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Ahmed Ferchiou, Guillaume Lhermie, Didier Raboisson. New standards in stochastic simulations of dairy cow disease modelling: Bio-economic dynamic optimization for rational health management decision-making. Agricultural Systems, 2021, 194, pp.103249. 10.1016/j.agsy.2021.103249 . hal-03483292

HAL Id: hal-03483292
https://hal.inrae.fr/hal-03483292v1

Submitted on 16 Oct 2023

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Keywords: optimization, bio-economics, animal health, dairy

JEL: C61, D24, Q12

Abstract

Bioeconomic models applied to animal health issues are now commonly observed in literature. This section of literature is very heterogeneous and the underlying methods are very diverse, from very simple methods (partial budgeting) to very complex ones. The objective of the present study is to build a new dynamic stochastic optimisation bioeconomic model applied to the dairy cow sector, that goes beyond some limitations usually found in methods used up to now. First, based on a critical literature review, we highlight four issues of bio-economic stochastic simulation models (BESSMs) applied to dairy cow diseases at the farm level. These models appear as partial (the farm system is not considered as a whole), unbalanced (between the economic and biological parts of the model), closed (to the farm environment) and only partially dynamic. To address these 4 main issues and improve the methodological standards in the microeconomics of dairy cow health management, we secondly develop a new bio-economic sequential optimization model (BESOM), called DairyHealthSim. DairyHealthSim aims to better consider both the context of decision-making and the farming system dynamics to define the best health management strategies in a given context. The biological part of the model simulates the complex dairy production cycle with a holistic approach. It is defined on a cow-week basis, and the weekly probabilities for all cow events, including production, reproduction and diseases, are simulated. The economic part of the model is a mean-variance optimization framework that dynamically represents the farmer's input allocation decision process under constraints. The biological and economic parts are closely integrated and the model is running with back and forth between the 2 parts of the bioeconomic model. Third, an application involving farmers' strategies related to biological risk management, labour willingness and market demand is proposed for dairy production and mastitis management. The results highlight the added value of the farming system-driven system coupled to economic optimization approach. DairyHealthSim identifies the optimal scenario for the entire ten-year simulation period or is based on yearly optimization (sequential modelling). The two different optimal solutions found show the usefulness of considering the dynamics and complexities of the actual field situation. The opportunity cost between the best and alternative solutions demonstrates that some solutions are economic equivalents. In conclusion, compared to approaches where the outcome is reduced to the monetary impact of diseases, DairyHealthSim is far more precise and appropriate for supporting decision-making.

1 – Introduction

Economic studies applied to animal health from the microeconomic to macroeconomic levels have mainly focused on analysing (i) the economic impact of animal diseases (Kobayashi et al., 2007; McKibbin and Sidorenko, 2006) and (ii) the economic viability of intervention (Bruijnis et al., 2010; Delabouglise and Boni, 2019) to support future private or public animal health interventions (policy-making or stakeholder rationales). In these studies, the economic evaluation relies on four pillars. First, these studies focus on the impacts of diseases on animals, i.e., direct and indirect production losses and extra expenditures, to define interventions that mitigate these impacts (Bruijnis et al., 2010). Second, they define prevention and control measures through the direct costs of prevention, the control costs and the opportunity costs (Østergaard et al., 2005). Third, market impacts are considered in the case of market restrictions or penalties due to the effects of animal disease on a livestock product or in the case of shocks to consumption demand, production offers or prices when diseases occur (Lhermie et al., 2019). Fourth, the analysis is extended to impacts beyond the livestock sector vis-à-vis impacts on public health, environmental change and food security (externalities) (Solomon and Oliver, 2014). Externalities are by definition not directly focused on models aiming at improving farmer's utility, but the outcomes linked to externalities (welfare, gaz emission …) are more and more often present as a daily constraint for the farmer, since production specification now often includes such criteria.

The majority of bio-economic stochastic simulation models (BESSMs) have been developed to assess animal health issues. For instance, at the scale of microeconomic analysis and for dairy cow health issues, BESSMs have been applied to production diseases such as mastitis, lameness, and reproductive disorders of cow replacement (Bekara and Bareille, 2019; Bérodier et al., 2019; Bruijnis et al., 2010; De Vries, 2004; Enting et al., 1997; Ettema and Østergaard, 2006; Gussmann et al., 2019c, 2019b; Huijps and Hogeveen, 2007; Huxley, 2013; Kalantari et al., 2016; Kossaibati and Esslemont, 1997; Kristensen, 1988; Mohd Nor et al., 2015; Scherpenzeel et al., 2016; Van De Gucht et al., 2018). These models are based on biological stochastic simulations of a disease dynamic, and the simulation results are then used to calculate the monetary impacts. A switch of models from static to dynamic and from deterministic to stochastic has been observed, but this shift does not guarantee that the approach is appropriate for answering the economic questions of interest. The differences between how economists and health specialists use economic data have enhanced the development of BESSMs, but there remain concerns regarding how economic concepts are used to support decision-making for health management on farms. Most models remain based on monetary approaches, with a system composed of a biological system simulator to which a monetary evaluation is added (Cha et al., 2011; Getaneh et al., 2017; Swinkels et al., 2005). In contrast, economics means resource allocation decision and not only money problem solving. Decision making consequently means not only focusing on money but more broadly on behaviour related to choices between opportunities, i.e. behaviour around decision making. As a consequence, contrary to models based on monetary approaches, the integration of a biological system representation and an economic decision-making simulation should offer a better frame for formulating recommendations on animal health management on farms. The aim of applying a BESSM to animal health issues at the farm level is to help farmers' decision-making while considering the various daily constraints they face. This issue cannot be summarized with a single monetary common denominator, whatever the model aims at explaining or supporting the farmer decision. Farmers' daily decisions and farm-level health management strategies are made in an uncertain and risky context, which is badly represented by monetary approaches. Additionally, the actual context of designing agricultural policies for dairy production can be mainly characterised by multiple political and societal concerns (multifunctional agriculture), such as animals' exposure to antimicrobials, animal welfare on farms, production system-related environmental externalities and farm economic viability. In this context, a bio-economic approach should offer a concrete response by making it possible to perform integrated multi-criteria analysis that simultaneously captures multiple objectives (Brouwer and van Ittersum, 2010; Flichman, 2011).

The European dairy sector is used here as a supporting example for three reasons. First, it is characterized by a long production cycle (e.g., a minimum of 2 years for a cow to produce milk, with subsequent milk production lasting several years), which induces a higher biological risk. Biological risk corresponds to higher disease or lower production risk, whereas management risk (or economic risk) is the economic (financial, extra labour etc) risk related to management decision. Confusion between biological and economic risk often occurs. Second, common dairy health disorders are multifactorial and have multiple direct and indirect impacts, and decisions are difficult to automate due to the high value of each individual animal. Third, the production process of this sector is extensively linked to its environment (European policy, regulatory and societal pressure, market liberalization, its moderate size with an important familial dimension), and dairy farmers' decisions are related to this environment and the related uncertainties. This sector is a perfect illustration of the need for a structure-improved BESSM that allow at a glance two major improvements. First, there is a need to improve the integration between the biological parts of the bioeconomic model, to fix the issues linked to interactions between diseases, multi-disease management and long-term driven decision. In such a purpose, 3 characteristics of the current BESSM will be highlighted in the section 2 be done in the present study and then address in section 3: models are partial (the farm system is not considered as a whole), too closed (not open to the farm environment) and only partially dynamic. Second, there is a need to improve the integration between the biological and economic parts of the bioeconomic model, since only a juxtaposition is often done in BESSM. This issue is called an unbalance between the economic and biological parts of the model, depply explained in section 2 to be address in a new model also in section 3.

