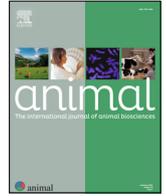




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A new approach and insights on modelling the impact of production diseases on dairy cow welfare



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ABSTRACT

Animal welfare is becoming an important consideration in animal health-related decision-making. Integrating considerations of animal welfare into the decision-making process of farmers involves recognising the significance of health disorder impacts in relation to animal welfare. Yet little research quantifies the impact, making it difficult to include animal welfare in the animal health decision-making process. Quantifying the impact of health disorders on animal welfare is incredibly challenging due to empirical animal-based data collection constraints. An approach to circumvent these constraints is to rely on expert knowledge whereby perceived welfare impairment weights are indicative of the negative welfare effect. In this research, we propose an expertise-based method to quantify the perceived impact of sub-optimal mobility (SOM) on the welfare of dairy cows, because of its welfare importance. We first quantified perceived welfare impairment weights of SOM by eliciting expert knowledge using adaptive conjoint analysis (ACA). Second, using the perceived welfare impairment weights, we derived the perceived welfare disutility (i.e., perceived negative welfare effect) of mobility scores 1–5 (1 = optimal mobility, 5 = severely impaired mobility). Third, using the perceived welfare disutility per mobility score, we quantified the perceived welfare impact at case- and herd-level of SOM for different SOM severity. Results showed that perceived welfare disutility increased with each increase in mobility score. However, the perceived welfare impact of SOM cases with lower mobility scores was higher compared to SOM cases with higher mobility scores. This was because of the longer-lasting duration of the SOM cases with lower mobility scores. Moreover, the perceived herd-level welfare impact was largely due to SOM cases with lower mobility scores because of the longer duration and more frequent incidence compared to the SOM cases with higher mobility scores. These results entail that better welfare of dairy cows with respect to SOM can be achieved if lower mobility scores are detected and treated sooner. Our research demonstrates a novel approach that quantifies the perceived impact of health disorders on animal welfare when empirical evidence is limited.

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Implications

We propose a novel method to quantify the perceived impact of health disorders on animal welfare that can be further used in animal welfare decision-making regarding health disorders. Sub-optimal mobility in dairy cows was chosen as a health disorder because of its high welfare importance to demonstrate the applicability of our method. Results showed that sub-optimal mobility cases with lower mobility scores have a larger perceived welfare impact on average due to their longer duration in comparison to sub-optimal mobility cases with higher mobility scores. More

timely intervention of sub-optimal mobility cases with lower mobility scores could improve dairy cow welfare.

Introduction

Farm animal welfare is an ever-pressing societal concern, especially in European countries (European Commission, 2016). For farmers, this means that animal welfare should be an aspect considered in the animal health management decision-making process. Among other welfare risks, health disorders are important factors in relation to impaired animal welfare (Broom and Corke, 2002). While there is a growing need to include farm animal welfare in the animal health decision-making process, decision-

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making in animal health is largely considered from an economic perspective (Hennessy and Marsh, 2021; McInerney et al., 1992; Rushton, 2009). Integrating considerations of animal welfare into the decision-making process of farmers involves recognising the significance of health disorder impacts in relation to animal welfare. However, quantifying these impacts is challenging, as demonstrated by the relatively few studies reporting the welfare impacts of health disorders (Bruijnis et al., 2012; Nielsen et al., 2021).

Animal welfare is complex and can be understood by considering various animal welfare indicators within different domains. This is for instance illustrated by the Five Domains model, whereby each domain encompasses factors pertaining to nutrition, environment, health, behaviour, and mental state. Within each domain, several welfare indicators are listed (Mellor et al., 2020). Understanding the impact of health disorders on these welfare domains through the welfare indicators can help identify their impact on overall animal welfare (EFSA, 2012). Using an expert knowledge-elicited weight-based approach is one method to assess the effect of various factors on animal welfare indicators, especially in instances when empirical evidence is lacking (EFSA, 2014). For example, the effect of different health disorders on various welfare indicators has been quantified, whereby the overall “welfare impact” is determined by summing the weights associated with the welfare indicators (Bruijnis et al., 2012; Nielsen et al., 2021; Teng et al., 2018). Similarly, this weight-based approach has also been used to assess the welfare impact of different housing and management systems in swine and dairy farming (Bracke et al., 2002; Ursinus et al., 2009).

The Delphi method is a commonly used expert knowledge elicitation method in animal welfare-related studies (Bertocchi et al., 2018; Lorenzi et al., 2022; Rioja-Lang et al., 2020). Bruijnis et al. (2012) and Nielsen et al. (2021) used derivations of the Delphi method in their health disorder welfare impact assessments for swine and dairy cows. However, using this method may lead to obscured weights because the welfare indicators are addressed individually, ignoring the health disorder's relative effect on other welfare indicators, while a health disorder may affect several welfare indicators simultaneously with varied effects per welfare indicator. Assessing welfare indicators simultaneously via comparison-based elicitation techniques may help obtain more accurate weights since the relative effect of a health disorder on welfare indicators is considered in the expert knowledge elicitation process. To date only Teng et al. (2018) used a paired comparison-based elicitation method to assess the welfare impact of disease. However, their study concerned companion animals and not farm animals. For now, assessing the welfare impact of health disorders in farm animals is mostly Delphi based, which lacks depth in the weighing process.

The objective of this study was to propose a new method for quantifying the impact of health disorders on animal welfare and to apply this method to an estimation of the welfare effect of sub-optimal mobility (SOM) in dairy cattle. Our method is expert knowledge based. Therefore, the impact of SOM on animal welfare is grounded in the perception of the experts towards the effects of SOM on animal welfare. In the first step, expert knowledge was used, in conjunction with scientific literature, to establish the physical effects of SOM on animal welfare indicators. In the second step, expert knowledge was elicited using a comparison-based elicitation technique known as Adaptive Conjoint Analysis (ACA) to obtain perceived welfare impairment weights in relation to the physical effects of SOM on animal welfare indicators. ACA is a fitting methodology because it allows for multiple welfare indicators to be assessed simultaneously, which is an advantage over the more commonly used Delphi method. Ultimately, these two expert knowledge-based steps contributed towards estimating the perceived overall welfare impact of SOM via simulation modelling.

We position this research in the context of dairy cow SOM because it is a common health disorder in dairy farming with high animal welfare importance (Broom and Corke, 2002; Welfare Quality®, 2009; Why and Shearer, 2017). SOM is characterised by different severities that are often described by mobility scores, such as the 5-point ordinal mobility scoring scale (1 = optimal mobility, 5 = severe SOM; Sprecher et al. (1997)). SOM is often referred to as lameness, but the definition of lameness in conjunction with mobility scores has shown to vary between studies. For example, some studies define a cow as lame with mobility scores ≥ 2 (Olechnowicz and Jaśkowski, 2015), ≥ 3 (Amory et al., 2006; Randall et al., 2018; Somers et al., 2019), or ≥ 4 (Kovács et al., 2016). By avoiding the term lameness, we can specifically focus on varying levels of SOM as defined by the mobility scores themselves. More recently, other studies have avoided the term lameness and focused on specific mobility scores to describe SOM (Edwardes et al., 2022a and 2022b; O'Connor et al., 2019 and 2020). Ultimately, using SOM as a case study demonstrates how our proposed method can identify the perceived welfare impact of different health disorder severities.

Material and methods

The approach used in this research was multi-faceted and is described in greater detail in the following sub-sections. Here, an overview is presented. Additionally, the schematic illustration in Fig. 1 describes the steps taken in the methodology.

