder; uniform distribution). The remaining two properties are DD specific. Property $j = 7$ represents the DD infectious lesion class (0, 1, 2, 3, 4) and $j = 8$ is the sojourn time of the DD lesion (uniform distribution).

2.3.1. Infection dynamics

Environmental infections. Infections of all hoof disorders, except for DD, were modelled as environmental infections with the Greenwood model. This model is suitable for the infection processes of hoof disorders when little is known about their spread dynamics and occurrence. It assumes that the probability of a susceptible hoof becoming infected with a disorder is independent of the number of already infected hooves with the same disorder once the infectious agent is present in a population, due to its sufficient abundance in the environment. In the Greenwood model, the prevalence or the incidence rate represent the probability of a cow receiving a hoof disorder per time unit (Becker, 1989). Parameters estimated and used in the Greenwood model are denoted by the subscript ε.

The infection process began with first identifying the total number of susceptible cows in the previous time step t. Susceptible cows ($S_{\varepsilon,t-1}$) were defined as the number of cows with at least one susceptible hoof: $\sum_{i=1}^{\Theta}[\![\sum_{k=1}^{4}\Omega_{i,j=1,k,t-1} < 4]\!]$ in a herd of Θ cows. Second, the probability ($P_{\varepsilon,t}^{(\text{total})}$) of susceptible cows becoming infected was estimated: $\sum_{d=1}^{7}\gamma_{d,l,t}$ where a daily infection risk $\gamma_{d,l,t}$ for each hoof disorder d occurring in period $l = (1 = \text{pasturing}, 2 = \text{housing})$ was stochastically drawn from a PERT distribution. With parameters $S_{\varepsilon,t-1}$ and $P_{\varepsilon,t}^{(\text{total})}$ the number of cows that will become infected ($I_{\varepsilon,t}$) was estimated by the binomial process

$$I_{\varepsilon,t} = B\left(S_{\varepsilon,t-1}, P_{\varepsilon,t}^{(\text{total})}\right). \tag{3}$$

Next, a bootstrap sample of length $I_{\varepsilon,t}$ was drawn from the vector of hoof disorders $D = (\text{HYP, IDHE, IP, OH, SH, SU, WLD})$ according to their relative risks of $\gamma_{d,l,t}$. We denote the bootstrap sample of disorders as $\overline{D}_t$ such that $\overline{d}_t \in \overline{D}_t$. With $\overline{D}_t$ disorders that infect $I_{\varepsilon,t}$ cows, the susceptibility of each cow is adjusted by the product of cow-level risk factors (i.e. parity, lactation stage, RPL and the number of susceptible hooves) corresponding to each $\overline{d}_t$. To calculate the cow-level risk factors, first parity cows in the first 30 days of lactation with a RPL between 41% and 60% were taken as the reference risk category. We included four parity risk factor classes (1, 2, 3, ≥4), four lactation stage, expressed as days in milk, risk factor classes (≤30, 31–60, ≥61 and dry) and five RPL classes (≤20%, 21–40%, 41–60%, 61–80% and >80%). A risk factor regarding the number of susceptible hooves was included to ensure that cows with one susceptible hind hoof were at less risk than cows with two susceptible hind hooves so that the proportional ratio of front to hind hooves infected with a disorder would approximately be 10%:90%, respectively (Alvergnas et al., 2019). The risk factor concerning the number of susceptible hooves for cow i was derived by summing the risk factors associated with each susceptible hoof k. The probability of a susceptible cow becoming infected with each $\overline{d}_t$ is then

$$P_{\varepsilon,\overline{d},i,l,t}^{(\text{infect})} = \gamma_{d,l,t} \times \prod_{r=1}^{4}\lambda_{d,i,r} \tag{4}$$

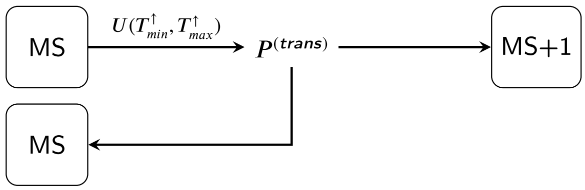
where $P_{\varepsilon,\overline{d},i,l,t}^{(\text{infect})}$ is the probability of susceptible cow i becoming infected with disorder $\overline{d}$ in time-step t of period l, $\gamma_{d,l,t}$ is the daily risk of infection for disorder d corresponding to $\overline{d}$, λ is the risk factor associated with susceptible cow i and disorder d corresponding to $\overline{d}$ and r is one of the four risk factors. Finally, a cow was then randomly selected according to the probability of infection in Eq. (4) by a sample distribution to be infected with $\overline{d}_t \in \overline{D}_t$. Once cow-level processes are completed and a susceptible cow for $\overline{d}_t \in \overline{D}_t$ was selected, a susceptible hoof k for each selected cow i was drawn from a sample of susceptible hooves according to their relative risks and the corresponding first two properties in Ω are updated such that the state of hoof k was infected with disorder $\overline{d}$:

$$\Omega_{i,j=1,k} = 1 \tag{5a}$$

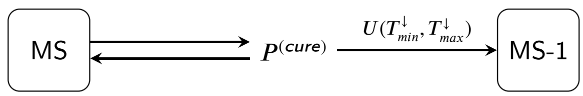
$$\Omega_{i,j=2,k} = \overline{d}. \tag{5b}$$

Contagious infections. Hooves that escaped an environmental infection in the current time-step were then subjected to the probability of becoming infected with DD. The Reed-Frost model was used to simulate this process where the probability of a susceptible hoof becoming infected with DD was dependent on the number of already infected hooves in the herd and the spread dynamics of the disease is explained by β (Becker, 1989). Throughout this subsection the parameters estimated and used in the Reed-Frost model are denoted by the subscript φ.

Unlike in the Greenwood model, the infection process of hooves occurred directly at the hoof-level since only one disorder was of concern. Consequently, more than one susceptible hoof per cow had the probability of becoming infected with DD in time-step t. The probability of a hoof becoming infected with DD was then calculated as follows



(a) Mobility score progression dynamics after infection.



(b) Mobility score regression dynamics after intervention.

Fig. 1. Diagram of the mobility score (MS) dynamics. In (a), the duration of each mobility score and the probability of transitioning to a succeeding score will continue until a mobility score 5 is reached unless a mobility score transition does not occur to which the hoof will no longer be subject to mobility score progression processes. In (b), mobility scores will regress until a mobility score 1 is reached after successful intervention. If intervention is unsuccessful the mobility score will remain.

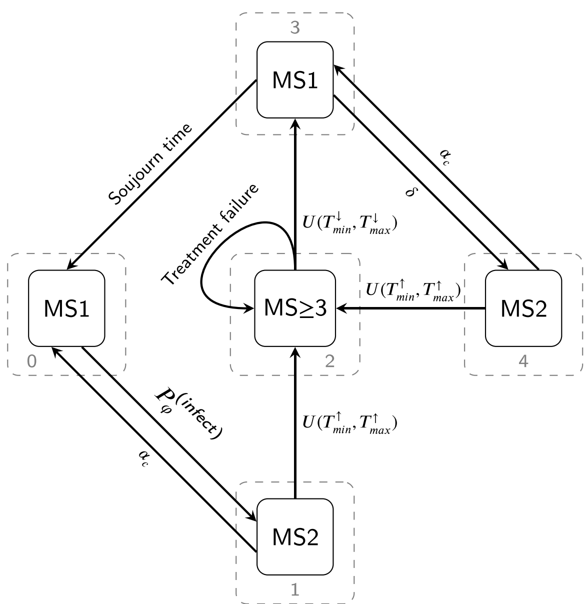


Fig. 2. Diagram of the mobility score (MS; solid lined nodes) dynamics with respect to the modelled digital dermatitis infectious lesion classes (m; dashed lined nodes).

$$P^{(\text{infect})}_{\varphi,i,k,t} = 1 - \exp\left(\frac{-\left(\sum_{m=1}^{4} \beta_m \times \eta \times I_{\varphi,m,t-1}\right) \times \prod_{r=1}^{4} \lambda_{i,k,r}}{N_{\varphi,t-1}}\right) \tag{6}$$

where $P^{(\text{infect})}_{\varphi,i,k,t}$ is the probability of infection for cow i with susceptible hoof k in time step t. Hooves infected with DD can go through multiple infectious lesion classes resulting in more than one β denoted by $m = (1, 2, 3, 4)$ (Biemans et al., 2018). The parameter $I_{\varphi,m,t-1}$ is the number of infected hooves with infectious lesion class m from the previous time-step: $\Sigma_{i=1}^{\Theta}\Sigma_{k=1}^{4}[\![\Omega_{i,j=7,k,t-1} = m]\!]$. Variation in the susceptibility for each susceptible hoof k of cow i was adjusted by the product of risk factors λ as described in the infection process of the Greenwood model except that the risk factors associated with front and hind hooves are no longer summed. By including risk factors, variation in the susceptibility of individual cows was accounted for but scaled the β's to the extent that the probability of infection and resulting trends of DD became unrealistic. Therefore, we included a calibration factor η that allowed the scaling of each β maintaining the relative ratio between the respective β's such that realistic infection rates and disorder trends would hold while still allowing for the effect of varied susceptibility between individuals. Lastly, the denominator $N_{\varphi,t-1}$ is the total number of hooves in the previous time-step. With $P^{(\text{infect})}_{\varphi,i,k,t}$ each susceptible hoof was then subject to this probability of becoming infected by a binomial process

$$\Omega_{i,j=1,k,t} = B\left(1, P^{(\text{infect})}_{\varphi,i,k,t}\right). \tag{7}$$

For each hoof that succumbed to a DD infection, the following properties $j = (2,\ 7)$ of infected hoof k were updated accordingly

$$\Omega_{i,j=2,k} = \text{DD} \tag{8a}$$

$$\Omega_{i,j=7,k} = 1. \tag{8b}$$

2.4. Mobility scores

The effect of hoof disorders on cow mobility were described by mobility scores. We used the 5-point ordinal scale mobility scoring method developed by Sprecher et al. (1997) where cows were scored 1 (optimal mobility) to 5 (severe SOM). A cow with a mobility score $\geq$2 is defined as sub-optimally mobile: a cow with SOM. Ultimately, mobility scores were expressed at the cow level, albeit certain processes were first modelled at hoof-level allowing the dynamics of hoof disorders and the consequential effects on cow mobility to be established. Each hoof of a cow will have its own mobility score where the maximum score between each of a cow's four hooves defines the cow-level mobility score. Modelling the dynamics of mobility scores is described in the following subsections.