The aim of the present study is to offer a critical literature review of BESSMs applied to animal health using the example of dairy cattle health (section 2) that allow to present a new bio-economic sequential optimization model (BESOM) as a proof of concept (section 3) and an application of this new model called DairyHealthSim (section 4).

2- What are the problems of bio-economic stochastic models applied to dairy cattle health?

Farm-level bio-economic models applied to animal health face 4 main issues in interaction. They are **partial,** as they focus only on the consequence of a specific problem or a subsystem-related intervention. They are **unbalanced** between an important biological part (minimal level of complexity) and less important economic part of the models (often limited to only monetary estimation). They are somewhat **closed** in that they look for only a narrow range of solutions. Finally, they are only **partially dynamic**, especially regarding the economic part of the BESSM. These four characteristics are detailed here using the example of dairy production.

2-1 Microeconomic models applied to animal health are partial and require systematic thinking

The bio-economic models used for dairy cattle health offer detailed representations of biological processes at a microeconomic level (individual farms). However, they remain partial because they do not transparently consider the interactions with the different subsystems of a dairy farm such as reproduction, milk production, animals growth, udder health, foot disorders, metabolic disorders, building, etc. Consequently, the results cannot be extrapolated from the set of situations considered, reducing the usefulness of the study results. This modelling is performed under an implicit unverified assumption that the subsystems are independent. With a partial representation, it is important to consider the effect attribution issue to ensure that the estimated economic impact is related to the analysed disease, not to other peripheral factors. For an appropriate understanding of a) dairy health management system and its components, models should avoid an isolated system component representation (Oberle and Keeney, 1991). Depending on the particular livestock system, the assumption of subsystem separability can be more or less appropriate or acceptable. For this reason, dairy production, which is linked to long-term open and complex dynamic systems, is highly impacted by the biases linked to the partial characteristics of BESSMs. An interdisciplinary whole-herd modelling approach is required (Calsamiglia et al., 2018; Schils et al., 2007) because the dynamic interactions between system components are the main determinants of the final herd behaviour (Drack and Schwarz, 2010) : modelled subsystems determines how the whole system reacts, and a partial representation can be misleading for some issues.

Such an approach requires the definition of at least three essential components and their interactions (Figure 1). A classic representation in production economics would be through a production function. In this study, production function (output production) is connected to damage functions (diseases) and damage control functions (treatment). This representation allows a transparent formulation of scenarios of health management decisions on farm. The complexity of the production functions in dairy production should be viewed as a process composed of inputs, outputs, and feedback loops, which is inserted into an environment that conditions its operation (Tanure et al., 2013). Damage functions represent second-level loops that modify the production process in the presence of health disorders. Damage control functions are third-level feedback loops that modify the damage functions when a therapeutic, preventive or curative tool is adopted and the correction of damage is partial or total, which depends on the disease. Damage control functions also have a direct impact on the production process through the inputs used and an indirect impact through the damage functions.

2-2 Microeconomic models applied to animal health are unbalanced and are based on very limited economic reasoning

BESSMs applied to animal health can also be characterized as unbalanced between their biological and economic parts. Between these parts, efforts are usually made to represent and simulate the complexity of biological processes, but a lack of effort is made when simulating decision-making processes, and economic evaluations are most often reduced to their monetary dimension. Thus, BESSMs can be described as primarily biological process models to which a minimal economic analysis component is added (Brown, 2000). Even if these approaches allow for an impact assessment, they propose a limited representation of the trade-offs in resources allocation of a biological processes and health management decisions in a given market context. In terms of strategic and managerial choices, the manner in which models simulate the decision-making process should be the focus. At the microeconomic level of the farm, herd health performance is strongly influenced by farm management (eg farmers' preferences) and the institutional context including market (price volatility) and consumer requirements (production system and product quality). Models should be able to consider the preferences of decision-makers and the constraints related to the environment in which they make decisions. Many studies have demonstrated that farmers are typically risk averse (Hardaker et al., 2004) and that price or revenue uncertainty has a significant influence on production decisions (Chavas and Holt, 1996). Yet, considering very limited disease prevention that take place in the farms, the level of risk aversion of farmers remains unclear. Ignoring risk-averse behaviour can lead to results that are unacceptable to farmers or that bear little relation to the decisions that they actually makes (Hazell and Norton, 1986). Moreover, farmers’ workload is an important driver of health decisions on the farm (Belage et al., 2019). To summarize, we need to produce models that are less normative and that better capture the reality in the field and the behaviours of real actors.

Authors using BESSMs as support for decision-making for health management on farms agree that an optimal strategy should be based on proper economic optimization (Carpenter et al., 2011; Kristensen, 2015). However, optimality is defined differently by authors, from reducing diseases cost to maximizing cost-efficacy ratios (Beyene et al., 2019; Cha et al., 2011; Derks et al., 2014; Scherpenzeel et al., 2016; Van De Gucht et al., 2018; van Soest et al., 2018). These utility functions consider only the monetary dimension of animal health, market conditions are assumed to be known and constant, and a farmer’s non-monetary constraints are not considered in the decision-making. The optimum should be defined following the Pareto-Koopmans concept of efficiency while considering market conditions: a decision-making unit is fully efficient if and only if it is not possible to improve any input or output without worsening some other input or output (Palmer and Raftery, 1999). Animal production activities are typically risky and involve multiple risk origins, e.g., price volatility, climate change, resource variations, and natural hazards. This riskiness causes farmers' incomes to be unstable and daily decisions to be made in a risky environment. In such a risky environment, a production decision has no unique known income; rather, it has a set of possible incomes for every state of nature or market state. From a practical perspective, a nature or market state corresponds to a particular year (i.e., years with too dry or too wet weather or with high/low milk prices). For economic analysis in agriculture, many different programming formulations for risk problems have been proposed (Hardaker et al., 2004; Hazell and Norton, 1986). The expected utility framework (Von Neumann and Morgenstern, 1947) is suitable for simulating the decision-making process while dealing with risky choices that involve uncertain outcomes and for considering the market risk-averse behaviour of farmers.

BESSMs should have a clear position in both the economic and biological scientific corpus, and the construction of each side should consider the specificity and conceptual basis of the other (Flichman et al., 2011). The economic part of BESSMs currently used for animal health decisions does not match the current scientific standards (i.e. integrating the decision maker constraints and preferences -risk aversion and time preferences- when trying to define which decision he should adopt, as done for instance in crop bioeconomcis applied to crop disease) and is not appropriate for answering the questions that researchers and stakeholders wish to address. For instance, dairy farming is one of the most multifunctional animal production activities and has several marketable (e.g., milk, meat, and live animals) and non-marketable (e.g., antimicrobial resistance, gas emissions, and territorial development) outputs. To represent the relationship of inputs to outputs, the focus should be on production processes instead of the products themselves (Koopmans, 1951) since a common unit of productivity is not appropriate for a multi-objective analysis. This concept implies that each production process will be defined as an activity by technical coefficients that represent the use of the inputs needed to produce different outputs. This representation allows a representation of all outputs produced by any dairy production activity and the different ways of producing a single product through the use of an engineering production function approach. Dairy herd health management can be seen as an activity, and 3 kinds of engineering production functions can be considered: a main engineering function for dairy production, a damage function that represents diseases and a damage control function that represents the disease control and management strategy. For the many BESSMs used for integrated multi-objective issues, these functions constitute the main link between the biological and economic parts of BESSMs (Flichman, 2011; Flichman and Allen, 2014).