First, we identified animal-based welfare indicators that are physically affected by SOM with reference to the 5-Domains model of Animal Welfare by Mellor et al. (2020) by using expert knowledge and scientific literature. Second, perceived welfare impairment weights were elicited from a second group of animal welfare experts for various levels of the animal-based welfare indicators using ACA (Orme, 2006; Sawtooth Software, 2007). Hence, the physical effects of SOM on welfare indicator levels (step 1) on the mental state were represented by perceived welfare impairment weights (step 2). Third, the relative importance of welfare indicators was estimated. Fourth, the perceived welfare disutility was estimated per mobility score by linking the perceived welfare impairment weights to mobility scores. Briefly, the perceived welfare disutility represents the combined perceived welfare impairment weights per mobility score for a combination of physical effects. Lastly, the perceived welfare impairment weights were used in a simulation model (Edwardes et al., 2022a and 2022b) to quantify the perceived overall welfare impact of SOM.

Animal-based welfare indicators

Animal-based welfare indicators are important in the assessment of animal welfare (EFSA, 2012). These welfare indicators offer more accurate insight into the response of, and the effects of, the individual animal when afflicted with a welfare-debilitating factor such as a health disorder. The 5-Domains model of Animal Welfare is a framework (Mellor et al., 2020) that includes several animal-based welfare indicators in the nutrition, health and behaviour domains. These animal-based welfare indicators can then be linked to the fifth affective experience domain (i.e., mental state) meaning that every animal-based welfare indicator that is affected may be followed by an emotional or subjective response that may also affect the mental state. For example, a reduction in food intake (i.e., welfare indicator) affects the nutrition domain and may lead to the experience of hunger, affecting the mental state domain.

We identified animal-based welfare indicators physically affected by the occurrence of SOM in dairy cows with reference to the nutritional, health, and behavioural domains of the 5-

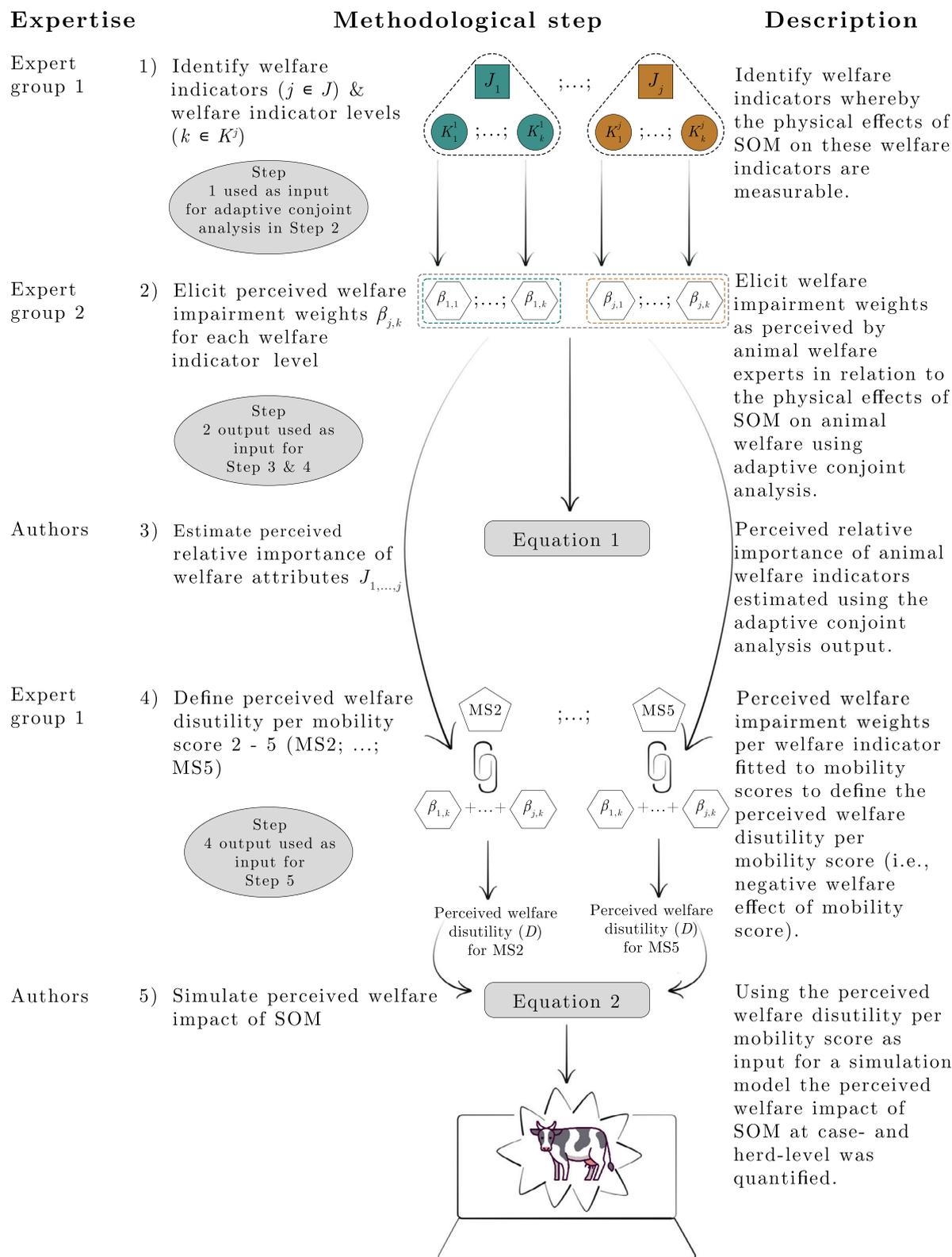


Fig. 1. Schematic illustration of the methodological steps undertaken for this research to quantify the perceived impact of sub-optimal mobility on dairy cow welfare.

Domains model of Animal Welfare (Mellor et al., 2020) in combination with scientific literature and expert discussions (expert group (1); EG1) regarding dairy cow SOM and hoof health (Fig. 1; step 1). The degree to which the welfare indicators are physically affected by SOM was defined by intervals in terms of welfare indicator levels.

The defined welfare indicators and respective welfare indicator levels (physical effects) are presented in Table 1. For the feed and water intake welfare indicator, cows with SOM may have a reduced feed and water intake of 0, 10 and 20% compared to a cow without SOM (Norrington et al., 2014). The functional impairment

Table 1
Dairy cow welfare indicators and respective welfare indicator levels.