2.4.1. Mobility score progression

Following an infection with any of the eight hoof disorders, a hoof was immediately assigned a mobility score 2 (Eq. (9a)). The hoof will hold a mobility score 2 until a random day scheduled by a stochastic draw from a uniform distribution (Eq. (9b))

$$\Omega_{i,j=3,k} = 2 \tag{9a}$$

$$\Omega_{i,j=4,k} = U(T^{\uparrow}_{\text{min},s,d}, T^{\uparrow}_{\text{max},s,d}) + t \tag{9b}$$

where $T^{\uparrow}_{\text{min},s,d}$ and $T^{\uparrow}_{\text{max},s,d}$ are the minimum and maximum transition intervals of T days from time-step t for mobility score s and disorder d, and the superscript $\uparrow$ denotes mobility score progression. For DD, $\Omega_{i,j=8,k} = \Omega_{i,j=4,k}$ will hold.

We assume that after infection the progression of mobility scores occurred in an ordered manner as illustrated in Fig. 1a. A hoof will hold a mobility score for a minimum number of days until $t = \Omega_{i,j=4,k}$, thereafter the probability of transitioning to a succeeding score was estimated with following equation

$$P^{(\text{trans})}_{i,k,t} = \Lambda^{(\text{ms})}_{i,k,s,t-1} \times \prod_{r=5}^{7} \lambda_{i,k,r} \tag{10}$$

where $P^{(\text{trans})}_{i,k,t}$ is the probability of hoof k for cow i to transition into a succeeding mobility score in time-step t, $\Lambda^{(\text{ms})}_{i,k,s,t-1}$ is the base risk of transitioning to a succeeding mobility score for cow i with hoof k and mobility score s in the previous time-step t, $\lambda_{i,k,r}$ is a risk factor and r one of the risk factors. With $P^{(\text{trans})}_{i,k,t}$ the probability of a hoof transitioning into a succeeding mobility score was then predicted by a binomial process

$$\Omega_{i,j=3,k,t} = B\left(1, P^{(\text{trans})}_{i,k,t}\right) + \Omega_{i,j=3,k,t-1}. \tag{11}$$

If hoof k progressed to a succeeding mobility score, Eq. (9b) was re-run.

Fig. 2 illustrates the dynamics associated with an infectious lesion class for a hoof infected with DD. As the mobility score of a hoof was updated (solid lined nodes in Fig. 2) the corresponding infectious lesion class (dashed lined nodes in Fig. 2; property $j = 7$) was updated accordingly. The process of mobility score progression continued until the maximum mobility score for hoof disorder d was reached. The hoof would then remain with this score until treated or cured spontaneously.

2.4.2. Intervention

Intervention of SOM occurred either by routine hoof trimming or by additional treatments. Routine hoof trimming was performed by a professional hoof trimmer who visited the farm at the start of each pasture and housing period. Hind hooves of every cow were trimmed by the hoof trimmer and exceptions were made for front hooves with a mobility score ≥3. Additional treatments occurred beyond hoof trimmer visits and followed SOM detection by the farmer during daily farm activities. Farmers are generally better at detecting cows with severe SOM compared to cows with mild SOM (Alawneh et al., 2012a); thus the probability of SOM detection was modelled as an exponential function to mimic an increased probability of detection with each day a cow was SOM as

$$P_{i,s,t}^{(\mathrm{detect})} = \phi_s \times \exp\left(\phi_s \times t_{i,t}^{(\mathrm{SOM})}\right) \tag{12}$$

where $P_{i,s,t}^{(\mathrm{detect})}$ is the probability of SOM detection for cow i with mobility score s as a function of the constant daily detection rate ϕ_s respective of mobility score s and $t_{i,t}^{(\mathrm{SOM})}$ is the duration in days that cow i is SOM from the onset of a mobility score 3. Modelling the probability of detection as an exponential function for each cow with SOM also ensures that it would not surpass a threshold duration of an undetected SOM period. The detection probability for a cow with SOM and a mobility score ≥3 was updated in each time-step t. A cow with SOM was then subject to the detection probability by a binomial process

$$\pi_{i,s,t} = B\left(1, P_{i,s,t}^{(\mathrm{detect})}\right) \tag{13}$$

where $\pi_{i,s,t}$ is the success outcome of detection for cow i experiencing SOM with mobility score s in time-step t.

Cows that were successfully detected by the farmer were then scheduled an intervention day respective of the mobility score they were detected with. An intervention day was stochastically drawn from a uniform distribution

$$\Gamma_{i,s} = U\left(\tau_{\min,s}, \tau_{\max,s}\right) + t \tag{14}$$

where $\Gamma_{i,s}$ is the intervention day for cow i with mobility score s, and $\tau_{\min,s}$ and $\tau_{\max,s}$ is the range of days it takes for intervention to occur after a cow with SOM and a mobility score s was detected. Since farmers are more likely to treat sooner if a cow is detected with a greater mobility score (Alawneh et al., 2012a), scheduled intervention days were updated accordingly if a cow progressed in a mobility score before the original intervention day had occurred. Once $\Gamma_{i,s}$ was determined, every hoof k of cow i with a hoof-level mobility score ≥3 was assigned an intervention day

$$\Omega_{i,j=5,k,t} = \Gamma_{i,s}. \tag{15}$$

A farmer may detect a cow with SOM and a mobility score 3, but treatment for these cows occurred only at the routine hoof-trimming. Cows with SOM and mobility score 4 that were detected by the farmer are assumed to be subsequently treated by the farmer. If the farmer detected cows with SOM and mobility score 5, the veterinarian was called to treat these cows. It was assumed that the veterinarian will also treat all cows with SOM and detected with a mobility score ≥4. On the treatment day where $\Omega_{i,j=5,k} = t$, hoof k was treated with a treatment type specific to the hoof disorder $\Omega_{i,j=2,k}$. The outcome of treatment then determined the mobility score regression dynamics.

2.4.3. Mobility score regression

The regression of mobility scores correspond to recovery and will succeed successful intervention ($P^{(\mathrm{cure})}$ in Fig. 1b), or spontaneous cure (DD only; α_c in Fig. 2). After successful intervention, a mobility score regression day (property $j = 6$) was scheduled for the successfully treated hoof by a stochastic draw from a uniform distribution respective of disorder the hoof was infected with

$$\Omega_{i,j=6,k} = U(T_{\min,s,d}^{\downarrow}, T_{\max,s,d}^{\downarrow}) + t \tag{16}$$

where $T_{\min,s,d}^{\downarrow}$ and $T_{\max,s,d}^{\downarrow}$ are the minimum and maximum transition intervals of T days from time-step t for mobility score s and disorder d, and the superscript ↓ denotes mobility score regression. Once a mobility score regression day was scheduled, $\Omega_{i,j=3,k,t} = \Omega_{i,j=3,k,t-1} - 1$ will occur when $t = \Omega_{i,j=6,k}$, and consequentially a new mobility score regression day was set. This process occurred until the mobility score for hoof k was 1. Thereafter, the hoof fully recovered and was in a susceptible state and all properties excluding $j = 3$ were reset to zero. In the case that successful intervention did not occur, the hoof remained with a mobility score until successful intervention did occur (Fig. 1b).

2.5. Production effects

2.5.1. Milk yield

The expected daily milk yield for cows was adjusted by a mean percentage reduction of their expected daily milk yield per mobility score. This realised an actual daily milk yield for each cow respective of mobility score. The actual daily milk yield was calculated with the following equation

$$M_{i,s,t}^{(\mathrm{amy})} = M_{i,s,t}^{(\mathrm{emy})} \times \left(1 - M_s^{(\mathrm{myr})}\right) \tag{17}$$

where $M_{i,s,t}^{(\mathrm{amy})}$ is the actual milk yield produced by cow i with mobility score s in time-step t, and $M_s^{(\mathrm{myr})}$ is the daily percentage milk yield reduction for mobility score s.

2.5.2. Discarded milk

Cows that were treated with antibiotics respective of disorder d had their actual daily milk yield discarded for 5 days: $M_{i,d,s,t}^{(\mathrm{discard})} = M_{i,d,s,t}^{(\mathrm{amy})}$.

2.5.3. Feed

As previously described in Section 2.2, feed requirements are modelled as VEM and expressed as a function of daily FPCM yield. The impact of mobility scores on VEM was calculated by taking the difference between expected VEM, as a function of expected daily FPCM yield, and actual VEM, as a function of actual daily FPCM yield.

2.5.4. Reproduction

Mobility scores affected the reproductive performance of cows in two ways. The first effect was associated with oestrus detection by the farmer. Walker et al. (2008) reported that cows with higher mobility scores dedicated less time to oestrus behaviour when compared to cows with lower mobility scores. Thus, decreasing the probability of oestrus detection by the farmer. A reduced probability in oestrus detection was accounted for by including a relative risk of oestrus detection for each mobility score where a cow with a mobility score 1 was taken as the reference category. The outcome of oestrus detection $\left(\Psi_{i,s,t}^{(\mathrm{oest})}\right)$ for cow i with mobility score s in time-step t was estimated by a binomial process

$$\Psi_{i,s,t}^{(\mathrm{oest})} = B\left(1, \Lambda^{(\mathrm{oest})} \times \lambda_s^{(\mathrm{oest})}\right) \tag{18}$$

where $\Lambda^{(\text{oest})}$ is the base risk of oestrus detection and $\lambda_s^{(\text{oest})}$ is the relative risk of oestrus detection with respect to mobility score s.

The second effect of mobility scores on reproduction dealt with conception. Insemination took place after oestrus was successfully detected by the farmer. The probability of conception depended on the number of previous inseminations and mobility score. Alawneh et al. (2011) found that cows with mobility scores ≥3 were less likely to conceive compared to cows with mobility scores ≤2. Since it is unclear how the specific mobility scores ≥3 effect conception, conception was scaled by relative risks associated with mobility scores ≥3 that were drawn from a PERT distribution. The probability of conception was calculated with

$$P_{i,s,t}^{(\text{conc})} = \Lambda_{i,n,t}^{(\text{conc})} \times \text{PERT}\left(\lambda_{\text{min},s}^{(\text{conc})}, \lambda_{\text{med},s}^{(\text{conc})}, \lambda_{\text{max},s}^{(\text{conc})}\right) \tag{19}$$

where $P_{i,s,t}^{(\text{conc})}$ is the probability of conception for cow i with mobility score s in time step t, $\Lambda_{i,n,t}^{(\text{conc})}$ is the base risk of conception respective of the nth insemination, and $\lambda_{\text{min},s}^{(\text{conc})}$, $\lambda_{\text{med},s}^{(\text{conc})}$ $\lambda_{\text{max},s}^{(\text{conc})}$ are the minimum, median and maximum relative risks used in the PERT distribution. Finally, the outcome of a successful conception is then determined by a binomial process

$$\Psi_{i,s,t}^{(\text{conc})} = B\left(1, P_{i,s,t}^{(\text{conc})}\right) \tag{20}$$

where $\Psi_{i,s,t}^{(\text{conc})}$ is the conception outcome.