2-3 Microeconomic models applied to animal health are closed, with restricted representation of the alternatives

The closed characteristics of BESSMs applied to animal health concern both the biological and economic parts of BESSMs. Simulation is performed through behavioural proxies used to represent biological complexity, but such simulation mainly implies a restricted representation of the alternatives to achieve a satisfactory goal. This issue is a critical concern since the results provided may not be the optimal result(s) because the optimal result(s) were not included in the range of possibilities. Models are by definition simplifications of the reality, and the limitation highlighted here is not a call for always more complex models. There is yet a trade-off to be find that allow to propose robust model, not biased by the so-called closed characteristics of the model.

For the biological part of BESSMs, this issue is mainly linked to an *a priori* BESSM, as illustrated by the example of animal culling. Some culling is often represented in BESSMs as a biological event, meaning that the biological model does not allow the characterization of the specific reasons for culling and creates an important *a priori* in the model (since if culling reasons are not explained or if the several reasons for the same culling are not adjusted for, a biased is created). Mechanistic models that explain with a limited *a priori* rule most of the biological events are required to avoid a closed BESSM. These closed characteristics of BESSMs in their biological part have indirect consequences for their economic part and limit the range of economic possibilities offered. For instance, overrepresented involuntary culling prevents a consideration of culling in the economic decision-making process (Fetrow et al., 2006) and in the health management strategies used by actors for strategic herd dynamics or for milk quality management (Gussmann et al., 2019c, 2019a).

Regarding the economic part of BESSMs, the closed characteristics have two main and very significant consequences. First, these characteristics are closely linked to the economic method and the way in which the economic question is addressed (cost assessment *versus* resource allocation behaviour). A disease cost or an intervention benefit is usually estimated relative to a do-nothing situation, which offers limited support for decision-making because this reference situation is rarely a common situation in the field. For example, to evaluate the total cost of a disease, an estimate is made relative to a healthy situation, but information on the avoidable cost between the common situation and the optimal situation would be more informative regarding the loss of income due to health management. That is, for the decision-maker, the opportunity cost of a given option compared to an optimal situation provides more information and is more likely to help decision-making. Thus, it is useful to define a contextualized and feasible optimal situation to assist decision-making in regard to animal health. Conversely, it is also important to properly assess the socioeconomic costs of achieving optimal performance, which can be compared to the present common situation. Several types of microecomic and bioeconomic models have been used to analyse animal health management decisions on dairy farm (Carpenter et al., 2011; Kobayashi et al., 2007; Mutambara et al., 2013; Rushton and Upton, 2006; Tomassen et al., 2002). However, most economic models and submodels have used methods that somehow interact a positive economic impact with a negative impact, such as methods using cost-benefit, cost-effectiveness and partial budget analyses. Most of them consider only a limited range of alternatives for the farmer.

Second, the issue of closed BESSMs arises due to inappropriate economic questions that this study attempts to answer. Many BESSMs applied to animal health investigate the relevance of a health intervention or the consequences of a disease with economic and biological variables. The underlying question is not truly an economic question related to resource allocation, and it can be seen (at best) as a step towards meeting such an objective. A typical example of this situation is the focus on the retention pay-off (RPO) value found in many publications in the form of either an optimization criterion (Cha et al., 2014; Groenendaal et al., 2004; Huirne et al., 1997) or a culling cost (Inchaisri et al., 2011). In brief, the RPO is the farmer's expected cash flow from not culling a cow. It is the difference between the net present values of keeping and replacing an animal. However, RPO reasoning does not allow, for instance, a consideration of the different strategies for reproduction management the farmer may adopt, and more aggressive reproduction management (either through more heat detection (labour) or more drugs) may change the subsequent RPO decision results. The more the BESSM aims to evaluate specific strategies without considering the system, the greater the likelihood that the model will miss an alternative opportunity that is associated with higher utility for the farmer.

2-4 Models are neither time related nor dynamic

Time preference refers to the decision maker behaviour (for instance, I prefer to win less and to get the money right now), and dynamics refers to the biologic sequences of actions and consequences (short or long term consequences of diseases). In a bioeconomic models, time preference and dynamics of biological process interacts (for instance, the timing of the intervention influence the benefit cost ratio). Most BESSMs applied to animal health fail to appropriately consider the question of time preferences. For dynamic and long-term processes such as those focused on here, this means more than simply applying a discount rate to the monetary evaluation obtained. Analysing long-term animal health management strategies requires a consideration of spontaneous changes in the behaviours of farmers over time and changes due to the evolution of the context (e.g., a new disease). The prevalence of diseases and external changes in disease risk exposure (due to the presence of risk factors) is recognized as a key driver of behavioural changes in farmers' animal health management strategy (McLaren et al., 2006; Valeeva et al., 2007). These changes in disease risk (damage functions) directly lead to changes in disease management (damage control functions; Figure 1). Market conditions also lead to changes in farmer behaviours. Consequently, sequential optimization approaches appear to be more appropriate for BESSMs to capture the continuous adaptation by farmers to herd characteristics and the farm context. Farmers acquire information progressively and consequently revise their decisions, which corresponds to the sequential characteristics of the optimization process. BESSMs applied to animal health often do not consider sequential decision-making even when they include different time slots. A consideration of time is even more important in that animal health status represents a value option for the farmer. In addition to the fact that animals represent a high capital investment *per se* for most agricultural firms (which is extremely important in low-income countries), their health status can be seen as an intangible value created by farmers' previous investments in cow health (time $t-1$), which were present as an option value at time t and were potentially transformed into cash through better productivity (higher inputs or lower outputs) at time $t+1$. Adjusting economic evaluations by using animal health capital as an intangible value requires long-term evaluations and sequential approaches since this issue is closely linked to risk considerations. Creating high-health capital animals through prevention can be a non-strategic decision if this capital cannot be valued as cash, for instance, because of new diseases that interfere with dairy operations or because husbandry conditions do not allow the realization of this potential. Examples include calf-rearing conditions that influence milk production characteristics and udder contamination by pathogens that cannot be cured, thus leading to culling.

The next step is to propose a new BESSM that goes beyond and addresses some of the issues described above and the links to partial, unbalanced, closed and partly dynamic BESSMs.

3- A new bio-economic sequential model for optimizing farmer utility under constraints

A new BESOM is developed to address the concerns highlighted above. This model consists of a biological simulation model coupled to an economic optimization model (Figure 2). The outcome of the model is the farmer's utility under the different combinations of constraints faced in his/her daily activities.

3-1- Biological mechanistic modelling based on the cow-week for a 10-year period

The biological model is defined on a cow-week basis and on the weekly probabilities for all cow events, including milk production, reproduction and diseases (Figure 3). This biological component aims at a dynamic representation of a dairy herd. It means that the model is based on cow-week and the farmer decision is made at the herd level (including a strategy with rules at the cow level, linked to cows' characteristics). The mechanistic model was built to avoid *a priori* rules within the model and to systematically plan each event. It is detailed in supporting information 1. In brief, from birth to death, each animal was characterized weekly by his/her physiological and production status (e.g., male calf, female calf, pregnant, in-milk cow, and dry cow). This framework was applied to 3 main types of functions (Figure 1), namely, production (e.g., growth and milk production and reproduction), diseases (as damage to production) and treatment (as one type of damage control). Milk production was simulated by Wood's curve. Reproduction was described by modelling each ovarian cycle from puberty to first conception and for all cows after the post-calving anoestrus period.