Welfare indicator (<i>j</i>)	Indicator abbreviation	Welfare indicator level (<i>k</i>)	Source
Feed and water intake (% reduction)	fwi	0 10 20	Norring et al. (2014); (EG1)
Functional impairment (mobility score)	fim	1 (no functional impairment) 2 (mild functional impairment) 3 (moderate functional impairment) 4 (marked functional impairment) 5 (severe functional impairment)	Sprecher et al. (1997)
Body condition score (point decrease)	bcs	0 0.5 1	O'Connor et al. (2019)
Behavioural change (% change)	bch	0 10 20	Expert discussions (EG1)
Cow-human interaction (withdrawal at an additional distance)	chi	0 cm 1–50 cm 51–100 cm >100 cm	Welfare Quality® (2009)

EG1 = Expert group (1).

welfare indicator refers to difficulties in performing everyday activities, and in this case, it is the functional use of a cow's hoof and leg. It is assumed a hoof is functionally impaired in relation to uneven weight distribution across the hooves or asymmetric gait due to the presence of a hoof disorder (e.g., Flower and Weary, 2006). Functional impairment is reflected by five mobility scores where 1 = no functional impairment and 5 = severe functional impairment (Sprecher et al., 1997). The body condition score (BCS) welfare indicator is a visual and an indirect estimate of energy balance and is associated with SOM (O'Connor et al., 2019). A cow experiencing sub-optimal mobility may decrease in BCS by 0, 0.5 or 1 (O'Connor et al., 2019). The behavioural change welfare indicator was based on a cow's activity budget. Within this budget, cows behave in certain ways based on activities. Due to SOM, the behaviour in relation to an activity may change, ultimately affecting at least one other behaviour since the activity budget is limited. For example, when afflicted with SOM, a cow can experience increased lying resulting in decreased standing (Walker et al., 2008). The behavioural change indicator was kept broad due to the inherent interaction of behaviours and to capture all changes in behaviour. Hence, three levels of behavioural change percentages were defined as 0, 10 or 20%. With respect to the cow-human interaction welfare indicator, sign of avoidance in distance, stepping back and/or turning head, is a measure of cow-human interaction (Welfare Quality®, 2009). For example, a cow with SOM may feel more vulnerable and perceive a human approaching as a threat and shows signs of avoidance (Sharma and Phillips, 2019). Three levels of cow-human interaction indicators were defined as signs of withdrawal at an additional distance of 0 cm, 1–50 cm, 51–100 cm, >100 cm (Welfare Quality®, 2009).

The welfare indicator levels are the physical and measurable effects of SOM on the respective welfare indicator. After identifying the welfare indicators and respective levels, we then estimated their effect on the mental state.

Eliciting perceived welfare impairment weights

We used ACA to elicit perceived welfare impairment weights. Traditionally used in economic and marketing research, ACA is centred on Lancaster's (1966) theory postulating that consumers make consumption decisions based on a combination of product aspects rather than the overall product itself. For example, consider a 1 litre milk carton: this product can be decomposed into multiple

attributes J where $j \in J$ (e.g., welfare label, origin, price, fat content) that vary by K^j attribute levels where $k \in K^j$ (e.g., high, medium, or low welfare for the welfare label attribute). ACA is designed as an experiment used to elicit consumer preferences for existing or hypothetical products with varying attribute levels. A consumer's preference for a product is based on a combination of attribute levels, one for each attribute, and reflected in the utility U for a specific product. The utility U is expressed as $\sum_{j \in J} \beta_{j,k}$ where $\beta_{j,k}$ is the part-worth utility for attribute j with attribute level k over J different product attributes. So, $\beta_{j,k}$ represents a "preference weight" that a consumer places on an attribute level of a product. Therefore, higher values of U are indicative of greater preference for a product with given a combination of attribute levels with the corresponding part-worth utilities. For additional information on ACA, see Orme (2006) and Sawtooth Software (2007).

To elicit perceived welfare impairment weights in relation to the physical effects of SOM on animal welfare indicators (Fig. 1; step 2), we adapted the ACA terminology to suit the objectives of this study. Welfare indicators J represented the *attributes* with $j \in J$ and welfare indicator levels K^j represented the *attribute levels* per welfare indicator j with $k \in K^j$. The perceived welfare impairment weight $\beta_{j,k}$ represented the *part-worth utility* for welfare indicator j with welfare indicator level k . Therefore, the combination of welfare indicator levels, one for each welfare indicator, represents the *product*. The sum of perceived welfare impairment weights that corresponds to the combination of welfare indicator levels reflects the welfare disutility D , representing *utility* (i.e., $D = \sum_{j \in J} \beta_{j,k}$). In other words, the welfare disutility D represents the perceived negative effect of SOM on the mental state in relation to the combined physical effects of SOM on the welfare indicator levels. Therefore, higher values of D are indicative of greater perceived welfare impairment for a combination of welfare indicator levels with the corresponding perceived welfare impairment weights.

The ACA took form of a survey and was distributed online to participants of the 54th Congress of the International Society of Applied Ethology (2nd–6th August 2021: (ISAE, 2021), which took place online due to the covid-19 pandemic). We chose this congress to reach animal welfare experts beyond The Netherlands. We assumed that by using this congress as a platform, we could reach international animal welfare experts given the congress's recognised importance in scientific animal welfare research. Elemental questions concerning the potential respondents' animal welfare expertise were asked in the survey. Prior to survey distri-

bution, it was unknown how many animal welfare experts would attend ISAE2021. By the end, 33 experts took part in the survey. From the pool of 33 experts, a total of 10 were removed from the original dataset for either not having completed the survey ($n = 7$) or showing a low degree of involvement ($n = 3$). The final sample of these 23 experts was termed **EG2**.

Survey design

The welfare indicators and respective welfare indicator levels were treated as inputs in the design of the ACA survey (Table 1). The survey took form in an electronic 3-step procedure and was designed in Lighthouse Studio (Sawtooth Software, 2021). In the design of the survey, prior information was specified for the welfare indicator levels for each welfare indicator assuming that welfare was impaired more for each increase in welfare indicator level. For example, a 10% reduction in feed and water intake will impair welfare more than a 0% reduction, and a 20% reduction in feed and water intake will impair welfare more than a 10% reduction.

Throughout the survey, respondents were asked questions on how they perceived the impact of physical effects implicitly associated with SOM on animal welfare. This was done to avoid explicit questions pertaining to the welfare effects of SOM on animal welfare. This nuanced approach focussing on the negative effects of animal welfare in relation to physical changes animal-based welfare indicators rather than the severity as a whole is a strength of ACA.

The first step of the survey dealt with collecting prior information from the experts whereby they specified the perceived relative importance of each welfare indicator. This was done by identifying the magnitude in differences among the considered welfare indicator levels. Magnitudes in differences between welfare indicator levels within a welfare indicator are more informative than importance specifications per welfare indicator level. Hence, experts were asked to specify the perceived importance of a change from the lowest to the highest welfare indicator level for each welfare indicator in terms of perceived welfare impairment. Seven possible answers ranged from “not important” to “extremely important”. This prior information was used in the second step of the survey.

In the second step of the survey, experts were shown a series of customised paired-comparison trade-off questions. These paired-comparison questions were defined in combination with the prior information from the first step of the survey. In each paired-comparison trade-off question, experts were shown two cards representing virtual cows with SOM where the effect of SOM on welfare indicators varied according to the respective welfare indicator levels. Each time, the two virtual cow cards were nearly equal in perceived welfare disutility, which is reflected in the sum of the perceived welfare impairment weights (i.e., $\sum_{j \in J} \beta_{j,k}$). After each paired-comparison question per expert, the perceived welfare impairment weights were updated with ordinary least squares regression (Sawtooth Software, 2007). The updated perceived welfare impairment weights were then used to select a combination of welfare indicator levels for the next paired-comparison question that would generate two virtual cow cards being nearly equal in perceived welfare disutility. This process ultimately forced the experts to consider the importance of the welfare indicator levels for each welfare indicator, which is a strength of ACA that helps identify the most important welfare indicator levels per welfare indicator per expert.

In the third step of the survey, the experts' degree of involvement during the survey was investigated. A series of questions were asked about a single virtual cow's welfare described by varying combinations of welfare indicator levels. Experts were asked to specify a “likely welfare impairment score” between 0 and 100

(0 = cow's welfare is not at all impaired; 100 = cow's welfare is most impaired). The degree of involvement was used to determine an intercept and regression coefficient for the perceived welfare impairment weights to best predict logits of likelihood responses (Sawtooth Software, 2007). The experts' degree of involvement was identified by correlating the experts' logit of likelihood responses and perceived welfare impairment weights (estimated in the preceding step of the survey).