2.5.5. Culling

The effect of mobility scores on culling occurred indirectly or directly. Indirect culling due to mobility scores occurred in the form of fertility related culling due to the impact of mobility scores on a cow's reproductive performance. In the case that a mobility score impacted the reproductive performance of a cow, the cow's conception period was lengthened. A longer conception period resulted in an increased risk of culling. Direct culling due to mobility scores occurred when a cow was ultimately culled for SOM, respective of SOM severity. The culling of a cow with SOM is based on a daily probability where the general culling rate was taken as the base risk and scaled by mobility score, parity and relative production level risk factors. Cows that were subject to culling were immediately removed on the day of culling. Furthermore, a culling rule based on a maximum number of additional treatments per lactation was assumed. A cow needing an additional treatment that would result in this maximum additional lactational treatment threshold being surpassed would be culled. We assumed a maximum of 3 additional lactational treatments.

2.6. Economic calculations

In order to calculate the net partial economic result for a farm, the economic in- and outflows were first calculated for each cow i with mobility score s in time-step t. The economic inflow is actual milk returns and the economic outflows are the costs concerning milk yield losses, discarded milk, feed, insemination, culling, hoof trimming, veterinary services, labour and additional treatments. The descriptions for each economic flow are described in the subsequent subsections.

2.6.1. Milk returns

Actual milk returns are based on the actual milk yield and was calculated with the following equation

$$R_{i,s,t}^{(\text{milk})} = M_{i,s,t}^{(\text{amy})} \times M^{(\text{price})} \tag{21}$$

where $R_{i,t}^{(\text{milk})}$ is the actual milk returns for cow i with mobility score s in time-step t and $M^{(\text{price})}$ is the milk price per kilogram of milk.

2.6.2. Milk yield loss

The cost of milk yield losses is based on the loss in expected milk yield due to a mobility score and is calculated with the following equation

$$C_{i,s,t}^{(\text{milk})} = \left(M_{i,s,t}^{(\text{emy})} - M_{i,s,t}^{(\text{amy})}\right) \times M^{(\text{price})} \tag{22}$$

where $C_{i,\text{st}}^{(\text{milk})}$ is the cost of milk yield losses for cow i with mobility score s in time-step t.

2.6.3. Discarded milk

The cost of discarded milk was calculated with the following equation

$$C_{i,s,t}^{(\text{discard})} = M_{i,s,t}^{(\text{discard})} \times M^{(\text{price})} \tag{23}$$

for cow i with mobility score s in time-step t.

2.6.4. Feed

Feed costs $\left(C^{(\text{feed})}\right)$ for each cow is based on the cost of VEM and a cows required VEM. Since VEM is dependent on $M^{(\text{amy})}$, feed costs are adjusted when the effect of mobility scores on milk production occurs.

2.6.5. Reproduction

Reproduction costs considered only the cost to inseminate a cow. The costs of insemination $\left(C^{(\text{ins})}\right)$ were accounted for on a per cow per insemination basis.

2.6.6. Culling

We calculated the cost of culling with a depreciation method (Steeneveld et al., 2019). Using a depreciation method allows for a more accurate assessment of the net worth of a farming operation and accrual adjusted income. Dairy cows are treated as capital that diminish in value over time. In other words, cows are culled at the end of their production life because they are no longer fit to produce. We used expected number of lactations instead of years of production life. For this depreciation method to work, the rearing costs, or purchase price of a replacement heifer, less the cull value of the cow is depreciated over its expected number of lactations. A cow needs to accumulate this depreciation at the end of its expected number of lactations so that the cull value is fully realised. If a cow is culled before completing the expected number of lactations, the cull value of the cow will not be realised and a capital loss is incurred, which is treated as a culling cost.

Replacement heifer rearing costs were sampled from a PERT distribution and averaged by the number of required replacement heifers. The revenue received for a culled cow was calculated by multiplying the slaughter weight of the cow with the slaughter price per kilogram. The slaughter weight was based on an average 60% carcass dressing of a cow's body weight (Rutten et al., 2014). The body weight of the cows that were culled for SOM reasons had their body weight decreased by an adjustment factor drawn from a PERT distribution (Alawneh et al., 2012b). The slaughter price per kilogram of slaughter weight was estimated by taking the mean of first to third grade slaughter cow prices (Wageningen Economic Research, 2020) sampled on the day of culling with a sample size equal to the number of culled cows. The cost of culling was calculated with the following equation

$$C_{i,s,t}^{(\text{cull})} = \frac{C_t^{(\text{rear})} - R_{i,s,t}^{(\text{cull})}}{L} \times \left(L - \left[\left(\text{Par}_{i,t} - 1\right) + \frac{M_{i,s,t}^{(\text{dim})}}{M_{i,s,t}^{(\text{end})}}\right]\right) \tag{24}$$

where $C_{i,t}^{(\text{cull})}$ is the cost of culling cow i with mobility score s in time step t, $C_t^{(\text{rear})}$ is the average of the rearing costs for the replacement heifers, $R_{i,s,t}^{(\text{cull})}$ is the revenue received for the culled cow i with mobility score s in

Table 1
Parameters used for the infection dynamics of hoof disorders. All parameters are implemented in daily time-steps.

Parameter	Description	Hoof disorder (d)[a]	Value	Lower bound	Upper bound	Source
γ	Risk of receiving disorder in period l[b, c]	HYP	4.63e–4; 4.12e–4	3.16e–4; 2.88e–4	5.85e–4; 5.56e–4	Somers et al. (2003), van der Spek et al. (2013), DigiKlauw (2020)
		IDHE	1.72e–5; 7.18e–4	1.44e–5; 7.18e–5	3.59e–4; 1.22e–3	
		IP	3.84e–4; 3.84e–4	1.28e–12; 1.29e–12	1.66e–3; 1.66e–3	
		OH	5.48e–5; 5.48e–5	5.48e–13; 5.48e–13	5.48e–5; 5.50e–5	
		SH	3.97e–3; 3.42e–4	1.78e–4; 1.10e–4	1.16e–3; 1.16e–3	
		SU	4.79e–4; 3.64e–4	3.16e–4; 3.07e–4	9.59e–4; 9.59e–4	
		WLD	6.58e–4; 1.13e–3	3.78e–4; 1.32e–4	1.32e–3; 1.64e–3	
β	Transmission rate[d]	DD	1.14e–3; 2.77e–3; 2.91e–3; 2.29e–2	–	–	Biemans et al. (2018)
δ	Probability of reinfection[e]	DD	0.0167	–	–	Döpfer et al. (2012)
α_c	Probability of spontaneous cure	DD[f]	1.04e–2; 3.71e–3	–	–	Biemans et al. (2018)
η	Calibration factor	DD	1.4	–	–	Calibrated input

[a] HYP = interdigital hyperplasia; IDHE = interdigital dermatitis/heel horn erosion; IP = interdigital phlegmon; OH = overgrown hoof; SH = sole haemorrhage; SU = sole ulcer; WLD = white line disease; DD = digital dermatitis.
[b] Ordered as pasturing (l = 1), housing (l = 2).
[c] Risk of receiving disorder is estimated by a PERT distribution, i.e. PERT (a = lower bound, b = mean, c = upper bound).
[d] Ordered as infectious class 1; 2; 3; 4.
[e] From DD lesion class 4 to 2.
[f] From DD lesion class 1 to 0; 4 to 3.

Table 2
Risk factors associated with mobility score transitions.

Risk factor (λ)	Mobility score	Class	Base risk	Relative risk	Source
$\Lambda^{(ms)}$[a]	2	–	0.15	–	Based on Frankena et al. (2009)
	3	–	0.083	–	
	4	–	0.03	–	
Parity $r = 5$		1	–	1	Reader et al. (2011)
		2	–	1.61	
		3	–	1.91	
		>3	–	2.03	
DIM[b] $r = 6$		<60	–	1.05	O'Connor et al. (2020a)
		60–120	–	1.9	
		>120	–	1	
		Dry	–	1	
RPL $r = 7$		<33.3%	–	1	O'Connor et al. (2020a)
		33.3–66.6%	–	1.22	
		>66.6%	–	1.4	

[a] Risk of transition from mobility score.
[b] Days in milk.

time step t, L is the expected number of lactations, $\mathrm{Par}_{i,t}$ is the parity of cull cow i in time step t, $M_{i,t}^{(\mathrm{dim})}$ is the day in milk for cull cow i in time step t and $M_{i,t}^{(\mathrm{end})}$ is the end day of milking for cull cow i in time step t of the current lactation. In summary, annual cow depreciation is reflected in the fraction on the left of the multiplication sign and the number of incomplete lactations is reflected within the round parentheses on the right of the multiplication sign. Mortality related culling costs were accounted for with a revenue of €0 and disposed of with a €39/cow cost.

2.6.7. Hoof trimmer

The hoof trimmer trimmed hooves twice a year. All hind hooves were trimmed and only front hooves with a mobility score ≥3. Hoof trimming costs $\left(C^{(\mathrm{ht})}\right)$ were estimated per trimmed hoof. These costs include treatments costs if hooves had a disorder.

2.6.8. Veterinary services

Costs for veterinary services $\left(C^{(\mathrm{vet})}\right)$ are estimated per cow considering the costs for the call out fee $\left(C^{(\mathrm{cof})}\right)$, the number of cows requiring veterinary assistance, hourly rate of the veterinarian $\left(C^{(\mathrm{vrate})}\right)$, the time spent ushering a cow into the trimming chute $\left(V^{(\mathrm{usher})}\right)$ and treatment time $\left(V^{(\mathrm{treat})}\right)$. Treatments per disorder and the associated costs are recorded as veterinary related treatment costs.

2.6.9. Labour

Labour costs $\left(C^{(\mathrm{labour})}\right)$ due to treating cows with SOM were only accounted for when the farmer was required to treat them. These costs were estimated on a per cow basis considering the time it would take to usher a cow with SOM into the trimming chute $\left(F^{(\mathrm{usher})}\right)$, the time to treat a hoof $\left(V^{(\mathrm{treat})}\right)$ and the hourly wage rate of the farmer $\left(C^{(\mathrm{frate})}\right)$. Treatments per disorder and the associated costs were recorded as farmer related treatment costs.

2.6.10. Additional treatments

The cost of additional treatments $\left(C^{(\mathrm{treat})}\right)$ concern all treatments applied by either the veterinarian or the farmer respective of hoof disorder. An exception for an additional treatment of HYP was made where only the veterinarian treated this hoof disorder since a claw-amputation was required. As a result, more time than $V^{(\mathrm{treat})}$ was needed to treat this

Table 3
Farmer detection and intervention parameters with respect to mobility scores.

Parameter	Description	Mobility score				Source
		2	3	4	5	
ϕ	Constant daily detection rate	0	0.014	0.1	0.5	Based on Alawneh et al. (2012a)
τ_{min}	Minimum days to intervene	–[a]	–	1	1	Authors' expertise
τ_{max}	Maximum days to intervene	–	–	21	3	

[a] – implies that a farmer will not intervene nor call a veterinarian for cow with these scores and rather wait until the routine hoof trimming carried out by the hoof trimmer.

disorder and the associated cost of HYP treatment by the veterinarian was adjusted by a time factor.