Health disorders were mechanistically defined weekly for each cow and calf (supporting information 1). For each simulated cow, the weekly disease occurrence for a given event depends on a computed final risk that combines a basic incidence risk, cow characteristic risks (e.g., weeks in milk, parity, and theoretical milk production levels), herd-level contamination risks, disease-related risks, farmer management-related risks, and treatment-related risks (relapse). The cows' diseases and treatments that were simulated included dystocia, subclinical hypocalcaemia, milk fever, placental retention, puerperal metritis, purulent vaginal discharge, subclinical endometritis, left and right abomasum displacement, lameness, subclinical ketosis, clinical ketosis and mastitis. Each treatment pattern (supporting information 1) was characterized by 3 items: (i) the treatment composition, including drugs (e.g., antimicrobials and anti-inflammatories) and the nature of the intervention (cow-side intervention, consultation, and surgery), (ii) the expected efficacy of the treatment with regard to the disease and relapse risk, and (iii) three socioeconomic implications, represented by the farmer's labour for disease management, the treatment cost and veterinary costs.

A herd-size objective was fixed for in-milk cows to consider barn constraints, and the actual in-milk herd size was calculated weekly, including newly calved cows. To mimic typical farmer behaviour, the set of rules was defined to make the culling decision dependent on herd size. Culling rules were applied to all cows each week and were based on cow milk yields, pregnancy status, lameness and udder health. These criteria represent the main criteria used by farmers for culling decisions (Kerslake et al., 2018). The other health disorders were not considered in culling, but they act indirectly through milk yields, reproduction performance, udder health and lameness. The criteria and thresholds used for culling depend on herd density to stabilize the herd size near the objective. The biological mechanistic modelling is relatively straightforward and has been used in many other papers, but never with all these diseases in one study, what is very difficult to obtain.

3-2- Economic optimization modelling considering technical constraints and farmer behaviour

The economic model developed is a recursive mean-variance optimization framework. It dynamically represents the farmer's input allocation decisions while maximizing his/her utility under constraints.

Dairy farmers' decision-making processes under business uncertainty were simulated using an expected utility framework (Von Neumann and Morgenstern, 1947). It implies that rational decision-makers maximize their expected utility with respect to a set of constraints. They choose between risky alternatives by comparing their expected utility values. Here, farmers are assumed to be risk minimizers. They are willing to sacrifice a portion of their income to avoid facing business risk. In a typical French dairy farm, milk sales represent more than 80% of income, and feeding costs represent 40% to 60% of a farm's variable costs. The uncertainty of milk and feed prices is the major source of dairy farm business risk (Valvekar et al., 2010).

The risks considered in the model are i) a market risk, which is related to the volatility in milk and feed prices (based on prices over the last 10 years), and ii) a climatic risk, which is assumed to affect the on-farm produced forage quality (and then leads to more or less forage concentrate purchased to compensate).

A Markowitz-Freund mean-variance objective function was used to incorporate risk-averse behaviour in farmer decision-making (Freund, 1956; Hardaker et al., 2004; Markowitz, 1959). The decision-maker's expected utility (F) can be represented as defined in Equation 1:

$$\max \mathbf{F} = \mathrm{E}\left[\mathrm{Z}_{\mathrm{k,t}}\right] - \frac{1}{2}\phi\sigma\left(\mathrm{Z}_{\mathrm{k,t}}\right) \qquad [1]$$

where F is the objective function of farmers, **E** denotes the expected values, **k** represents the state of nature (defined here as the possible price level), $\boldsymbol{Z_{k,t}}$ is the equivalent-gross margin generated per state of nature **k** in year **t**, $\boldsymbol{\phi}$ is the risk aversion coefficient, and $\boldsymbol{\sigma(Z_{k,t})}$ is the standard deviation of income. According to Anderson and Dillon (1992), the risk aversion level of individuals may be represented by a relative risk aversion coefficient as follows: this coefficient is less than or equal to 0.5 for hardly risk-averse to risk-neutral individuals and greater than or equal to 4 for extremely risk-averse individuals. However, most authors consider values above 5 to be very unlikely (Kocherlakota, 1996). The risk aversion coefficient was set to 1, and a sensitivity analysis was conducted for values from 0 to 5, as these values represent different farmers' attitudes towards risk.

The equivalent-gross margin $\boldsymbol{Z_{k,t}}$ generated per state of nature **k** in year **t** is equal to the difference between revenue $\boldsymbol{R_{k,t}}$ and expenditures $\boldsymbol{Ex_{k,t}}$ per state of nature **k** in year **t** (Equation 2):

$$\mathrm{Z}_{\mathrm{k,t}} = \mathrm{R}_{\mathrm{k,t}} - \mathrm{Ex}_{\mathrm{k,t}} \qquad [2]$$

Expenditures are the sum of health and veterinary expenses (e.g., purchased medicines including antibiotics, veterinary consultations/interventions and surgery) ($\boldsymbol{Ex\_Vet_{k,t}}$), changes in food expenses due to changes in strategy (e.g., purchases of concentrate), ($\boldsymbol{Ex\_Feed_{k,t}}$) and other expenses ($\boldsymbol{Ex\_Oth_{k,t}}$), including related expense surcharges for housing and milking hygiene, insemination and other practices that have changed (Equation 3). Dairy revenues (Equation 4) are the sum of the revenues from each product sold, namely, milk ($\boldsymbol{R\_Milk_{k,t}}$), one-month-old calves, heifers ready for calving $\boldsymbol{R\_Ani_t}$ and cull meat ($\boldsymbol{R\_Cull_t}$):

$$\mathrm{Ex}_{k,t} = \mathrm{Ex\_Vet}_{k,t} + \mathrm{Ex\_Feed}_{k,t} + \mathrm{Ex\_Oth}_{k,t} \quad [3]$$

$$\mathrm{R}_{k,t} = \sum_{L} \mathrm{R\_Milk}_{k,t} + \sum_{A} \mathrm{R\_Ani}_{t} + \mathrm{R\_Cull}_{t} \quad [4]$$

where L denotes the cytological qualities of milk and A denotes the types of animals sold (e.g., heifers or male calves).

The weekly milk quantities produced and sold by the farm are recorded, and the mean weekly milk cytological and biochemical (fat and protein) qualities are considered to determine the monthly milk price paid to the farmer according to the usual payment criteria (Table 1). Cytological quality refers to the milk somatic cell count (SCC), which is a proxy for udder health and mastitis occurrence.

Four main categories of constraints are used during the optimization. First, the structural constraint of the barn is accounted for through a defined barn capacity $\boldsymbol{Capacity_t}$ and a simulated number of occupied places $\boldsymbol{X_{t,s}}$ for year **t** and management strategy **s**. This constraint is independent of herd size and can vary somewhat around the barn capacity (see herd density; supporting information 1):

$$\sum_{t,s} \mathrm{X}_{t,s} \leq \mathrm{Capacity}_{t} \quad [5]$$

Second, the workload is considered a management constraint on dairy cattle farms. Because the daily labour flow is difficult to capture and describe, changes in labour if there are changes in practices or new treatments for a given strategy are considered here. The additional labour time $\boldsymbol{W_{t,s}}$ the farmer has to bear in year **t** for management strategy **s** is limited to a threshold $\boldsymbol{W_{Threshold}}$ that corresponds to the additional workload that farmer **f** is willing to bear, as indicated in Equation 6:

$$\sum_{t,s} \mathrm{W}_{t,s} * \mathrm{X}_{t,s} \leq \mathrm{W\_Threshold}_{f} \quad \mathbf{[6]}$$

Third, the model is assumed to feed dairy cows with corn silage produced at the farm level and with a market supply of concentrated feed (e.g., wheat and soybean meal). The dietary composition is based on corn silage at 61% ± 10% of the dry matter requirement, on hay for 10% of dry matter, and on wheat concentrate and soybean meal at 29% ± 10%. The dietary composition must also meet the needs of cows for energy and crude protein. Risk applied to corn silage quantity and quality leads to changes in concentrate quantities (for compensation), which are considered to be purchased. Based on how food is included in the model, $\boldsymbol{Z_{k,t}}$ must be called the equivalent-gross margin instead of the gross margin.