Data processing and analysis

The final set of perceived welfare impairment weights for each expert was extracted from Lighthouse Studio (Sawtooth Software, 2021) and then processed and analysed with R in RStudio (R Core Team, 2022). Experts that showed a low degree of involvement ($R^2 < 0.5$, estimated in step 3) were removed from the final data set because their degree of involvement was not correlated with their perceived welfare impairment weights (estimated in step 2). With the remaining expert responses ($n = 23$), the mean and SD of perceived welfare impairment weights for each welfare indicator level were calculated (Fig. 1; step 3). In addition, the perceived relative importance of each welfare indicator was calculated per expert by finding the range between perceived welfare impairment weights per welfare indicator divided by the sum of all welfare indicator impairment weight ranges. Hence, the perceived relative importance $\rho_{i,j}$ of welfare indicator j in J welfare indicators for expert i is expressed as

$$\rho_{i,j} = \frac{\max_{k \in K^j} (\beta_{i,j,k}) - \min_{k \in K^j} (\beta_{i,j,k})}{\sum_{j \in J} \left[\max_{k \in K^j} (\beta_{i,j,k}) - \min_{k \in K^j} (\beta_{i,j,k}) \right]} \quad (1)$$

where $\beta_{i,j,k}$ is the perceived welfare impairment weight for expert i with respect to welfare indicator level k in K^j welfare indicator levels for welfare indicator j across J welfare indicators. With $\rho_{i,j}$, the mean of the experts' perceived relative importance, and the SD between experts per welfare indicator was also calculated.

Perceived disutility of sub-optimal mobility on animal welfare

After estimating the perceived welfare impairment weights for all welfare indicator levels, we then identified the perceived welfare disutility for different severity of SOM (Fig. 1; step 4). Identifying the perceived welfare disutility per mobility score was a necessary step to quantify the perceived welfare impact of SOM since the perceived welfare disutility reflects the total perceived effect of SOM on the mental state. In Edwardes et al. (2022a and 2022b), SOM severity is described by a 5-point ordinal mobility scoring scale (1 = optimal mobility, 5 = severe SOM) as per Sprecher et al. (1997). To identify the perceived welfare disutility per mobility score, we asked the SOM and hoof health experts in EG1 to participate in a questionnaire. Per welfare indicator, they were asked to specify the welfare indicator level that best fitted each mobility score 1–5. Experts in EG1 were blind to the elicited perceived welfare impairment weights obtained from the experts in EG2. After experts in EG1 completed the questionnaire, the median welfare indicator level per welfare indicator per mobility score was calculated. Thereafter, the corresponding perceived welfare impairment weights per median welfare indicator level per welfare indicator per mobility score were identified and used as input for the simulation model. Furthermore, the perceived welfare disutility D_l for mobility score l was estimated: $D_l = \sum_{j \in J} \beta_{j,k,l}$. In other words, D_l represents the perceived negative effect of the mobility score on the mental state.

Modelling the perceived sub-optimal mobility welfare impacts

In brief, the model described in Edwardes et al. (2022a and 2022b) simulates a typical Dutch dairy herd in daily time-steps where cows are housed in cubicles with concrete slatted floors in Autumn and Winter, have pasture access for > 6 hours a day in Spring and Summer, and have their hooves routinely trimmed at the start of Spring and Autumn. SOM is modelled at cow-level using a 5-point ordinal mobility scoring scale (1 = optimal mobility, 5 = severe SOM; Sprecher et al. (1997)) and could occur due to the incidence of eight different hoof disorders (digital dermatitis, interdigital hyperplasia, interdigital dermatitis/heel-horn erosion, interdigital phlegmon, overgrown hoof, sole haemorrhage, sole ulcer, and white-line disease). Hoof disorders and SOM were first modelled at the hoof-level (detailed explanation in Edwardes et al. (2022a and 2022b)), this means that a cow could have four possible mobility scores (i.e., one for each hoof; detailed explanation in Edwardes et al. (2022a and 2022b)). If no hoof disorder or a latent digital dermatitis lesion was present, the hoof was assigned a mobility score 1. If a hoof became affected with any of the eight hoof disorders, a mobility score 2 was first assigned to the hoof. Thereafter, mobility score transitions were probabilistically determined after a minimum mobility score duration occurred respective of hoof disorder. Minimum mobility score durations were determined by sampling from uniform distributions respective of mobility score and hoof disorder. After these hoof-level processes were simulated, the cow-level mobility score dynamics were determined in each time step as the maximum mobility score between the four possible hoof-level mobility scores resulting from the underlying hoof disorders.

The incidence and duration of SOM cases (mobility score ≥ 2) were then quantified for a one-year period. SOM cases were allocated to a Maximum Mobility Score SOM Case (MMSC) category because a SOM case can be composed of more than one mobility score. Hence, four MMSCs were defined as MMSC2, MMSC3, MMSC4, and MMSC5 for maximum mobility scores 2–5, respectively. For each of these MMSC categories, the duration of mobility scores within a SOM case was also quantified. MMSC incidence and duration were used as input to quantify the welfare impact of SOM at MMSC- and herd-level (Supplementary Table S1).

Simulating the perceived welfare impact

The corresponding perceived welfare impairment weights per mobility score (identified in Perceived disutility of sub-optimal mobility on animal welfare) were used as inputs to quantify the perceived welfare impact per SOM MMSC (i.e. MMSC2, MMSC3, MMSC4, MMSC5) incident that occurred in a one-year period (Fig. 1; step 5). The duration of mobility scores within an MMSC per incident per cow were respectively weighed by the perceived welfare impairment weights with the following equation:

$$WI_{h,i} = \sum_{j=1}^4 \sum_{l \in L^h} \beta_{j,k,l} \times \alpha_{h,i,l} + \sum_{l \in L^h} \beta_{j=5,k,l} \times \gamma_{h,i,l} \tag{2}$$

where $WI_{h,i}$ is the total welfare impact of SOM case h for cow i , $\beta_{j,k,l}$ is the perceived welfare impairment weight for welfare indicator j with welfare indicator level k in association with mobility score l in the L^h set of mobility scores that occurred during SOM case h , $\alpha_{h,i,l}$ is the duration (days) of mobility score l during SOM case h for cow i , and $\gamma_{h,i,l}$ is the number of cow-human interactions directly related to SOM (i.e., treatments) for mobility score l during SOM case h for cow i . Cow-human interactions were separated from the summation of the four other welfare indicators to limit the indirect effects of SOM on cow-human interactions that may occur during daily farming activities.

The perceived welfare impact was analysed at MMSC-level and normalised to the maximum perceived welfare impact to obtain values between 0 and 100. The means (5th and 95th percentiles) of MMSC-level perceived welfare impact scores produced by the 500 simulations were then calculated. The normalised MMSC-level perceived welfare impact scores per MMSC were aggregated to obtain herd-level perceived welfare impact per MMSC category.