2.7. Model parameterisation

Input parameters are tabulated in Tables 1–4 (and Tables A1–A10 in Appendix A) and were derived from the most recent and available literature. Input parameters were chosen in such a way to represent the Dutch situation as much as possible. This was done by choosing, where possible, input parameters with respect to Dutch research first. The next best alternatives of input parameters considered research conducted in countries with similar dairy production systems such as the UK and Germany. Lastly, input parameters that were needed but were not associated with the aforementioned countries were finally accepted. Expert opinion was relied upon for input parameters that were not at all available in the literature. Inputs regarding risk factors reported in the literature as odds ratios were converted to relative risks depending on the information and methods used to derive the odds ratios as described in the respective studies. Inputs associated with mobility scores described by scoring methods that were not the method of Sprecher et al. (1997) were adapted according to the definition of scores best fitting that of the mobility scoring method of Sprecher et al. (1997).

Table 1 details the hoof disorder infection inputs. Inputs with respect to the modelled non-infectious hoof disorders (i.e. γ) were based on the prevalence estimates from the relevant literature and unpublished data from DigiKlauw (2020). With respect to DD, Biemans et al. (2018) described five infectious lesion classes (M1, M2, M3, M4, M4.1). We collapsed M3 and M4 into one class since they are considered as latent infections that are assumed to have a similar effect on mobility and because their transmission rates differed by 1.4×10^{-4}. This resulted in four infectious lesion classes (***m***; Biemans et al., 2018).

To the best of our knowledge, little information exists on the dynamics of mobility scores. Therefore, the risk in transitioning from one mobility score to a succeeding score ($\Lambda^{(ms)}$) was based on the prevalence and incidence of mobility scores reported by Frankena et al. (2009) and Tadich et al. (2010). O'Connor et al. (2020a) reported associations between lactation stage and mobility scores; to account for the progression of mobility scores given the lactation stage we shifted these relative risks

Table 4
Economic inputs and parameters used for economic variable computations.

Parameter	Default input(s)	Description	Source
$M^{(price)}$	0.3502	Average monthly milk price (€/kg) for the years 2016–2020	Wageningen Economic Research (2020)
$C^{(kVEM)}$	0.1766	Average monthly cost of supplements (€/kVEM) for the years 2019–2020	Wageningen Livestock Research (2020)
$C^{(HT)}$	3.5	Cost of hoof trimmer adapted to a per hoof basis (€/hoof)	Blanken et al. (2016)
$C^{(ins)}$	12.85	Cost per insemination (€/insemination)	Blanken et al. (2016)
Culling			
L	6	Expected minimum number of lactations	Authors' expertise
$C^{(rear)}$	PERT (919; 1790; 3307)	Rearing costs per replacement heiffer (€/heifer)	Nor et al. (2015)
$P^{(dress)}$	0.6	Carcass dressing; factor of live body weight	Rutten et al. (2014)
$R^{(kg)}$	sample (2.77, 2.44, 2.06)	Sample price received (€/kg) for first to third grade slaughter cows; average monthly prices for the years 2016–2020	Wageningen Economic Research (2020)
$P^{(bw.adj)}$	PERT (0.81; 0.83; 0.88)	Adjustment factor for the live body weight of cows culled for SOM	Based on Alawneh et al. (2012b)
Labour			
$C^{(frate)}$	30.7	Farmer hourly wage rate (€/h)	Blanken et al. (2016)
$F^{(usher)}$	10	Time for farmer to usher cow into hoof trimming chute (min/cow)	Authors' expertise
$F^{(treat)}$	10	Time for farmer to treat hoof (min/hoof)	Authors' expertise
Veterinarian			
$C^{(cof)}$	31.35	Call out fee (€/visit)	Expertise
$C^{(vrate)}$	139.2	Veterinarian hourly rate (€/h)	Expertise
$V^{(usher)}$	10	Time for veterinarian to usher cow into hoof trimming chute (min/cow)	Authors' expertise
$V^{(treat)}$	10	Time for veterinarian to treat hoof (min/hoof)	Authors' expertise
Treatments			Expertise
$C^{(SH)}$; $C^{(SU)}$; $C^{(WLD)}$	8.1		
$C^{(IP)}$; $C^{(IDHE)}$	0.6		
$C^{(DD)}$	2.61	Additional treatment costs (€) per disorder per hoof applied by either veterinarian or farmer	
$C^{(OH)}$	0		
$C^{(HYP)}$ [a]	182.02[b]; 0[c]		

[a] Only differences between costs for veterinarian and farmer deal with interdigital hyperplasia (HYP) since only a veterinarian will perform a clawamputation; high costs account for the time involved for this procedure and zero additional treatment costs are incurred by the farmer.
[b] Veterinarian treatment costs.
[c] Farmer treatment costs.

back by one class (Table 2). The interval between mobility score transitions respective of hoof disorder are elicited from expert opinion (Table A7).

The constant daily detection rate (ϕ) was estimated by ensuring that a 100% probability of detection would occur after a reasonable number of days of transitioning into a respective score and were based on Alawneh et al. (2012a) and the authors' expertise. Cure rates reported in the literature are sparse with regards to specific hoof disorders. We adapted cure rates reported in the literature (i.e. Holzhauer et al., 2008a; Bruijnis et al., 2010) and relied on the authors' expertise (Table A8). Variation in cure rates due to cow characteristics and the duration of a hoof disorder was accounted for by including relative risks based on Reader et al. (2011) (Table A9).

The effect of mobility scores on production are detailed in Table A10. Production losses per mobility score were derived by taking the quotient of an average 305d yield production loss per mobility score reported by O'Connor et al. (2020b) and the fraction of a median duration of a SOM episode of a maximum mobility score output by the model. O'Connor et al. (2020b) reported that no production losses were associated with a mobility score 1 of the Agriculture and Horticulture Development Board (2020) scoring method; congruent to a mobility score 2 of Sprecher et al. (1997). To estimate the effect of mobility scores on milk production corrected for 305-day lactation we excluded the duration of mobility score 2. The effect of mobility scores on fertility was estimated by including relative risks of oestrus detection and conception; respective of mobility score. Walker et al. (2008) reported that cows with SOM dedicated 64% less of their time to oestrus behaviour compared with cows that were not SOM. Therefore, the relative risk of oestrus detection was incremented by -0.09 from 1 to 0.64 for cows with a mobility score 1 to 5 since it was assumed that cows with mobility score 1 are more easily detectable when in oestrus compared to cows with SOM and a mobility score 5. The relative risk of conception after successful oestrus detection, followed by insemination, is based on Alawneh et al. (2012a). The probability of culling due to mobility scores is the product of the general culling rate per parity and the relative risk of culling per mobility score where the general culling rate is taken as the base risk (Table A3 and A10).

The economic parameters are found in Table 4. Where monthly price data was available the average of the monthly price was taken as the default input.

2.8. Model calibration and validation

Model calibration was a necessary step in model development since inputs were drawn from various literature sources and expert opinion. Calibrated inputs were validated in five rounds of rational validation by the authors. This included outcome testing of various scenarios to test output credibility (i.e. setting certain parameters to 0 or 1); individual cows were tracked and traced in the output data; logical testing of processes through debugging modes allowing for the inspection of computations during a live simulation; and face validity were performed internally. External validation was performed through discussions with experts and by comparing certain model outputs with results reported in the literature and unpublished data.

2.9. Model outputs and simulation

Epidemiological outputs include prevalence and cumulative incidence of hoof disorders and mobility scores as well as the cumulative incidence of hoof disorders per mobility score at the cow-level for either daily, periodical or yearly time horizons. Daily prevalence of mobility scores at the cow-level further allow for outputs concerning the duration of SOM episodes. A SOM episode is defined as the period a cow is scored a mobility score ≥ 2 and the mobility score associated with this episode is the maximum mobility score of the episode. Four maximum mobility score SOM episode categories were defined as **MMSE2**, **MMSE3**, **MMSE4** and **MMSE5** accounting for maximum mobility scores 2–5, respectively. Mild forms of SOM are represented by **MMSE2**, **MMSE3** and severe forms by **MMSE4**, **MMSE5**.

Economic outputs include the economic in- and outflows per cow i per mobility score s in each time-step t. In turn, the difference between the sum of the economic inflows and the sum of the economic outflows represent the net partial economic results for a farm with a distribution of mobility scores and in turn a combined SOM prevalence. The net partial economic results reflect both the direct and indirect economic effects due to SOM for a farm. The economic effects due to SOM were evaluated during the economic analysis.

2.10. Economic analysis

In order to assess the mean total annual economic effect (Δ) due to SOM in a one year time horizon, the net partial economic results of two scenarios, each of 500 simulations, were compared. The first scenario ($z = 0$) was one where hoof disorders were absent and consequently SOM was also absent: a "without" scenario. The second scenario ($z = 1$) was one where hoof disorders were present and consequently SOM was also present: a "with" scenario. By this approach, the direct as well as the indirect economic effects due to SOM could be evaluated (Rushton, 2009).

Before obtaining Δ, three preceding procedures were conducted. First, for each of the 500 simulations ($y = 1, \ldots, 500$) in both scenarios, the economic in- and outflows for all cows during the one year time horizon were summed to obtain the annual total of each economic flow, respectively in Eqs. (25a) and (25b). With respect to the total annual economic outflows calculated with Eq. (25b) we denote $X = \{milk, discard, feed, ins, cull, ht, vet, labour, treat\}$ where $x \in X$ for notational convenience:

$$\mathrm{TR}^{(\mathrm{milk})}_{y,z} = \sum_{i=1}^{\Theta} \sum_{t=1}^{365} R^{(\mathrm{milk})}_{i,t,y,z} \tag{25a}$$

$$\mathrm{TC}^{(x)}_{y,z} = \sum_{i=1}^{\Theta} \sum_{t=1}^{365} C^{(x)}_{i,t,y,z} \tag{25b}$$

where $\mathrm{TR}^{(\mathrm{milk})}_{y,z}$ is the total annual actual milk returns and $\mathrm{TC}^{(x)}_{y,z}$ is the total annual economic outflow x in simulation y of scenario z.

Secondly, the net partial economic result was calculated with

$$\Upsilon_{y,z} = \mathrm{TR}^{(\mathrm{milk})}_{y,z} - \sum_{x=\mathrm{discard}}^{X} \mathrm{TC}^{(x)}_{y,z} \tag{26}$$

where $\Upsilon_{y,z}$ is the annual net partial economic result for simulation y of scenario z. To avoid double counting of the total costs in milk losses $\mathrm{TC}^{(\mathrm{milk})}_{y,z}$ was excluded from the summation of the total annual economic outflows because it had already been accounted for in $\mathrm{TR}^{(\mathrm{milk})}_{y,z}$ since $\mathrm{TR}^{(\mathrm{milk})}_{y,z}$ is based on actual milk returns.