Fourth, agro-ecological principles and sustainable dairy production are accounted for by antimicrobial use (AMU). Guaranteeing that the optimum condition is not obtained through extra AMU is a key point since the model may use a high level of antimicrobials to find optimal solutions and this situation does not match actual field practices. Equation 5 defines the percentage decrease in exposure to antimicrobials ($\boldsymbol{Reduction\_AM}$) compared to the reference scenario ($\boldsymbol{ALEA\_Threshold_{t,s}}$) to be applied to the antimicrobial exposure levels $\boldsymbol{ALEA_{t,s}}$ for year **t** and management strategy **s**:

$$\sum_{t,s} \mathrm{AMU}_{t,s} * \mathrm{X}_{t,s} \leq \left(1 - \frac{\mathrm{Reduction\_AM}}{100}\right) * \sum_{t,s} \mathrm{AMU\_Threshold}_{t,s} \qquad [7]$$

4- Usefulness of balanced, open and sequential bio-economic optimization modelling: a proof of concept

We apply here the concepts previously highlighted to a simple sample of common dairy health management strategies as a proof of concept by using the example of a common current concern in the dairy industry, namely, the goal of decreasing antimicrobial use without impacting farm profitability.

4-1- Farmers' strategies related to biological risk management, labour willingness and market demand

Three kinds of strategies that match the main concerns of the dairy industry were combined in the present study (e.g., AMU, labour…). They represent different choices that farmers can make for i) technical interventions related to disease treatment and ii) global farm management decisions (e.g., food and hygiene practices) as well as iii) the reactions of farmers to disease impacts (individual cow milk is discarded if high SCC levels are present to maintain low bulk milk tank SCCs that prevent any penalties).

The first type of strategy represents the options that farmers have regarding antibiotic treatment at dry off (mastitis represents the most important reason for AMU in the dairy industry) (Table 2).

The second type of strategy is designed to account for farmer choice regarding labour (Table 3). Strategies related to hygiene and feeding are mainly linked to labour time and, to a small extent, to extra material inputs. These strategies also represent farmer profiles, which are linked to the habits of farmers, and they delay routines from a behavioural perspective and lead to good (1), medium (2) or deteriorated (3) biological situations. They are declined for housing hygiene (time and straw, **Mh**), milking hygiene (time and extra products for udder cleaning, **Mm**) and food practices (mainly time because this is more closely linked to dry off diet management than to the diet cost, **Mf**).

The third type of strategy refers to farmer behaviour related to market constraints (Table 4). Bulk milk SCC is the main health-related criterion that influences the milk prices paid to farmers through regulation by premiums and penalties upon milk collection. It corresponds to the milk-quantity-weighted mean of a cow's SCC, which is related to cow mastitis. To avoid penalties or to reach a premium, farmers are accustomed to withdrawing high SCC milk from the few cows that contribute the most to bulk milk SCC. A cow's milk is considered to be withdrawn if it contains more than 800,000 SCC/mL of milk (E800), more than 10,000,000 SCC/mL of milk (E10m), i.e., almost no milk withdrawal, or more than 800,000 SCC/mL of milk if the bulk milk SCC is > 300,000 SCC/mL (E800T). These numbers refer to the strategic behaviour of the farmer and the trade-off between the quantity and quality of milk sold in relation to the strategies for udder infection risk management and mastitis treatment previously linked.

4-2- A broad range of biological situations is associated with heterogeneous utility

The application of combined strategies to bio-economic modelling allows us to draw upon a large range of technical situations that match the field situation in accordance with the open characteristics of the model.

From 5% to 48% of cows had no mastitis for a given lactation, depending on the scenario. The average clinical incidence of mastitis per cow and year (Figure 4b) is increased under strategy T2 (i.e., no AMU and no sealant if SCC is low before dry off) combined with low hygiene (e.g., Mh, Mu and Mf in the half-worst situation). This result is in agreement with the higher percentages of low-quality milk produced in these scenarios (Figure 4a). Up to 35% of the milk is then produced in the average SCC classes under strategy T2, whereas this figure reaches a maximum of 8% under strategies T1 and T3. Changes in culling rates and their reasons are observed (Figure 5a) with, for instance, a 5% increase in total culling under strategy T2. The overall limited change in culling is in accordance with the SCC and clinical mastitis thresholds used and with the limited change in bulk milk tank SCCs for the herd (Figure 4), and it demonstrates the ability of the model to precisely reproduce i) farmer adjustments in the decision process and ii) multilevel herd dynamics (a set of continuous multilevel solutions instead of drawer-like solutions). Maintaining low culling rates and high milk quality remains possible through extra labour for hygiene, and the amount of extra labour is not particularly high, at up to 17 extra hours per month (Figure 5c). The utility clearly shows that farmers with good practices maintain high revenue and that strategy T2 is usually associated with lower utility for farmers, except for those with good practices (Figure 6). The utility is lower when the withdrawal conditions are strict (e.g., E800 < E800T < E10m) and is in accordance with the high quantity of milk withdrawn under these strategies; then, the biological risk for mastitis treatment is high (strategy T2).

4-3- Economic optimization by combinations of strategies

Combining utility and constraints by hand, as was done above, allows us to obtain the optimal solution from a limited number of combinations. Economic optimization with a balanced and open modelling framework, as proposed here, allows us to go further in identifying the best strategies through 3 levels of analysis of the previously proposed results (Figures 4 and 5).

First, identifying the optimal scenario for the entire 10-year simulation period based on the highest utility under constraints leads to the same conclusion as that reached by the hand analysis presented above (Table 5, first line). Scenario T3_Mh1m2f1_E10m is identified as optimal over an average of 10 years of simulation according to the average farmer's expected utility (Figures 6a to 6c). This result demonstrates the importance of hygiene in the milking parlour; one conclusion may be that hygiene must be prioritized. The optimal choice proposed by the model is scenario T3_Mh4m4f2_E800T when labour constraints are considered. This scenario is a situation with deteriorated hygiene (labour saving) and a medium feeding strategy that is compensated for by a higher technical ability (i.e., compared to scenario Mh4m5f2, which has a lower workload efficiency). Constraints on AMU lead scenario T3_Mh1m2f1_E10m to be the optimal scenario, and no optimal strategy is found if both criteria are considered since this is not considered to be possible in the technical calibration (Tables 2 to 4).

Second, the sequential analysis based on yearly optimization instead of optimization of the entire period reaches different conclusions for the different optimal solutions for each year

(Table 5, years 1 to 10). This step clearly shows that the whole-period analysis has obscured the dynamics and complexity of the field situation and does not represent the optimal solution obtained from yearly combinations of scenarios.