Sensitivity analysis

A global sensitivity analysis was run to assess the variation in total MMSC perceived welfare impact at herd-level (i.e., output) attributable to the variation in perceived welfare impairment weights per welfare indicator per mobility score (i.e., input parameter $\beta_{j,k,l}$). Variation attributable to perceived welfare impairment weights were represented by first- and total-order sensitivities and were quantified with a variance decomposition method (Saltelli et al., 2008). First-order sensitivity indices indicate the contribution of variation in output caused by the variation in $\beta_{j,k,l}$ without interactions with other input parameters. Total-order sensitivity indices indicate the contribution of variation in output caused by the variation in $\beta_{j,k,l}$ including all variation caused by its interactions, of any order, with any other input parameter. In summary, first- and total-order sensitivity indices indicate the relative importance of $\beta_{j,k,l}$ with higher values indicative of larger effects on the output variance. First- and total-order sensitivity indices were computed after Azzini et al. (2020) in R (R Core Team, 2022) using the sensobol package (Puy et al., 2022), and sensitivity indices of >0.05 were reported. Gamma distributions of 5 000 draws for each $\beta_{j,k,l}$ were drawn with a Latin hyper cube sample design to efficiently cover the parameter space of each $\beta_{j,k,l}$. To gain better insight into the variation in perceived herd-level welfare impact attributable to the variation in perceived welfare impairment weights, we fixed the duration (i.e., α) and number

Table 2 Elemental information on survey respondents (n = 23) partaking in the adaptive conjoint analysis (ACA) in relation to the perceived welfare impairments of sub-optimal mobility on dairy cow welfare indicators.

Respondent information	Number of respondents
Primary profession	
Research and/or university education	19
Other	4
Years of animal welfare experience	
0	0
0–1	0
1–5	5
6–10	5
>10	13
Years of dairy cow experience	
0	3
0–1	4
1–5	8
6–10	4
>10	4
Country	
Argentina	1
Australia	1
Austria	1
Brazil	3
Canada	4
Denmark	1
Germany	2
Israel	1
Macedonia	1
New Zealand	1
Nigeria	1
Sweden	1
United Kingdom	2
United States of America	3

of cow-human interactions (i.e., γ) per mobility scores per MMSC to their means.

Results

Elemental information on animal welfare experts

Table 2 shows elemental information of the 23 animal welfare experts who took part in the ACA survey. Among the participants, 83% were primarily engaged in research and/or university education, 57% had over ten years of experience in animal welfare, and 35% had 1–5 years of experience with dairy cows. Furthermore, the survey had international participation, with experts from 14 different countries.

Perceived relative importance of welfare indicators and welfare indicator level impairment weights

Results from the 23 experts were included in the final data set and are presented in Table 3. From the five welfare indicators included in the ACA experiment, functional impairment and reduced feed and water intake were respectively the most (38.1%) and second most (20.8%) important welfare indicators perceived by the experts. For all welfare indicators, the perceived welfare impairment weights indicate that experts collectively agreed that each increase in welfare indicator level increases welfare impairment. A note of caution is that individual perceived welfare impairment weights between different welfare indicators cannot be compared, but changes in perceived welfare impairment weights within a welfare indicator can be compared between welfare indicators. For example, a change from no functional impairment to mild functional impairment can be compared with a change in behaviour from 0 and 10%, and, in this example, these changes are equal in terms of perceived welfare impairment.

Mobility score perceived welfare disutility

The perceived welfare disutility, reflecting the perceived total effect on the mental state, of mobility scores on animal welfare

was identified by fitting the perceived welfare impairment weights per welfare indicator to mobility scores (Table 4). Mobility score 1 was considered not to impair animal welfare since the perceived welfare impairment weights were 0 across all welfare indicators. Mobility score 2 was considered to impair animal welfare only through the mild functional impairment welfare indicator level belonging to the functional impairment welfare indicator. Mobility scores ≥ 3 impaired animal welfare across all welfare indicators. Mobility score 3 was considered to impair animal welfare less than mobility scores 4 and 5, across all welfare indicators except the cow-human interaction welfare indicator.

Perceived welfare impact of maximum mobility score sub-optimal mobility case

Using the perceived welfare disutility per mobility score as input, the simulation model calculated the perceived welfare impact per MMSC. Aggregating these individual impacts produced the overall perceived welfare impact at the herd-level. The distribution of MMSC's relative contributions to the total perceived herd-level welfare impact can be found in Table 5. The less severe MMSC2 and MMSC3 contribute the most (~87%) to the total perceived herd-level welfare impact with MMSC3 being the dominant contributor. This is due to the more frequent cumulative incidence and longer duration of MMSC2 and MMSC3 despite the lower perceived welfare disutility associated with mobility scores 2 and 3. MMSC4 and MMSC5 contribute less (~13%) to the total perceived welfare impact at herd-level because of the lower incidences although the perceived welfare disutility associated with mobility scores 4 and 5 are highest.

The average perceived welfare impact due to SOM was 14 (0; 60), considering all MMSCs. For specific MMSC, MMSC2 had the lowest average perceived welfare impact of 4 (0; 14) and MMSC3 had the highest average perceived welfare impact of 30 (1; 91). Average perceived welfare impact for MMSC4 and MMSC5 were 20 (3; 64) and 17 (2; 66), respectively. Perceived welfare impacts were not indicative of specific MMSC due to variations in duration within and between MMSC (Fig. 2). For all MMSCs, the perceived welfare impact increased as the MMSC duration increased. For

Table 3

Mean (SD between experts) perceived relative importance of dairy cow welfare indicators and perceived welfare impairment weights per dairy cow welfare indicator level (SD between experts).

Welfare indicator and levels	% Perceived relative Importance		Perceived welfare impairment weight	
	Mean	SD	Mean	SD
Feed and water intake (% reduction)	20.8	7.26		
0			0.00	0.18
10			0.57	0.16
20			1.14	0.28
Functional impairment (mobility score)	38.1	9.58		
1 (no functional impairment)			0.00	0.22
2 (mild functional impairment)			0.42	0.30
3 (moderate functional impairment)			1.01	0.24
4 (marked functional impairment)			1.46	0.20
5 (severe functional impairment)			2.06	0.37
Body condition score (point decrease)	14.2	5.95		
0			0.00	0.26
0.5			0.39	0.18
1			0.67	0.24
Behavioural change (% change)	14.4	5.78		
0			0.00	0.21
10			0.42	0.18
20			0.75	0.19
Cow-human interaction (withdrawal at an additional distance)	12.5	4.90		
0 cm			0.00	0.23
1–50 cm			0.20	0.18
51–100 cm			0.40	0.19
>100 cm			0.62	0.22

Table 4
Perceived dairy cow welfare impairment weight $\beta_{j,l}$ for dairy cow welfare indicator j and mobility score l .

Mobility score (l)	Welfare indicator (j)					Perceived welfare disutility ($\sum_{j \in J} \beta_{j,k,l}$)
	Feed and water intake	Functional impairment	Body condition score	Behavioural change	Cow-human interaction	
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.42	0.00	0.00	0.00	0.42
3	0.57	1.01	0.39	0.42	0.20	2.59
4	1.14	1.46	0.67	0.75	0.20	4.22
5	1.14	2.06	0.67	0.75	0.20	4.82

Table 5
Maximum Mobility Score sub-optimal mobility Cases (MMSC) relative share of perceived total dairy cow herd-level welfare impact.