Thirdly, the annual net partial economic results of the 500 simulations required for model convergence for both scenarios were then bootstrapped 1500 times, rendering $y = 1, \ldots, 750{,}000$ (i.e. 500×1500), before comparing the net partial economic results of both scenarios. Bootstrapping the annual net partial economic results ensured that an adequate comparison of all simulations would be achieved.

Lastly, a comparison of the annual net partial economic results for both scenarios was performed and Δ due to SOM was obtained with the following equation

$$\Delta = \frac{\sum_{y=1}^{750{,}000} \Upsilon_{y,0} - \Upsilon_{y,1}}{750{,}000} \tag{27}$$

where $\Delta > 0$ entails an economic loss and $\Delta < 0$ entails an economic

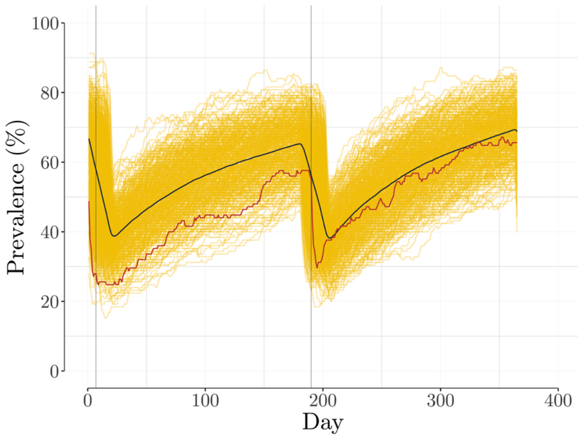


Fig. 3. Daily cow-level mobility score ≥2 prevalence. The figure depicts the mean daily prevalence (dark line) of the 500 iterations (yellow lines) and one random iteration (red line). The black vertical lines represent the median day of hoof trimmer visits in the pasturing and housing period at day 7 and 190, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Summary of mobility score mean prevalence (%) and SOM episode mean cumulative incidence per 100 cows per period rounded to 2 decimal points (5th and 95th percentiles shown in parentheses).

	Pasture period	Housing period
Mobility score	Prevalence	
1	45.37 (35.03; 57.33)	43.36 (32.94; 55.02)
2	33.43 (26.24; 40.52)	34.85 (28.14; 41.41)
3	20.33 (13.12; 27.44)	20.85 (13.91; 27.97)
4	0.85 (0.36; 1.45)	0.91 (0.39; 1.54)
5	0.02 (0.00; 0.08)	0.03 (0.00; 0.08)
SOM episode	Cumulative incidence	
MMSE2	33.66 (23.20; 46.00)	38.59 (28.80; 50.00)
MMSE3	16.38 (10.40; 23.00)	19.15 (12.00; 26.00)
MMSE4	7.07 (3.20; 11.00)	7.72 (4.00; 12.00)
MMSE5	0.65 (0.00; 2.00)	0.81 (0.00; 2.00)

gain. Δ is the total annual economic effect due to SOM, which includes both the direct and indirect economic effects due to SOM. We evaluated Δ further to gain insight on the distribution of the direct and indirect economic effects due to SOM.

The direct economic effects include economic outflows that are attributable to a SOM episode **MMSE2**–**MMSE5**. These are: the cost of direct milk yield losses ($C^{(\text{milk})}$), the cost of discarded milk ($C^{(\text{discard})}$), the cost of feed ($C^{(\text{feed})}$), the cost of culling for SOM reasons ($C^{(\text{cull})}$), the cost of hoof trimming ($C^{(\text{ht})}$), the cost of veterinary services ($C^{(\text{vet})}$), the cost of labour ($C^{(\text{labour})}$), and the cost of additional treatments ($C^{(\text{treat})}$). For convenience we introduce $\overline{X} = X \setminus \{\text{ins}\}$ where $\overline{x} \in \overline{X}$ to represent the direct economic outflows due to SOM. These direct economic outflows occurred only in the scenario when SOM was present (i.e. $z = 1$: the "with" scenario). This meant that a summation of these direct economic outflows during the year per SOM episode **MMSE2**–**MMSE5** obtained the total annual direct economic effect due to SOM per direct economic outflow. We denote $\text{DTC}^{(\overline{x})}_{e,y,1}$ as the total annual direct economic outflow $\overline{x}$ per SOM episode $e =$ (**MMSE2**, **MMSE3**, **MMSE4**, **MMSE5**) for simulation y in scenario $z = 1$.

The indirect economic effects include herd-level changes in the expected milk returns, changes in culling costs for non-SOM reasons and changes in insemination costs between scenarios $z = 0$ and $z = 1$. Because these economic flows occurred in both scenarios the annual totals of these economic flows per simulation were compared and are respectively described by Eqs. (28a)–(28c)

$$\text{ITR}^{(\text{milk})}_{y} = -\left[\left(\text{TR}^{(\text{milk})}_{y,1} + \text{TC}^{(\text{milk})}_{y,1}\right) - \text{TR}^{(\text{milk})}_{y,0}\right] \tag{28a}$$

$$\text{ITC}^{(\text{cull})}_{y} = \left(\text{TC}^{(\text{cull})}_{y,1} - \sum_{e=\text{MMSE2}}^{\text{MMSE5}} \text{DC}^{(\text{cull})}_{e,y,1}\right) - \text{TC}^{(\text{cull})}_{y,0} \tag{28b}$$

$$\text{ITC}^{(\text{ins})}_{y} = \text{TC}^{(\text{ins})}_{y,1} - \text{TC}^{(\text{ins})}_{y,0} \tag{28c}$$

where $\text{ITR}^{(\text{milk})}_{y}$ is the total indirect economic effect on total expected milk returns, $\text{ITC}^{(\text{cull})}_{y}$ is the total indirect economic effect on culling costs for non-SOM reasons and $\text{ITC}^{(\text{ins})}_{y}$ is the total indirect economic effect on insemination costs, for simulation y due to SOM.

2.11. Sensitivity analysis

A local sensitivity analysis was performed to assess the effect of parameter adjustments on the mean total annual economic loss due to SOM for the default scenario. This was performed by 206 parameter adjustments of the default parameter inputs (Tables 1–4 and A6 –A10). Parameters used for the infection dynamics of HYP, IDHE, IP, OH, SH, SU and WLD were independently increased and decreased by 25% in both periods. The DD transmission rate, probability of reinfection, and spontaneous cure were increased and decreased by 10 and 20%, and the calibration factor was adjusted by 5%. The transitional risk of mobility scores 2, 3, 4 and 5 were independently increased and decreased by 20%. Mobility score progression intervals respective of hoof disorder were doubled and halved. Cure rates of hoof disorders respective of mobility score were increased and decreased by 20% for farmer, hoof trimmer and veterinarian treatments. Relative risks were all increased and decreased by 20%, In addition, the relative risks with respect to the effect of mobility scores on oestrus detection together with conception were set to 1 so that they would not have an effect on reproductive performance. The detection constant for all scores was increased and decreased by 20%. The maximum number of days for the farmer to treat a cow with a mobility score 4 after successful detection was decreased to 11 and 7 days. Maximum additional lactational treatments was increased to 4, 5, and 7. The daily milk yield percentage loss for mobility scores 2, 3, 4, and 5 were each increased and decreased by 20%. For the milk and slaughter price per kg, minimum and maximum prices were approximately 20% of the respective means (Wageningen Economic Research, 2020). Therefore, the milk and slaughter price per kg were increased and decreased by 20%. For the rearing costs, minimum and maximum prices were already included in the PERT distribution for the default situation. Therefore, the entire distribution was shifted in either direction by 20%.

3. Results

Convergence was tested by running 1000 simulations for 10 years. Visual inspection of variance in total milk produced, totals of all hoof disorder incidence, total mobility score 3, 4 and 5 incidence and total number of cows culled showed that results stabilised at 500 simulations. Visual inspection of all daily hoof disorder and mobility score prevalence showed consistent trends from the beginning of the sixth year. Herd demographics with respect to parity distributions matching the initial inputs from the beginning of the sixth year implied that culling rates had also stabilised by this time. Hence, a 5 year burn-in period was warranted. After model convergence and the burn-in period was identified the following results were derived from a stable year simulation.

Fig. 3 depicts the daily prevalence of cows with SOM showing that the prevalence of these cows decreased twice during the year, which happened after routine hoof trimming. The mean daily prevalence of cows with SOM increased during the housing period from 38% at the start of the housing period (after hoof trimming) to 69% at the end of the

Table 6
Summary of mean hoof disorder cumulative incidence per 100 cows per period rounded to 2 decimal points (5th and 95th percentiles shown in parentheses).

Hoof disorder[a]	Pasture period	Housing period
DD	28.99 (7.20; 49.60)	29.42 (8.00; 51.20)
HYP	8.21 (4.76; 12.00)	7.34 (3.20; 12)
IDHE	3.19 (0.80; 5.60)	12.42 (7.96; 17.60)
IP	9.41 (4.80; 13.60)	9.50 (5.60; 13.60)
OH	1.31 (0.80; 2.40)	1.31 (0.80; 2.44)
SH	8.90 (4.76; 13.60)	8.00 (4.00; 12.80)
SU	9.30 (5.56; 13.60)	8.16 (4.80; 12.00)
WLD	12.70 (8.00; 17.60)	17.75 (12.00; 24.00)

[a] DD = digital dermatitis; HYP = interdigital hyperplasia; IDHE = interdigital dermatitis/heel horn erosion; IP = interdigital phlegmon; OH = overgrown hoof; SH = sole haemorrhage; SU = sole ulcer; WLD = white line disease.

Table 7
Mean hoof disorder prevalence per annual SOM episode cumulative incidence per 100 cows per year (5th and 95th percentiles shown in parentheses).