Third, reasoning that focuses on opportunity cost calculations helps provide a better overview of the sets of optimal solutions that have similar economic meaning. Table 6 represents the opportunity costs for the whole period, and supporting information 2 gathers the same information for the sequential approach. The reasoning for using opportunity costs clearly shows that the previous conclusions (see the first and second items) were biased since there is a set of economic-equivalent (in the sense of very low opportunity costs, i.e., with similar economic meanings) optimal solutions instead of only one solution with the set of constraints being fixed. For the whole period, the opportunity cost for scenario T3_Mh4m4f2_E800T compared to scenario T3_Mh1m2f1_E10m, which were identified in the first step as optimal solutions when including labour constraints and with no constraints, respectively (Table 5), is €4,390. This value represents the opportunity cost of not consenting to the 15 hours per month of extra workload. The expected extra revenue in the case of extra labour under these specific conditions is this value of the opportunity cost. For T2 (Table 6) and E800 (Table 6), the opportunity cost is high, but it is null to low under the other strategies (Figure 6). This result demonstrates that the economic reasoning and the appropriate way of using and interpreting the sets of results with low opportunity costs involve focusing on the differences in constraints instead of maximizing utility (since they are of the same order of magnitude). For the sequential approach (supporting information 2), an example for the sixth year shows that choosing scenario T3_Mh2m1f1_E10m instead of scenario T3_Mh1m1f2_E10m costs €802, while choosing scenario T3_Mh5m5f2_E800 costs the farmer €17,344.

Analysing the empirical results in detail, we see that the opportunity costs of using T1 or T2 instead of T3 are higher (Table 6, lines 2 and 3) for farmers with good practices (e.g., m1, m2, h1 and h2) compared to those with deteriorated management practices (e.g., m4, m5, h4 and h5). This result is in accordance with the effective efficiency of antimicrobial inputs at drying off, which is lower in farms with good practices compared to deteriorated situations. Strategy T2 is never the optimal solution except for some years in the sequential approach and for farmers with good practices (m1, m2, h1 and h2). The opportunity cost for T2 compared to T3 is still very low (the main difference is the teat sealant cost for cows with low SCC), but the 2 strategies are highly different in the risks accepted by the farmer in the case of a context change; here, the opportunity cost represents the insurance that the farmer may pay for to prevent any deterioration in milk quality (higher biological risk of new infections) in cases of involuntary hygiene deterioration (such as temporary very wet weather, heat waves, farmer familial events, or a new general pathogen that leads to immunosuppression).

5- Discussion

The aim of the present study to describe a new BESOM, DairyHealthSim, that addresses the concerns linked to the partial, unbalanced, closed and partially dynamic characteristics seen in many BESSMs. The discussion section focuses on how the present model helps overcome these issues more than on highlighting the empirical results used as a supporting example. Table 7 summarizes the previously highlighted concerns and the way they are addressed in the BESOM proposed.

5-1- The proposed model in relation to the problem of partial, unbalanced, closed and partially dynamic BESSMs

First, multi-criteria optimization helps address the partial and closed characteristics of BESSMs. It accounts for the multi-functionality of agriculture and prevents the technical solutions proposed from being based only on one criterion (e.g., the maximization of financial returns in most BESSMs applied to animal health). The results clearly show that multi-criteria analysis is a key component of economic assessment and that the criteria considered dramatically change the results obtained (e.g., the best strategy or set of best strategies), which may appear to be self-evident; however, such an approach is rare in BESSMs applied to animal health, regardless of the species or country. Multi-criteria optimization also requires a broad range of technical solutions proposed by the biological part of the model, which must be sufficiently open (Table 7). Multiple criteria are also linked to unbalanced characteristics since the criteria selected may come from the economic part, not from the biological part (see section 5.2). In the present work, bio-economic optimization was based on only 3 criteria, although work in progress will help find solutions that account for one-welfare (e.g., farmer labour, working conditions and lowest animal morbidity and mortality), agro-ecological impacts (e.g., AMU and carbon footprint reduction) and animal longevity (disability-adjusted life year (DALY)-like criteria).

Second, the present study clearly demonstrates the added value of opportunity cost reasoning; without this reasoning, the present work would support one strategy (or combination of strategies) for a given set of constraints (step 1 of section 4.3), even though there might be several technical solutions (i.e., several strategies) that lead to utility-equivalent solutions (step 2 of section 4.3). This approach allows us to reduce the normative characteristics that arise from many BESSMs applied to animal health and supports a growing trend in agriculture according to which there are no “one size fits all” solutions, in accordance with the agro-ecological perspective (Wojtkowski, 2008). Opportunity cost reasoning is a practical consequence of the present rebalancing of BESSMs in the animal health domain, with our BESOM centred on i) the economic questions that have been asked and ii) the resource allocations (Table 7) applied to address the closed and unbalanced concerns, instead of focusing on the costs of disease.

Third, risk aversion and considerations of farmer behaviour are key improvements in the present work compared to the BESSMs that are usually seen in the animal health literature (see section 1). This is supported by extensive improvement in economic functions (Figure 2) when applying balanced model principles to the broad range of economic solutions proposed, limiting *a priori* rules in the economic part of the model and accounting for intangible animal characteristics and the optional value they represent. The model we proposed here introduces the concept of economic risk in addition to the concept of biological risk. There is much confusion between these two risks in the context of the economics of animal health. Economic risk is directly linked to the strategies and decisions of actors and is not related to the risk of production changes or the risk of disease in cases involving changes in practices. Economic risk is not considered in most BESSMs applied to animal health, with the economic part being limited to monetary translations of epidemiological events.

Fourth, the present model demonstrates that sequential considerations are required since the solutions proposed for the whole period are very different from those provided by the sequential approach. This difference is made possible by linking the economic and biological parts of the model (input-output matrix, Figure 2) and is in accordance with the field situation, where the farmer quickly changes behaviours when biological processes change and often before they become unmanageable. The combination of the 4 types of solutions proposed (Table 5) is relevant since risk aversion and farmer behaviour may be considered in cases of technical downgrades, mimicking the differences in the reactions of farmers to the same technical red flag. Similarly, the criteria that may cause farmers to change their behaviour can vary.

Interestingly, the added value of the sequential approach, as demonstrated in the present work, is slightly diminished by the application of opportunity costs since the nuances brought by the sequential approach are diminished by the opportunity cost approach (for all scenarios with low opportunity costs). This diminishment serves to smooth the solutions provided by the model by offering a continuous set of solutions that can be ordered by their opportunity cost value. This precision-like approach is likely to be close to the field and more appropriate than artificial highly discriminatory results.

5-2- Interlinking biology and economics

The present model is built on two pillars (Figure 2), i.e., biological and the economic models, programmed with PYTHON (Python Software Foundation. Python Language Reference, version 3.5) and GAMS (GAMS Development Corporation. General Algebraic Modelling System (GAMS) Release 25.1.2, Fairfax, VA, USA, 2017), respectively. The apparent dichotomy and separation hide an intensive interrelation in the ways these two parts are linked, used and programmed. Socioeconomic considerations are included in the biological part of the BESOM, for instance, through the way treatments and farmer actions are chosen, implemented and conceptualized (see section 3.1). Similarly, culling and hygiene management strategies are implemented in the biological part and are simultaneously considered in the economic part through the optimization criteria retained. All strategies defined in the present BESOM that aim to mimic farmer behaviour are translated in both the biological and economic parts simultaneously. The close relationship between the two parts of the model supports the open characteristics of DairyHealthSim. The results clearly show that many situations proposed by the biological part of the model may not be observed in the field (and are at the frontier of technical possibilities). These situations are a direct consequence of limiting *a priori* rules within the BESOM, which is done because there are no limitations in the choices of combinations of strategies and technical conditions, even if some of them lead to atypical situations. The present results clearly demonstrate that these scenarios are never retained as optimal, nor are they even considered when optimization under constraints is performed. Thus, these scenarios should be seen as artefacts of the study process, induced by the wish to keep the model as open as possible and without any biasing of the final results.