MMSC	Mean	Percentiles	
		5th	95th
2	16.43	12.06	22.18
3	70.49	62.36	77.31
4	12.06	6.41	18.72
5	1.17	0.12	3.38

MMSC2, the perceived welfare impact is the result of the presence of mobility score 2 only. Because of this, no variation in perceived welfare impact for specific durations were observed. The variation in perceived welfare impact for MMSC3, MMSC4 and MMSC5 increased with increasing MMSC duration. This was due to the composition of mobility score duration within the MMSC. For example, keeping MMSC3 duration constant (i.e., at the mean MMSC3 duration), the perceived welfare impact was higher when the proportion of mobility score 3 duration was more than half the total MMSC3 duration (brown points) in comparison to the lower perceived welfare impact when the proportion of the mobility score 3 duration was less than half the total MMSC3 duration (green points). Due to the composition of mobility score durations within an MMSC, MMSC4 and MMSC5 with higher perceived welfare impact and longer durations mostly occurred because of preceding mobility scores with a longer duration.

Sensitivity analysis

The global sensitivity analysis showed that the perceived herd-level welfare impact per MMSC is most sensitive to variations in perceived welfare impairment weights regarding functional impairment as it was the prominent occurring welfare indicator

across the perceived herd-level welfare impact per MMSC (Fig. 3). For MMSC2 and MMSC3, the perceived welfare impairment weights respective of the maximum mobility score of the MMSC contributed most to the variation in perceived welfare impact per MMSC. For MMSC4 and MMSC5, the perceived welfare impairment weights respective of mobility scores preceding the maximum mobility score of the MMSC contributed the most to the variation in perceived welfare impact per MMSC. Complete first and total order sensitivity indices for perceived herd-level welfare impact per MMSC are found in [Supplementary Tables S2 and S3](#).

Discussion

We proposed a multi-faceted approach that can contribute to future research concerning the impact of health disorders on animal welfare. Our research is positioned in the context of SOM due to its welfare importance (Broom and Corke, 2002; Welfare Quality®, 2009; Whay and Shearer, 2017). The first step was to identify animal welfare indicators whereby the effect of SOM on these welfare indicators can be physically measured. The second step in this research was to estimate the perceived welfare impairment weights per welfare indicator level that were indicative of the welfare effects of SOM through the welfare indicators, and the relative importance of welfare indicators. With the first and second steps complete, the third step could be achieved, and this was to quantify the perceived welfare impact of SOM.

For our approach, it was important to use an animal welfare framework to guide our research. Several frameworks are available for this purpose. For instance, the Five Freedoms of animal welfare list five aspects of animal welfare that should be ensured to mitigate negative animal welfare (Farm Animal Welfare Council, 2009). While this framework is important, it has a broad focus, as each aspect can encompass several components crucial for ani-

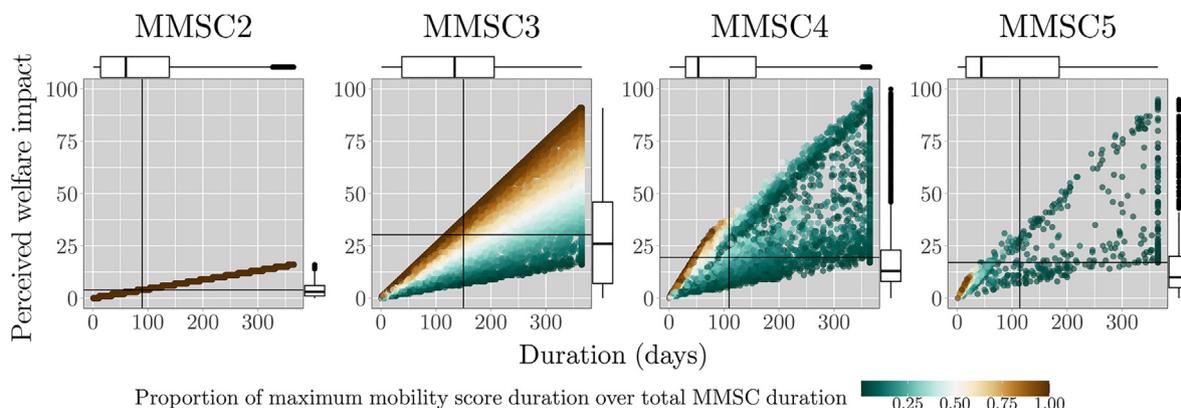


Fig. 2. Relationship between dairy cow welfare impact score and duration of Maximum Mobility Score sub-optimal mobility Case (MMSC). Each point represents a sub-optimal mobility case per MMSC category that occurred in the 500 simulations for 1 year. Point colours represent the proportion of the maximum mobility score duration over the total MMSC duration. Black horizontal and vertical lines respectively indicate the mean MMSC welfare impact score and MMSC duration. Boxplots indicate the interquartile range for MMSC welfare impact scores and MMSC duration.

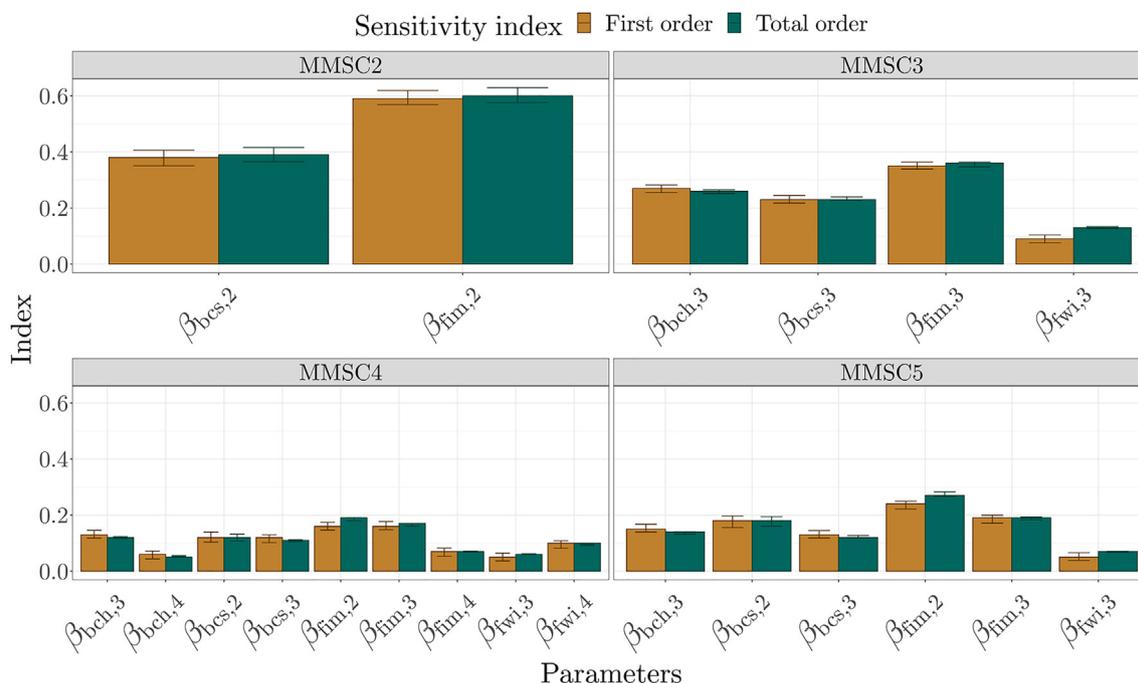


Fig. 3. First and total-order sensitivity indices >0.05 for dairy cow welfare impairment weight parameters $\beta_{j,l}$ for dairy cow welfare indicator j and mobility score l per Maximum Mobility Score sub-optimal mobility Case (MMSC). Dairy cow welfare indicator j abbreviations: bch = behavioural change; bcs = body condition score; fim = functional impairment; fwi = feed and water intake.

mal welfare. Moreover, it does not provide specific guidance on how to quantify animal welfare. On the other hand, the Welfare Quality protocol offers a valuable system for quantifying overall animal welfare by concentrating on various animal welfare indicators (Welfare Quality®, 2009). However, it uses the occurrence of health disorders as an indicator and therefore has limitations when it comes to quantifying the impact of those health disorders on animal welfare. For animal health management, it is crucial to understand how health disorders, with varying severities, affect animal welfare. This understanding is essential to enhance decision-making processes related to animal health in the context of animal welfare. Since animal health disorders can affect animal-based welfare indicators, which are important in understanding how an individual animal responds to and is impacted by factors that can compromise its welfare, we chose the 5-Domains model of Animal Welfare (Mellor et al., 2020) to guide our research.