Hoof disorder[a]	SOM episode			
	MMSE2	MMSE3	MMSE4	MMSE5
DD	30.68 (7.47; 46.83)	33.91 (9.07; 54.49)	29.56 (0.00; 52.66)	24.98 (0.00; 100.00)
HYP	9.12 (5.49; 13.67)	8.74 (3.84; 14.48)	7.27 (0.00; 19.05)	–
IDHE	10.57 (6.73; 15.67)	10.06 (4.57; 16.67)	6.90 (0.00; 17.42)	5.51 (0.00; 50.00)
IP	9.57 (5.56; 14.03)	5.08 (1.23; 9.79)	22.43 (6.21; 40.00)	35.80 (0.00; 100.00)
OH	1.22 (0.00; 2.66)	–	–	–
SH	11.64 (7.26; 17.16)	10.91 (5.22; 18.45)	7.88 (0.00; 20.00)	4.89 (0.00; 50.00)
SU	9.59 (6.21; 14.20)	10.67 (4.80; 17.58)	9.09 (0.00; 20.00)	7.79 (0.00; 50.00)
WLD	17.62 (11.81; 24.81)	20.63 (12.67; 30.80)	16.87 (4.17; 32.13)	21.03 (0.00; 100.00)

[a] DD = digital dermatitis; HYP = interdigital hyperplasia; IDHE = interdigital dermatitis/heel horn erosion; IP = interdigital phlegmon; OH = overgrown hoof; SH = sole haemorrhage; SU = sole ulcer; WLD = white line disease.

housing period (before hoof trimming). Overall, the mean yearly prevalence of cows with SOM was 57% (45%; 68%).[2] Table 5 shows the mean prevalence of mobility scores and the cumulative incidence of SOM episodes per 100 cows per period. Both metrics showed that there were more cows with SOM during the housing period compared with the pasture period. Most of these cows had mobility scores 2 and 3, and **MMSE2** and **MMSE3** in both the pasture and housing periods. In contrast, there were fewer cows with severe SOM in both periods: mobility scores 4 and 5, and **MMSE4** and **MMSE5**. Despite the low prevalence of mobility score 5 and **MMSE5** cumulative incidence per period in both periods, they increased the most when moving from pasture to housing compared with the relative increase in mobility scores 2–4 prevalence and **MMSE2**–**MMSE4** cumulative incidence.

The median duration of SOM episodes in general was 80 (4; 365) days. **MMSE3** had the longest median duration of 134 (7; 365) days spending a median of 10 (1; 218) days with a mobility score 2 during the SOM episode. The median duration of **MMSE2**, **MMSE4** and **MMSE5** were shorter with 60 (4; 322), 53 (10; 365) and 44 (6; 365) days, respectively. The median duration of mobility score 4 of **MMSE4** lasted a median of 17 (2; 46) days and mobility scores 4 and 5 of **MMSE5** respectively lasted a median duration of 5 (1; 15) and 5 (2; 13).

The cumulative incidence per 100 cows per period for infectious hoof disorders increased during the housing period while it decreased for non-infectious hoof disorders, except for WLD (Table 6). Small differences were seen in the cumulative incidence per 100 cows per period between the pasture and housing period for most hoof disorders. The hoof disorders that showed the largest difference in cumulative incidence per 100 cows per period between the pasture and housing period were IDHE and WLD. Most hoof disorders had a cumulative incidence per 100 cows per period below 10 in both periods while WLD and DD were the only two hoof disorders with a cumulative incidence per 100 cows per period above 10. The DD cumulative incidence per 100 cows per period during both the pasture and housing periods was highest of all hoof disorders. Table 7 shows that the high DD cumulative incidence per 100 cows per period accounted for approximately a third of **MMSE2** (30%), **MMSE3** (33%) and **MMSE4** (29%) SOM episodes. Although the IP cumulative incidence per 100 cows per period in both periods were lower compared with DD (Table 6), IP accounted for most of the **MMSE5** SOM episodes (38%). Wide variations between 0 and 100% were seen in

Table 8
Mean total annual direct economic losses (€) due to SOM episodes (5th and 95th percentiles shown in parentheses).

Cost variable	SOM episode				Total
	MMSE2	MMSE3	MMSE4	MMSE5	
Milk production loss	0 (0; 0)	2580 (1714; 3399)	2055 (1159; 3161)	136 (0; 357)	4771 (3320; 6223)
Culling	700 (0; 2186)	454 (0; 1618)	1579 (0; 3703)	79 (0; 643)	2812 (626; 5482)
Discarded milk	429 (166; 707)	240 (70; 464)	200 (39; 387)	28 (0; 95)	898 (483; 1331)
Veterinary services	0 (0; 0)	0 (0; 0)	223 (0; 667)	222 (0; 594)	445 (0; 1217)
Labour	0 (0; 0)	0 (0; 0)	276 (148; 440)	5 (0; 20)	281 (154; 445)
Treatments	0 (0; 0)	0 (0; 0)	174 (59; 469)	19 (0; 49)	193 (68; 480)
Hoof trimmer	0 (0; 0)	18 (3; 41)	2 (0; 7)	0 (0; 0)	20 (3; 45)
Feed	0 (0; 0)	− 194 (− 255; − 129)	− 155 (− 239; − 87)	− 10 (− 27; 0)	− 360 (− 468; − 251)
Total	1129 (265; 2644)	3098 (1978; 4498)	4354 (0; 1368)	480 (0; 1459)	**9061 (5932; 12,983)**

[2] 5th and 95th percentiles of the 500 simulations are shown in parentheses.

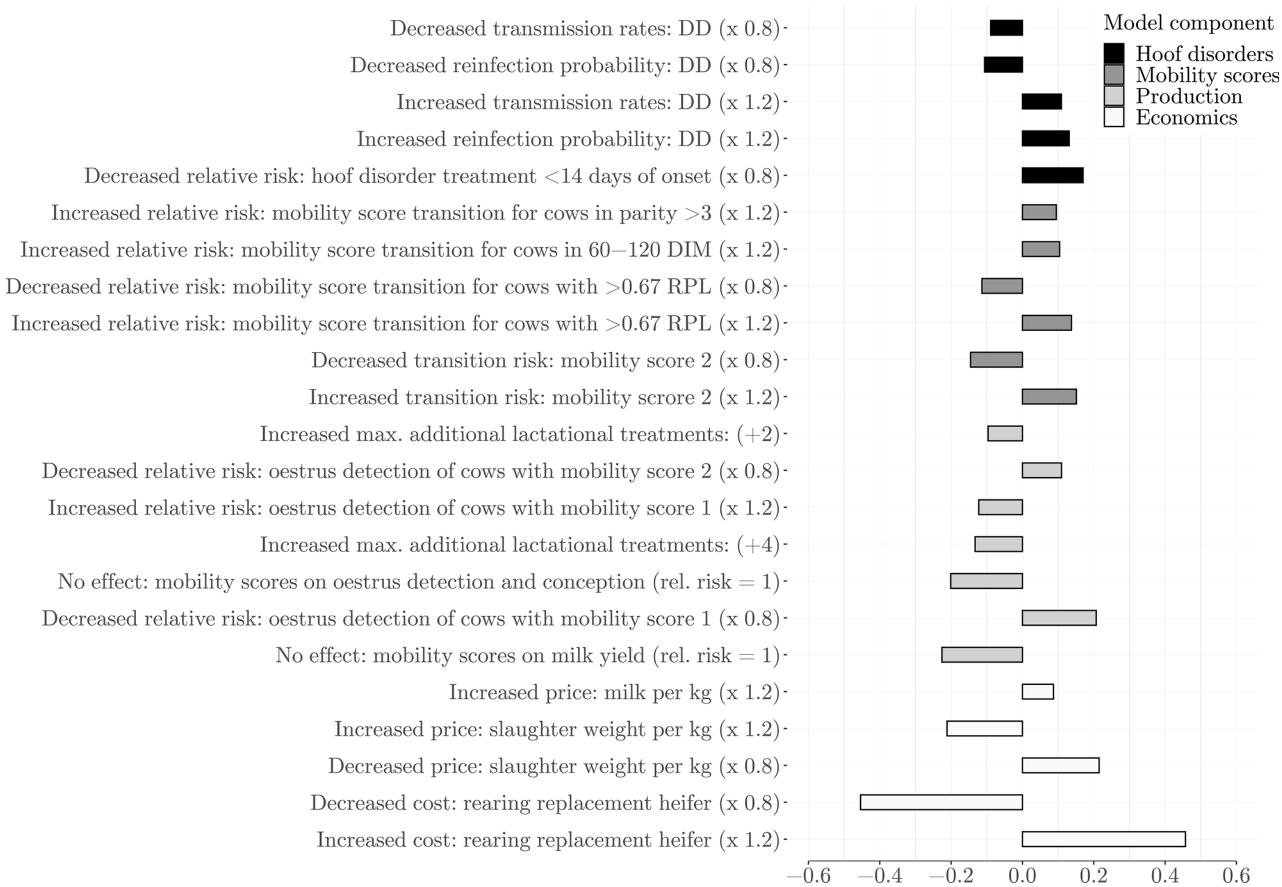


Fig. 4. Top 10% most important results from the sensitivity analysis, showing the positive or negative effect of parameter adjustments on the total annual economic loss due to SOM ordered by magnitude of effect per model component. The *y*-axis shows the important parameters with their respective adjustments in parentheses. The *x*-axis shows the relative effect of parameter adjustments on the total annual economic loss due to SOM.

the DD, IP and WLD prevalence of **MMSE5** cumulative incidence per 100 cows per period due to the low cumulative incidence per 100 cows per period of **MMSE5**.

Cows that had SOM during their conception period had on average 6 (− 23; 57) additional days to their first service compared with cows that were not SOM during their conception period. The number of additional days to the first service for cows with a maximum mobility score 2 during their conception period was 7 (− 23; 57) days compared with cows that had a maximum mobility score 1 during their conception period. The number of additional days to the first service increased linearly with each increase in maximum mobility score during the conception period to 25 (− 7; 76) days for cows with a maximum mobility score 5 during the conception period. Only 2 (0; 5) cows with a mobility score 1 during the conception period were culled due to fertility reasons. In contrast, 19 (12; 26) cows with a maximum mobility ≥2 were culled for fertility reasons: most with mobility scores 2 (42%) and 3 (47%). The mean number of cows culled for SOM reasons was 6 (2; 11). The total number of cows culled per mobility score for SOM reasons was on average 2 (0; 4), 1 (0; 3); 3 (0; 6) and 0 (0; 1) for mobility score 2–5, respectively. Milk yield losses of 270 (0; 704) and 181 (0; 437) kg for **MMSE4** and **MMSE5** were greatest, respectively. Cows experiencing **MMSE3** had an average milk yield loss of 86 (0; 270) kg and no milk yield losses occurred for cows experiencing **MMSE2**.

The mean total annual economic effect (Δ) due to SOM resulted in an annual economic loss of €15,342 (€2562; €28,904): an annual loss of €122 per average cow. Total annual production losses[3], expenditures[4] and labour contributed 96%, 2% and 2% to the total annual economic loss, respectively.

As shown in Table 8, the mean direct annual economic loss amounted to 59% of the mean total annual economic loss and was mostly composed of direct milk yield losses (52%) and culling (31%). A significant amount of the direct milk yield losses was due to **MMSE3** (54%) and **MMSE4** (43%), and for culling mostly due to **MMSE4** (56%). **MMSE3** and **MMSE4** SOM episodes during the year respectively contributed 34% and 48% to the mean direct annual economic loss.

The mean indirect annual economic loss was €6281 (€− 6174; €19,499). The largest contributor to the mean indirect annual economic loss was due to changes in culling costs for cows not directly culled as a result of SOM. This loss amounted to €4053 (€ − 2883; €11,373). The second largest indirect annual economic loss arose due to herd-level changes in the expected milk returns and amounted to €2185 (€ − 8242; €13,143). The third and last indirect annual economic loss was due to changes in insemination costs amounting to €43 (€ − 270; €360).