Importantly, two important items (food and labour) are included in a relative manner and not in an absolute manner. Under the main European systems (and in many other locations worldwide), for dairy cattle, the feeding costs are unknown. The parameters refer to uncertainty since there is almost no way to have even a rough estimate of this value because i) the jurisdictional status of lands (ownership or not, tax systems), ii) political considerations (CAP and land-coupled subsidies), iii) extensive systems of farming with low information on production costs (farming machine depreciation and fiscal optimization strategy), and iv) the lack of a real market for hay or corn silage or equivalent (except for marginal quantities). Many BESSMs applied to animal health have used feeding prices as stated by farm advisors or from other sources, potentially with a sensitivity analysis. Considering the previously highlighted limitations, estimations of feed prices for moderately sized farms with dairy production should be considered as an uncertainty and not as a risk. This means that it is impossible to include a feeding price per litre of milk produced (or the equivalent) without including a very large *a priori* rule, which here is clearly frightening. The proposed solution is to adjust the change in forage quality and quantity available on the farm as a consequence of climatic/weather risk through products with well-known market prices or opportunity costs. Such a solution makes even more sense because it represents the main behaviour of farmers facing short-term climatic constraints. Similarly, there is no known precise description of the time spent by farmers on different daily tasks, and such time is associated with very high variability. Here, we preferred not to consider through the use of a risk (i.e., a probability) an item that is considered to be related to uncertainty, and we implemented labour changes according the strategies that farmers adopt. This solution also matches very well the spontaneous behaviour of farmers in the field. These concerns may be addressed when matching the present BESOM with farm-level models that include whole-labour and land-use modelling, assuming that only one animal operation is present on the farm.

5-3- Empirical considerations

The present empirical results are in accordance with the literature and demonstrate the possibility of using alternative strategies that fix societal concerns (such as AMU) without decreasing farm profitability (Down et al., 2017; Scherpenzeel et al., 2018). The present results are based on criteria for selecting cows for treatment patterns that are feasible in the field, as recommended in previous studies (Scherpenzeel et al., 2014; Torres et al., 2008). Milk SCC is available in routines on most dairy farms worldwide. One weakness of the present model is that it does not directly consider the extra labour required to make decisions themselves, i.e., to capture the information of the SCC value for a given cow, apply the decision tree accordingly and treat the animal, compared to when the same treatment is applied to all cows. However, the present results demonstrate that the marginal cost of reducing AMU is important in cases where farmers do not want to or cannot change their suboptimal practices. Importantly, extra labour is seen as a key lever for reducing AMU, and the failure to include labour constraints in decision models may lead to biased conclusions. Strategy T3 can be seen as a new biotechnical solution (teat sealant) that represents an AMU alternative. The results show that strategy T3 is a key driver of AMU decreases since it allows this decrease in combination with average management practices. In the case of no new biotechnical solution (strategy T3), the only alternative to AMU decreases would have been strategy T2 combined with farmers with very good practices and extra labour. This result calls for new biotechnical solutions that help farm sustainability with adverse input reductions and with one-welfare and farm profitability stabilization. The strategy with cow-level milk withdrawals (E800) is never viewed as optimal here, and selling most of the milk (E10m) is always associated with the optimal situation due to the high quantity of milk sold and with only a slight deterioration in quality. The overall low-to-moderate milk SCCs in the present work are permitted by important culling rates (Figure 5a), preventing any optimization from including low SCCs and important cow longevity.

6- Conclusion

Based on limitation of existing bioeconomic model in the area of animal health, a new dynamic stochastic optimisation bioeconomic model applied to the dairy cow sector was proposed. The present study shows that building a model with a balanced biological and economic part is possible and that this allows economic assessment that support farmer’s decision. Importantly, the biological and economic parts of the new model (DairyHealthSim) are very closely integrated and the model is running with back and forth between the 2 parts of the bioeconomic model. DairyHealthSim identifies the optimal scenario for the entire ten-year simulation period or is based on yearly optimization (sequential modelling). The opportunity cost between the best and alternative solutions for a set of fixed constraints demonstrates that some solutions are economic equivalents (very low opportunity cost; similar economic meaning). DairyHealthSim is far more precise and appropriate for supporting decision-making compare to approaches where the outcome is reduced to the monetary impact of diseases.

Acknowledgements

This research was funded by the French Ministry of Agriculture (grant number: Ecoantibio n°2017-096).

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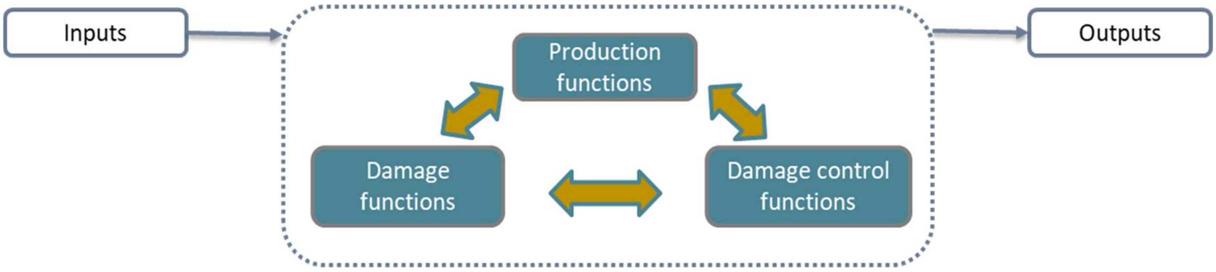