The 5-Domains model of Animal Welfare (Mellor et al., 2020) lists and discriminates between four physical domains and one affective experience domain. The nutrition, health and behaviour domains list several animal-based welfare indicators whereby the effect of a health disorder on these welfare indicators can be physically measured. It is possible to measure the physical effects of a health disorder in relation to the animal-based welfare indicators. For example, the physical effects of SOM in relation to feed intake activity have been measured before (Navarro et al., 2013; Norring et al., 2014; Walker et al., 2010; 2008). Although the physical effects possess information on the degree to which the welfare indicators are physically affected in relation to the health disorder, these physical effects do not provide information on the associated degree of animal welfare impairment. Linking these physical effects on the animal-based welfare indicators in the physical domains to the affective experience domain (i.e., mental state) is much more difficult and seems impossible in animals. This is because our abilities to ask the animal directly, based on the physically affected welfare indicators we can measure, remain limited. What we can do is reflect upon the limitations of a health disorder

on each welfare indicator in relation to the physical effects and infer how the welfare of the animal is affected based on expert knowledge. Hence, with expert knowledge, the physical effects of a health disorder on welfare indicators can be represented by perceived welfare impairment weights. We are aware that perceived welfare impairment weights do not reflect the actual welfare impairment experienced by animals. Until methods become available to measure actual welfare impairment through direct measures, relying on expert knowledge developed over years of research and experience (Holtrop et al., 2021) is the best we can do when information is limited (EFSA, 2014). In fact, using expert knowledge is quite a common approach in animal welfare risk assessment. Additionally, it is extensively used in the EFSA opinions that underlie the proposals for changes in EU welfare legislation (e.g., Nielsen et al., 2022, 2023a, 2023b, 2023c, and 2023d).

We used ACA as a tool to elicit expert knowledge and derive perceived welfare impairment weights in relation to the physical effects of SOM on welfare indicators. Although ACA is grounded in consumer utility, we emphasise that our utilisation of ACA was not to translate animal welfare into a consumer utility framework. Rather, our approach aimed to derive the perceived negative welfare effects (i.e., welfare impairment weights) that correspond to different varying physical effects (i.e., welfare indicator levels) of a health disorder on animal welfare through corresponding animal welfare indicators. The use of ACA in this study provided a structured and quantitative way to do so. ACA has been used elsewhere to elicit expert opinion on the perceived risk factors for different animal health disorders (e.g., van der Fels-Klerx et al., 2000; van Schaik et al., 1998). In addition, we used ACA as an elicitation method instead of the Delphi method proposed by the EFSA (2014) often used in animal welfare-related research (Bertocchi et al., 2018; Bruijnjs et al., 2012; Lorenzi et al., 2022; Nielsen et al., 2021; Rioja-Lang et al., 2020) because ACA is advantageous over the Delphi method. ACA is a paired-comparison elicitation method that allows for the degree of SOM welfare impairment on multiple welfare indicators to be assessed relative to each other instead of

independently like in the Delphi method. This feature of ACA allows for a more realistic assessment of SOM welfare impairment on welfare indicators because SOM can affect these indicators simultaneously. Moreover, the selection of welfare indicator levels is chosen with mathematical reasoning per expert respondent ensuring that the welfare indicator levels with similar welfare impairment weights are properly compared relative to other welfare indicator levels. A relative assessment of perceived SOM welfare impairment on welfare indicator levels contributes to a better understanding of the relative importance of welfare indicators, which in turn provide more informed perceived welfare impairment weights. This expert-derived information is essential to aid informed decision-making related to animal health and welfare, especially when empirical evidence is limited (EFSA, 2014).

The perceived welfare impairment weights were determined based on the input from 23 respondents, representing a considerably larger sample size when compared to other expert knowledge elicitation-based studies, which involved between 8 and 16 respondents (Bertocchi et al., 2018; Bruijnijis et al., 2012; Lorenzi et al., 2022; Nielsen et al., 2021; Rioja-Lang et al., 2020). A common criterion for expertise in expert knowledge elicitation animal welfare studies is a minimum of 10 years of animal welfare experience (e.g., Bertocchi et al., 2018; Lorenzi et al., 2022). Out of our respondents, 13 had over 10 years of experience in the field of animal welfare. We used this subgroup as our primary expert group. The reliability of expert knowledge can be grounded in the mental models developed through years of practical experience and research (Holtrop et al., 2021). To limit the potential biases associated with individual experts' perspectives, we aggregated the responses across the primary expert subgroup to capture a more comprehensive view of the perceived welfare impairment weights. Additionally, a Welch Two Sample t-test revealed no significant differences in the perceived welfare impairment weights between respondents with more than 10 years of animal welfare experience and those with less. Consequently, we based our analysis on the average welfare impairment weights from our entire sample. Our expert elicitation process also involved rigorous techniques for ensuring transparency, reliability, and validation of the experts' mental models through the iterative process of the ACA.

We used five welfare indicators based on available information concerning the physical effects of SOM in relation to these animal-based welfare indicators. With sufficient resources, it is possible to measure the physical effects of SOM (or other health disorders) on more welfare indicators. This information can then further contribute to future ACA-based welfare impairment weight estimations derived from expert knowledge.

In the current study, functional impairment was the welfare indicator with highest average perceived relative importance in terms of welfare impairment. Using mobility scores to describe the functional impairment welfare indicator may have subconsciously influenced respondents to select the cow card with the highest mobility score always because SOM overall is an indicator of poorer welfare (Welfare Quality[®], 2009; Why and Shearer, 2017) and is described by mobility scores. Ultimately, this may have resulted in an overestimated perceived relative importance and welfare impairment weights for functional impairment. In other words, the welfare impact in a functional impairment level may have been perceived to be greater than the level itself, leading to an overestimated functional impairment relative importance and welfare impairment weights per functional impairment level. However, if the cow card with the highest mobility score was always chosen, we could expect a 100% relative importance for the functional impairment indicator. Our results show the relative importance of functional impairment per respondent ranged between 22 and 56%, meaning that other indicator levels were considered to impact animal welfare more than the highest level of

functional impairment shown. Respondents may have selected the cow card with the higher functional impairment level more frequently because higher mobility scores are associated with increasing levels of pain (Dyer et al., 2007). These results imply that the subjective experience of pain, a welfare indicator in the mental state domain (Mellor et al., 2020), is an important contributor to impaired animal welfare.