The sensitivity analysis showed that economic parameters concerning the cost of culling are important for the total annual economic loss due to SOM. Increasing replacement heifer rearing costs by 20% resulted in an increase of the total annual economic loss to €22,354 while reducing these costs resulted in €8379 (Fig. 4). A 20% increase and decrease for the price received per kg of slaughter weight for a culled cow respectively resulted in a decrease of the total annual economic loss

[3] Milk production losses, culling, discarded milk.

[4] Veterinary services, treatments, hoof trimming, inseminations and feed.

to €12,097 and increase to €18,640. In addition, the economic importance of culling due to SOM was shown by the sensitivity analysis in two ways. Firstly, allowing the maximum number of additional treatments in one lactation to be increased by 2 and then 4 treatment reduced the total annual economic loss to €13,862 and €13,305, respectively. Secondly, when mobility scores had no effect on oestrus detection and conception, by setting the respective relative risks to 1, less cows were culled for fertility reasons resulting in a reduced total annual economic loss of €12,257. Increasing and decreasing the transitional risk from a mobility score 2 respectively increased and decreased €17,662 and €13,110. Adjustments in the parameters concerned with only DD infection dynamics showed to have an important effect on the total annual economic loss due to SOM.

4. Discussion

The bio-economic simulation model we developed is the first to simulate the economic effect of all SOM episode severities in association with the incidence and dynamics of hoof disorders at hoof level, providing insight on the direct and indirect economic effect due to SOM. It includes two epidemiological modules, the Greenwood and the Reed-Frost model. This makes our model the first bio-economic model with respect to hoof disorders and SOM to simulate the incidence of infectious DD infections with a contagious disease spread module. Although our model includes other infectious hoof disorders (i.e. IDHE and IP), their incidence was modelled as environmental infections due to a lack in information pertaining to their transmission dynamics. As this information for these infectious hoof disorders become more available, they can be included in the contagious disease spread module.

The simulated mean annual prevalence of hoof disorders in our study was 58%, which is lower than the 80% prevalence previously reported by Somers et al. (2003). However, unpublished data from DigiKlauw (2020) showed that the prevalence of hoof disorders in the Netherlands has been decreasing since 2007 reaching a 55% prevalence in 2020. Despite this, the prevalence of hoof disorders in our study are longitudinal estimates that consider changes in hoof disorder prevalence after hoof trimming occurred. Whereas in practice, prevalence estimates are cross-sectional at the time of hoof trimming (DigiKlauw, 2020).

The routine hoof trimming showed visible positive effects as the prevalence of HYP, IDHE, IP, OH, SH, SU, and WLD decreased after hoof trimmer visits. The positive effect, however, were only short lasting since the prevalence increased quickly after hoof trimming. Consequently the prevalence of mobility scores $\geq$2 increased, which has also been observed by Frankena et al. (2009). On the other hand, a positive effect of hoof trimming on the prevalence of DD was not as clear. Small increases in DD prevalence occurred for approximately 3 months after hoof trimming in both periods before an observable decrease in DD prevalence occurred. This corresponds to the positive associations of DD prevalence and short hoof trimming intervals (<6 months) compared with longer hoof trimming intervals ($\geq$12 months) that have previously been observed (Holzhauer et al., 2006).

Parameterisation of the transitional risks between mobility score progression per hoof disorder was challenging due to a lack of relevant information. Therefore, a general transitional risk per mobility score was assumed irrespective of hoof disorder, while studies have shown that some hoof disorders are more prevalent in mild forms of SOM than in severe forms and vice versa (Tadich et al., 2010; Blackie et al., 2013). Despite this, the simulated results from our study showed that DD, IP, and WLD were the three most common hoof disorders that occurred with the severe **MMSE4** and **MMSE5** forms of SOM. These disorders also have previously been reported as the more common hoof disorders associated with severe SOM (Tadich et al., 2010; Charfeddine and Pérez-Cabal, 2017; Dolecheck et al., 2019). On the other hand, SU is often associated with higher mobility scores due to its large impact on a cow's gait (Tadich et al., 2010; Blackie et al., 2013) and this is not shown in our results. The general transitional risk between mobility scores and assuming that a hoof could not have more than one hoof disorder at a time could restrict the potential losses in production if the hoof disorder with highest prevalence had the lowest effect on mobility, thus the lowest impact on production, or vice versa. This demonstrates a limitation in the model. More information on the transitional risks between mobility scores respective of hoof disorders as well as hoof level comorbdities are needed to simulate these specific dynamics more accurately.

The annual distribution of mobility scores in our model corresponds with what has been previously reported (Frankena et al., 2009; Tadich et al., 2010; O'Connor et al., 2019). The annual prevalence of cows with SOM from our model was 56%. This is higher than the 17% found in The Netherlands (Amory et al., 2006), 20% found in Ireland (Somers et al., 2019) and 21% found in the UK (Randall et al., 2018). Our annual prevalence of cows with SOM is higher because we included mobility score 2 in our definition of SOM, whereas the aforementioned studies omit this mobility score in their definitions. When we omitted mobility score 2 from the annual prevalence of cows with SOM in our study the annual prevalence was 21%; corresponding to the aforementioned studies.

Other studies investigating the economic losses associated with hoof disorders exist (Willshire et al., 2009; Guard, 2008; Bruijnis et al., 2010; Cha et al., 2010; Charfeddine and Pérez-Cabal, 2017), but do not include the effect of hoof disorders on cow mobility. Therefore, comparing the economic losses of SOM episodes from our study with the economic losses of mild or severe hoof disorder cases reported in the aforementioned studies is difficult. However, results from our model show that culling and milk yield losses contribute the most to the total direct economic loss due to SOM. These results are in general agreement with other studies investigating the economic losses due to hoof disorders (Willshire et al., 2009; Guard, 2008; Bruijnis et al., 2010; Cha et al., 2010; Charfeddine and Pérez-Cabal, 2017).

Simulation studies that estimated the direct economic loss due to SOM have only considered severe SOM. The mean economic loss in our study for severe SOM episodes **MMSE4** and **MMSE5** were respectively €226 and €259 (a combined mean of €229). These results are higher than the estimated mean economic loss of €192 per SOM episode reported by Ettema and Østergaard (2006) but within the range of €185–€333 reported by Liang et al. (2017). New results from our model show that the costs associated with mild forms of SOM per **MMSE2** and **MMSE3** were respectively €13 and €49: significantly lower than the losses of **MMSE4** and **MMSE5**. However, these mild forms of SOM contribute 47% to the total direct economic loss due to SOM because of the high **MMSE2** and **MMSE3** incidence suggesting that previous studies underestimate the total direct economic losses due to SOM. In addition, these new calculations imply that the herd-level economic losses due to mild forms of SOM are no less important than those due to severe forms of SOM. This observation is supported by the results from the sensitivity analysis whereby adjustments made to the transitional risk from a mobility score 2 to a mobility score 3 increased the total annual economic loss by 15%. Cows with mild forms of SOM are treated during the routine hoof trimming that happens twice a year. Treating these cows on a more regular basis may help reduce the economic losses associated with mild SOM, reduce the number of cows transitioning to a mobility score 4 and increase cow welfare.

An interesting result of our study is the distribution of total annual economic losses of SOM. We discovered that the indirect economic losses due to SOM contributed 41% to the total annual economic loss, which is a substantial proportion. The economic analysis showed that changes in culling costs for non-SOM reasons and herd-level changes in expected milk returns were the most significant.

An increase in indirect culling costs due to culling for non-SOM reasons arose because of the effect that SOM had on reproductive performance (i.e. oestrus detection and conception). This meant that more cows on average were culled for fertility reasons before completing their expected number of lactations. This was confirmed in the validation rounds showing that there was no mean effect on the number of cows culled for fertility reasons in a scenario where SOM had no effect on reproductive performance compared with the "without" SOM scenario. Poor reproductive performance is often the primary cause of culling (Nor et al., 2014). However, culling is multi-factorial in practice and fertility related culling may be due to a culmination of health problems that lead to poor reproductive performance. Results from the "with" SOM scenario showed that most of the cows culled for fertility reasons had a maximum mobility score 2 or 3 during the conception period. These results further suggest that better detection leading to earlier intervention of the mild mobility scores may benefit reproductive performance, in turn reducing the risk of fertility related culling costs indirectly due to SOM.

The second indirect economic losses in expected milk returns reflect production losses that arose with more young replacement heifers entering the herd due to an increased culling rate because of SOM. Young replacement heifers produce less milk than older cows. Therefore, the total milk yield of a younger herd in the "with" SOM scenario is lower when compared with an older herd in the "without" SOM scenario. This was confirmed in the validation rounds when the mean total annual milk yield in a scenario where SOM had no effect on culling was the same as that of the "without" SOM scenario. The wide variation between the 5th and 95th percentiles for the losses in expect milk yield in the "with" SOM scenario is due to the stochastic determination of each cows RPL that was either culled or entered the herd.

Our simulation study has helped provide insight on the direct and indirect losses due to SOM for all level of severity resulting from the hoof disorders under study. At herd-level, the results show that mild SOM contributes significantly, both directly and indirectly, to the total annual economic loss due to SOM. Farm personnel are less sensitive in detecting mild forms of SOM, and if detected treatment is often prolonged (Alawneh et al., 2012a). This may be due to farmers perceptions and attitudes towards SOM (Bruijnis et al., 2013) or work plan. It is also possible that mild SOM is not detected by farmers at all because farmers perceive SOM prevalence to be lower than the actual SOM prevalence (Bruijnis et al., 2013). This entails that mild SOM is often only treated twice a year during routine hoof trimming. Emphasis must be placed on the economic importance of mild forms of SOM that occur more frequently than severe forms. The use of sensors to continuously monitor the mobility of cows may help identify cows with mild SOM faster and more frequently, promote cow specific intervention in a more timely manner and in turn reduce the economic losses due to SOM and improve cow welfare. In addition, sensor generated data could help better parameterise uncertain input variables used in our model and other bio-economic simulation models.

The developed bio-economic model is flexible and can be applied for a wide range of options for various situations with necessary parameter adjustments. With the model's ability to simulate the dynamics of SOM per mobility score, it can be further applied to evaluate cost-effectiveness of different management strategies tailored to the dynamics of specific mobility scores found in other dairy systems. In addition, the model also provides a foundation for research on the impact of mobility scores on cow welfare.