Feed and water intake was the welfare indicator with second highest average perceived relative importance in terms of welfare impairment. Scientific literature is limited concerning the effects of SOM on feed and water intake. Additionally, there is some disagreement in concerning the effects of SOM on feed intake. While Thorup et al. (2016) found that SOM did not have effects on feed intake, González et al. (2008), Palmer et al. (2012), and Norring et al. (2014) found that it did. Consequentially we included SOM to influence feed intake in our study. Although research has not been done on the effects of SOM on water intake, we decided to combine it with feed intake to broadly encompass the nutritional domain in the 5 Domains of the Animal Welfare model (Mellor et al., 2020). Hence, the levels do not solely reflect either feed or water intake but is a combination of both based on scientific literature and expertise (i.e., EG1). The results we found concerning feed and water intake having the second most perceived relative importance emphasise the need to further investigate the effects of SOM on feed and water intake for animal welfare reasons.

Defining the behavioural change welfare indicator and respective welfare indicator levels regarding SOM for the purpose of the ACA was challenging and may impose a limitation to the ACA. We defined it as a broad welfare indicator to capture all behavioural changes for a cow afflicted with SOM. Behaviour can be expressed as activities performed during an activity-budget and SOM is known to effect behavioural activities in various ways (Navarro et al., 2013; Walker et al., 2010; 2008). Therefore, we considered that a change of $x\%$ in the duration of one activity would lead to a cumulative change of $x\%$ in the duration of all other activities within the activity budget. This description may have influenced the respondents' degree of attention towards the welfare indicator and respective welfare indicator levels ultimately affecting the welfare impairment weights resulting in the lower relative importance of behavioural change. On the other hand, a behavioural change for a cow afflicted with SOM may also benefit animal welfare because the negative effects are compensated for to cope with SOM. Respondents may have considered this lending explanation to the lower relative importance of the welfare indicator because a change in behaviour may not always impair welfare when afflicted with a health disorder.

The BCS welfare indicator and perceived welfare impairment should be interpreted with caution. Although associations between BCS and SOM exist (O'Connor et al., 2019; Randall et al., 2015), it is difficult to determine the causal relationship between these two variables. In the instance that cows with a low BCS have a greater risk of becoming SOM, it would entail SOM does not affect animal welfare through changes in body condition, but rather changes in body condition affect animal welfare through increased risk of SOM.

The distribution of welfare impairment weights per welfare indicator were expected: the weights increased with each increase in welfare indicator level. Using ACA permitted us to link welfare indicator levels to mobility scores per welfare indicator to obtain a welfare disutility per mobility score, emulating what is typically done with ACA. Resultingly, we found that the welfare disutility was non-linear in increasing mobility scores. By using the welfare impairment weights linked to specific mobility scores as inputs for the simulation model, we were able to assess the welfare impact of SOM. A better understanding of the welfare impacts of SOM at MMSC-level over time was realised.

Interestingly, MMSC5 on average had the second lowest welfare impact score despite mobility score 5 having the highest welfare disutility (i.e., strongest negative welfare effect). This is because the duration of mobility score 5 during the cases was short on average. Conversely, the longer MMSC3 had the highest welfare impact score despite mobility score 3 having an intermediate welfare disutility. These results imply that disease severity at individual animal-level should be assessed over the duration of the case to assess the welfare impacts because a cross-sectional assessment does not capture the entirety of the welfare impact. Moreover, the total welfare impact at herd-level was largest for MMSC3 SOM cases due to the high frequency in MMSC3 cumulative incidence. In practice, better animal welfare concerning SOM can be achieved at cow- and herd-level if cows with lower mobility scores are detected and treated sooner since they contribute significantly to impaired animal welfare.

The global sensitivity analysis showed interesting results regarding the effects of welfare impairment weights associated with mobility scores 2 and 3 on the total MMSC4 and MMSC5 welfare impact scores at herd-level. The results showed that the uncertainty in welfare impairment weights for mobility scores 2 and 3 outweighed the uncertainty in welfare impairment weights for mobility scores 4 and 5. This means that efforts in understanding the welfare impairment of longer-lasting mobility scores 2 and 3 should be prioritised because of the cumulative effect they have on cow welfare under current SOM management.

The welfare impact of SOM per MMSC was calculated based on cow-level mobility scores. However, it could be that a cow has more than one mobility score (i.e., each hoof can be scored individually). Future research should consider the effect of multiple less severe mobility scores at hoof-level compared to a single mobility score at cow-level. Future research should also focus on coping mechanisms associated with mobility scores that reduce the negative welfare impact of a mobility score over time. These coping mechanisms could be represented by dynamic marginal changes in welfare impairment weights. Our simulation model does not include dynamic marginal changes in welfare impairment weights. Including dynamic marginal changes could help attain welfare estimates more representative of “actual welfare” as aggravating or coping mechanisms are captured for each additional day spent with a mobility score. This could be achieved by including a time variable in the adaptive conjoint analysis to obtain a time-adjusted welfare impairment weight.

We focussed on the welfare impact of SOM, without considering the effect on mortality and early culling, therefore forgetting the length of life. Welfare Adjusted Life Years (WALY; Teng et al., 2018) is a metric that takes both into account, where the effect of a health disorder on life years is corrected for. It may be of interest for future studies to combine our approach with the WALY approach to provide additional insight into the life-year corrected welfare impact of health disorders.

Our approach can be expanded to quantify the welfare impact of multiple health disorders at the same time. This can be achieved by identifying multiple welfare indicator levels across multiple health disorders. Using ACA welfare impairment weights can be estimated per welfare indicator level irrespective of health disorder. Then, the welfare disutility per health disorder per severity can be obtained by linking health disorder severities to corresponding welfare indicator levels, as we did for mobility scores (Table 3). Using this elicitation approach to quantify the welfare impact across multiple health disorders, with simulation modelling for example, ensures that the quantified welfare impacts across health disorders and severities are comparable because the underlying welfare impairment weights are elicited relative to each other. Additionally, the comparison of welfare impacts across health disorders and respective severities with simulation

modelling makes it possible to evaluate the effects of disease prevention and/or management that can support disease management decisions concerning animal welfare.

Conclusion

In this research, we demonstrate a multi-faceted approach to estimate the welfare effect of a health disorder. The approach consisted of an estimation of the effect of a disorder on welfare indicators in combination with a weighing of these indicators regarding the total welfare. This approach allowed us to quantify the welfare impact of the health disorder on animal welfare given the derived animal welfare weights. Our research shows that ACA is a suitable methodology to elicit expert knowledge to simultaneously evaluate the effect of a health disorder, SOM in this case, on various animal welfare indicators and to obtain the relative importance of welfare indicators and welfare impairment weights per welfare indicator level. This is an advantage of this method because welfare impairment weights per health disorder severity class, mobility scores in this case, can be derived. Our results showed that welfare impairment weights were non-linearly increasing in mobility score severity. Albeit, cases of SOM with lower mobility scores had the largest impact on herd-level welfare. This demonstrates the importance of early detection and treatment of lower mobility scores to improve animal welfare and that welfare impacts of different health disorder severities should be assessed over the duration of a case and not only at a cross-sectional level.

Supplementary material

Supplementary material to this article can be found online at <https://doi.org/10.1016/j.animal.2023.101056>.

Ethics approval

Not applicable.

Data and model availability

None of the data were deposited in an official repository. The model was not deposited in an official repository. Data and the model are available upon request.

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

During the preparation of this work, the author(s) used Microsoft Word and ChatGPT to proofread, and check spelling and language clarity. After using these tools, the author(s) reviewed and edited the content as needed, and take full responsibility for the content of the publication.

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Declaration of interest

None.

CRediT authorship contribution statement

F. Edwardes: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. van der Voort:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **T.B. Rodenburg:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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