5. Conclusion

The dynamic, stochastic and mechanistic bio-economic simulation model described in this study is a novel simulation model that provides an estimation on the economic losses due to SOM in relation to the hoof disorders described within this study. The total annual economic loss due to SOM for a typical Dutch dairy farm of 125 cows was €15,342. This loss was composed of direct and indirect economic losses. The total direct economic loss was €9061, of which 47% was due to cows with mild forms of SOM. The model generated novel insights on the indirect economic losses due to SOM: making up 41% of the total annual economic loss due to SOM. These indirect economic losses were mostly due to decreases in the expected milk returns and increases in culling costs for non-SOM reasons. These results, along with the direct economic losses, imply that the economic losses due to SOM are more substantial than farmers might think. The results from this study can help stimulate dairy farmer awareness with respect to the economic importance of SOM, especially in the mild forms. Timely intervention of cows with SOM could reduce the economic losses and lead to improved cow health and welfare provided suitable intervention methods can be established.

Authors' contribution

Francis Edwardes: conceptualisation, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft, writing – review and editing, visualisation, project administration. Mariska van der Voort and Henk Hogeveen: conceptualisation, methodology, validation, resources, writing – review and editing, project administration, supervision. Tariq Halasa: methodology, software, validation, resources, writing – review and editing. Menno Holzhauer: validation, resources, writing – review and editing.

Conflict of interest

The authors have no competing interests.

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Appendix A. Model parameters and inputs

Table A1
Distribution of cow parity.

Parity	Default input	Distribution	Description	Source
1	0.31	Sample	Frequency of cows in parity 1–≥5	CRV (2019)
2	0.26			
3	0.20			
4	0.12			
≥5	0.11			

Table A2
Fertility and reproduction parameters.

Parameter	Default input(s)	Distribution	Description	Source
First oestrus		Sample	Days to first oestrus post-calving	Authors' expertise
Parity 1	14–27			
Parity ≥2	18–21			
Following oestrus	21	Fixed	Days to next oestrus after previous oestrus	Authors' expertise
$\Lambda^{(oest)}$	0.55	$B(n,p)$	Base risk of oestrus detection	Based on Rutten et al. (2014)
$\Lambda^{(conc)}$		$B(n,p)$	Base risk of successful conception for insemination number 1–≥6	Inchaisri et al. (2011)
Insemination 1	0.69			
Insemination 2	0.58			
Insemination 3	0.54			
Insemination 4	0.50			
Insemination 5	0.42			
Insemination ≥6	0.16			
Gestation (days)	$\mu = 281$; $\sigma = 3$	$N(\mu,\sigma)$	Length of gestation period	Based on Inchaisri et al. (2010)
VWP (days)	84	Fixed	Voluntary waiting period before first insemination post-calving	Inchaisri et al. (2010)
DPL (days)	56	Fixed	Dry period length before calving	Inchaisri et al. (2010)

Table A3
Culling and replacement parameters.

Parameter	Default input(s)	Distribution	Description	Source
General culling		$B(n,p)$	Daily probability for general culling reasons for cows in parity 1–≥5	Calibrated input
Parity 1	6.58e − 5			
Parity 2	1.53e − 4			
Parity 3	1.53e − 4			
Parity 4	2.19e − 4			
Parity ≥5	4.38e − 4			
Yield threshold	15	Fixed	Daily milk yield (kg) threshold for cows culled due to infertility	Authors' expertise
Mortality	0.02	$B(n,p)$	Probability of general cull cow succumbing to death	Authors' expertise
Replacement	0.30	Geometric	Probability of heifer replacing a dead cow on a given day within a month	Calibrated input

Table A4
Cow lactation curve parameters.

Parameter	Default input(s)	Distribution	Description	Source
$M^{(ady)}$		Fixed	Average daily yield (kg) for cows in parity 1–≥3	Kok et al. (2017)
Parity 1	23.9			
Parity 2	28.9			
Parity ≥3	30.5			
a		Fixed	Factors modelling shape of curve	Kok et al. (2017)
Parity 1	31.6			
Parity 2	40.6			
Parity ≥3	44.1			
b		Fixed		
Parity 1	− 0.0447			
Parity 2	− 0.0708			
Parity ≥3	− 0.0835			
c	− 16.1	Fixed		
k	0.06	Fixed		

Table A5
Cow energy requirement (VEM) parameters.

Parameter	Default input(s)	Distribution	Description	Source
Growth		Fixed	Daily growth energy requirements for cows in parity ≤2	van Es (1978)
Parity 1	660			
Parity 2	330			
Pregnancy stage		Fixed	Daily energy requirements for pregnant cows from 4 months to last month before calving	Remmelink et al. (2016)
4 months pre-calving	450			
3 months pre-calving	850			
2 months pre-calving	1500			
1 months pre-calving	2700			

Table A6
Risk factors associated with hoof disorder *d*.

Risk factor (λ)	Class	Hoof disorder relative risks								Source
		HYP	IDHE[a]	IDP	OH	SH	SU	WLD	DD[a, b]	
Parity	1	1	1; 1	1	1	1	1	1	1; 1.05	Somers et al. (2005a,b)
$r = 1$	2	1	1.25; 1.55	1	1	1	1	1.51	0.97; 1.01	Holzhauer et al. (2008b)
	3	1	1.92; 1.89	1	1	1	1.31	1.9	0.91; 0.95	Barker et al. (2009)
	≥4	1	1.97; 2.04	1	1	1	1.92	2.92	0.62; 0.66	
Lactation stage	≤30	1	1	1	1	1	1	1	1	Somers et al. (2005a)
$r = 2$	31–60	1	1.51	1	1	1	1.32	1	1.2	Holzhauer et al. (2008b)
	>60	1	1.78	1	1	1	1.63	1	1.2	Holzhauer et al. (2006)
	Dry	1	0.72	1	1	1	1.16	1	1	
RPL	≤20%	1	1	1	1	1	1	1	1	
$r = 3$	21–40%	1	1	1	1	1	1	1	1	
	41–60%	1	1	1	1	1	1	1	1	
	61–80%	1	1	1	1	1	1	1	1	
	>80%	1	1	1	1	1	1	1	1	
Hoof	Front	0.05	0.02	0.02	0.05	0.05	0.05	0.05	0.05	Based on
$r = 4$	Hind	1	1	1	1	1	1	1	1	Alvergnas et al. (2019)

[a] Parity risk factors are provided for both periods (pasturing; housing).
[b] Effect of housing on parity risk factor is adjusted by approximate estimation.

Table A7
Time spent with each mobility score before probable transition to the succeeding mobility score for hoof disorder *d*.

Parameter[a]	Mobility score	Days[b]							
		HYP	IDHE	IDP	OH	SH	SU	WLD	DD
$T^{\uparrow}_{min}$	2	7	9	0	0	7	3	1	14
	3	7	14	0	0	13	3	2	4
	4	14	7	0	0	4	3	2	4
$T^{\uparrow}_{max}$	2	7	17	1	0	17	4	2	17
	3	7	22	1	0	28	4	2	7
	4	14	14	1	0	14	4	3	7
$T^{\downarrow}_{min}$	2	2	2	0	0	5	2	2	2
	3	2	2	0	0	0	2	2	2
	4	1	1	1	0	0	2	2	1
	5	1	1	1	0	0	1	1	1
$T^{\downarrow}_{max}$	2	3	3	1	1	10	3	3	3
	3	3	3	1	0	0	2	2	3
	4	2	2	1	0	0	2	2	3
	5	2	2	1	0	0	1	1	1

[a] Intervals between score transitions; superscripts ↑ and ↓ denote mobility score progression and recovery, respectively.
[b] Mean values of expert opinion except for DD mobility score 2 where $T^{\uparrow}_{min} = 14$ and $T^{\uparrow}_{max} = 17$ were derived by the sojourn time a DD lesion would spend in lesion class M1 as per Biemans et al. (2018).

Table A8
Hoof disorder cure rates after treatment by farmer, hoof trimmer or veterinarian.

Hoof disorder[a]	Mobility score base cure rates				Source
	2	3	4	5	
Treated by farmer					
DD	0.79	0.79	0.79	0.79	Holzhauer et al. (2008a)
HYP[b]	0	0	0	0	Authors' expertise
IDHE	0.65	0.65	0.6	0.5	Authors' expertise
IDP	1	0.98	0.98	0.98	Bruijnis et al. (2010)
OH	1	1	1	1	Authors' expertise
SH	0.7	0.6	0.55	0.45	Authors' expertise
SU	0.79	0.68	0.63	0.53	Authors' expertise
WLD	0.79	0.68	0.63	0.53	Authors' expertise
Treated by hoof trimmer or veterinarian					
DD	0.79	0.79	0.79	0.79	Holzhauer et al. (2008a)
HYP	1	0.8	0.8	0.8	Authors' expertise
IDHE	0.8	0.7	0.65	0.6	Authors' expertise
IDP	1	1	0.98	0.98	Bruijnis et al. (2010)
OH	1	1	1	1	Authors' expertise
SH	0.75	0.65	0.6	0.5	Authors' expertise
SU	1	0.8	0.75	0.75	Authors' expertise
WLD	1	0.8	0.8	0.8	Authors' expertise

[a] Base cure risks had to be estimated due to the little information available. Where information was available it was used.
[b] Farmers will not treat a case of interdigital hyperplasia (HYP) since a veterinarian is required to perform a claw-amputation.

Table A9
Risk factors associated with cure of hoof disorder.

Risk factor (λ)	Class	Relative risk	Source
Parity	1	1	Reader et al. (2011)
$r = 8$	2	1.05	
	3	0.91	
	≥4	0.8	
Lactation stage	<90	1	Reader et al. (2011)
$r = 9$	90–180	0.92	
	>180	0.8	
	Dry	1	
Duration of disorder (days)	<14	1	Reader et al. (2011)
$r = 10$	15–28	0.7	
	29–126	0.54	
	>126	0.28	

Table A10
Mobility score effects on production.

Parameter	Class					Source
	Mobility score					
	1	2	3	4	5	
$M^{(myr)}$ [a]	0	0	0.05	0.48	0.53	Based on O'Connor et al. (2020b)
$\lambda^{(oest)}$ [b]	1	0.91	0.82	0.73	0.64	Walker et al. (2008)
$\lambda^{(conc)}$ [cd]	1	1	PERT(0.41, 0.78, 0.88)			Alawneh et al. (2011)
Culling[e]	1	1.07	1.18	1.48	1.48	Walker et al. (2008)
	Parity					
	1	2	3	4	≥5	
Culling[e]	1	1.1	1.2	1.3	1.5	O'Connor et al. (2020b)
	Relative production level					
	≤20%	21–40%	41–60%	61–80%	≥80%	
Culling[e]	1	0.34	0.24	0.16	0.06	Booth et al. (2004)

[a] Daily percentage milk yield reduction per mobility score.
[b] Relative risk of oestrus detection where the default input in Table A2 is taken as the base risk.
[c] Relative risk of conceiving after successful oestrus detection and artificial insemination (AI) where the default probability of conception after insemination inputs in Table A2 are taken as the base risks.
[d] PERT(min, med, max) distribution is distributed over mobility scores ≥3.
[e] Relative risk of a cow being culled with mobility score 1–5 in parity 1–≥5 and in one of five relative production level classes where general culling rate in Table A3 is taken as the base risk.

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