Figure 1: Holistic animal health system thinking for dairy production systems

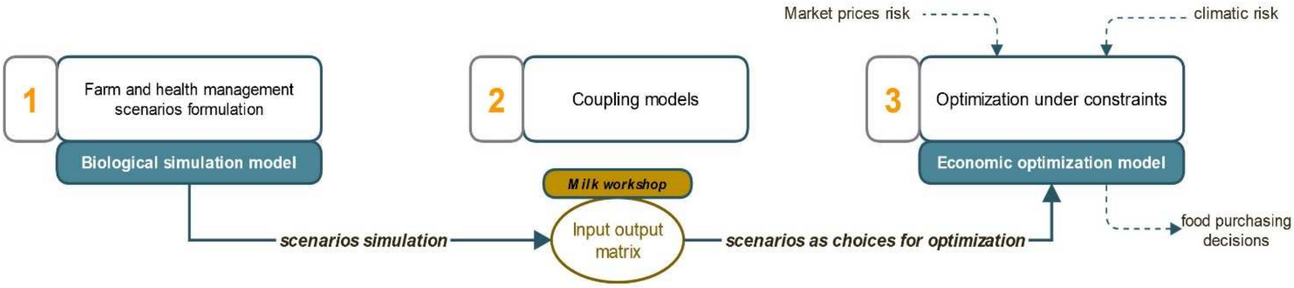

Figure 2: Overview of the proposed bio-economic model

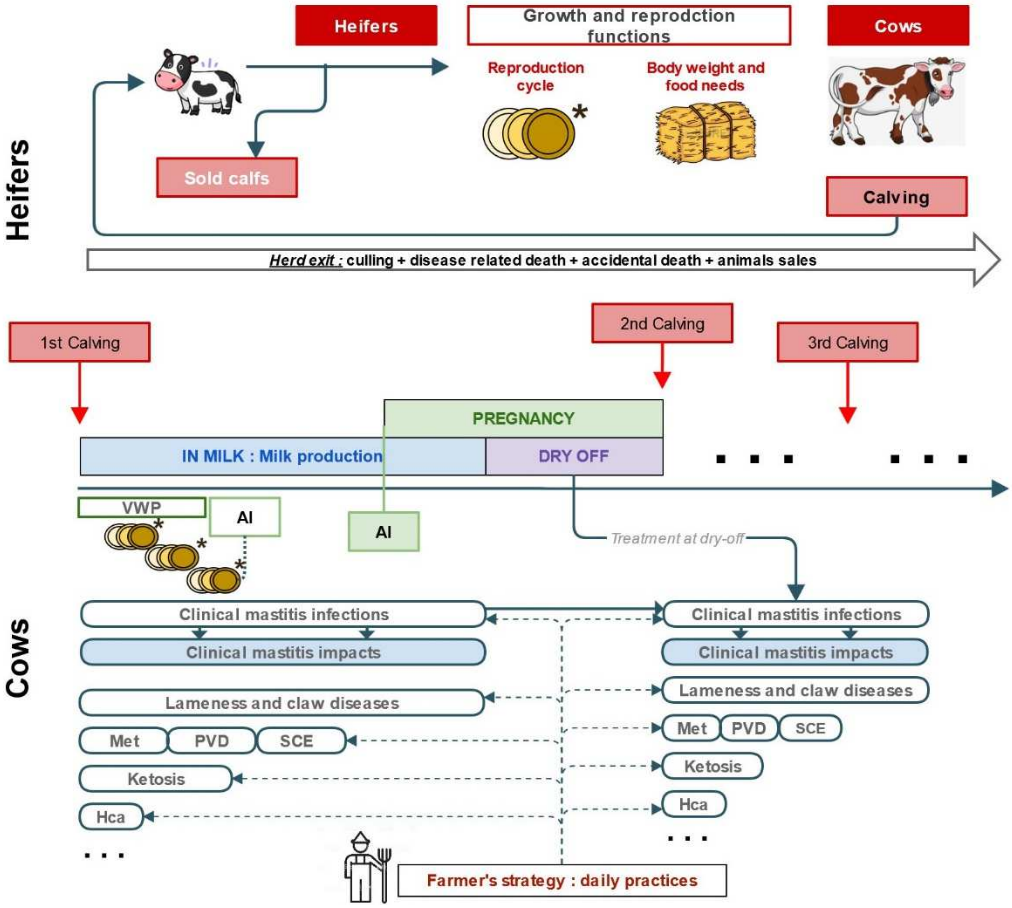

Figure 3: DHS biological model overview

VWP: farmer's voluntary waiting period before insemination, IA: artificial insemination, SCE: subclinical endometritis, PVD: purulent vaginal discharge, Met: metritis, Ketosis: clinical and subclinical ketosis, Hca: hypocalcaemia and milk fever. (*) Cow reproduction simulation as a state machine with atypical cycle simulation.

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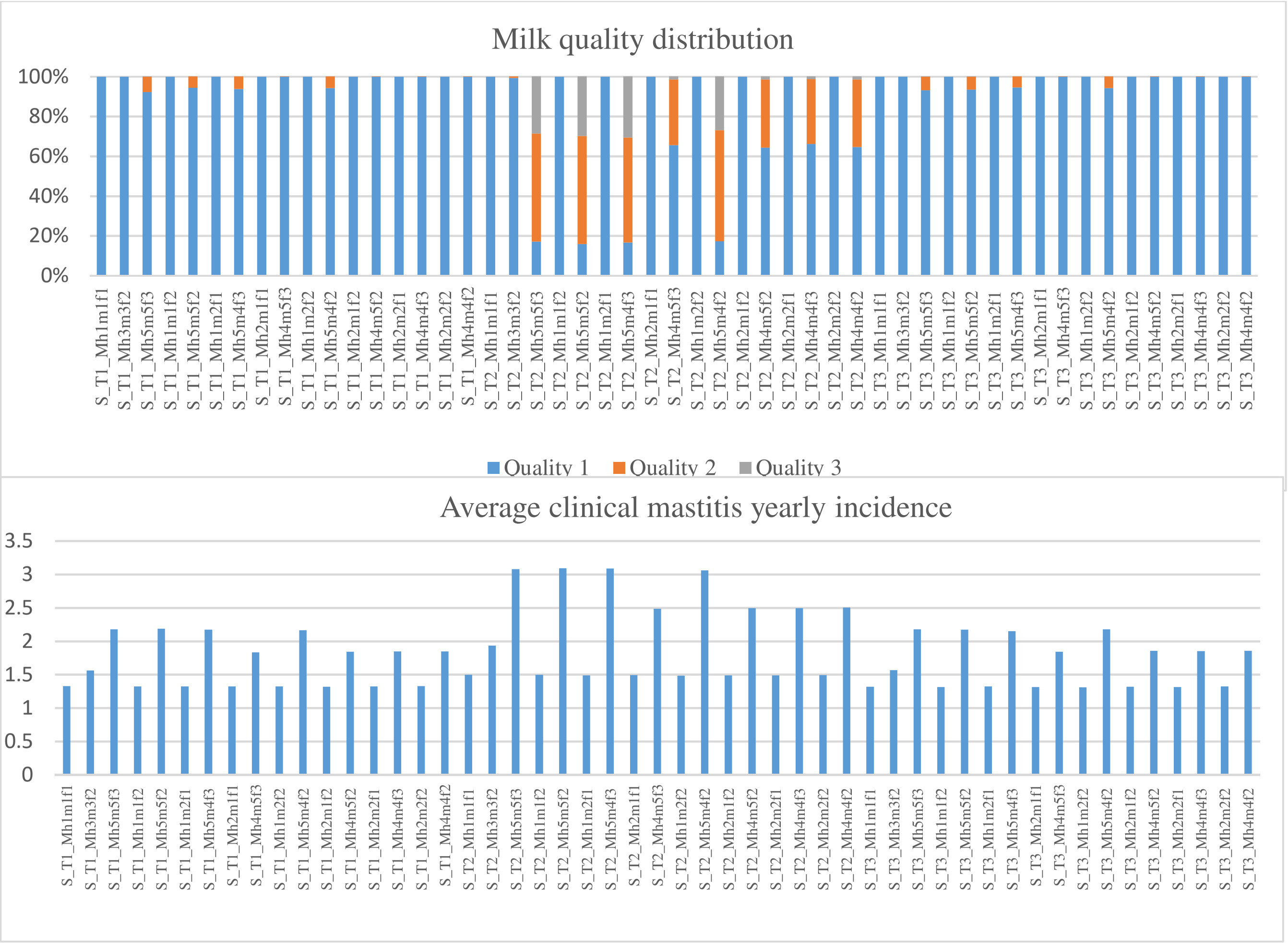

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963 Figure 4a and 4b: (a) Average clinical mastitis incidence per scenario (T and M, EVT fixed);
964 (b) median milk quality distribution per scenario (T and M, EVT fixed). Qualities 1, 2 and 3
965 represent milk with less than 250,000 SCC/ml of milk, between 250,000 and 300,000 SCC/ml
966 of milk and between 300,000 and 400,000 SCC/ml of milk, respectively.

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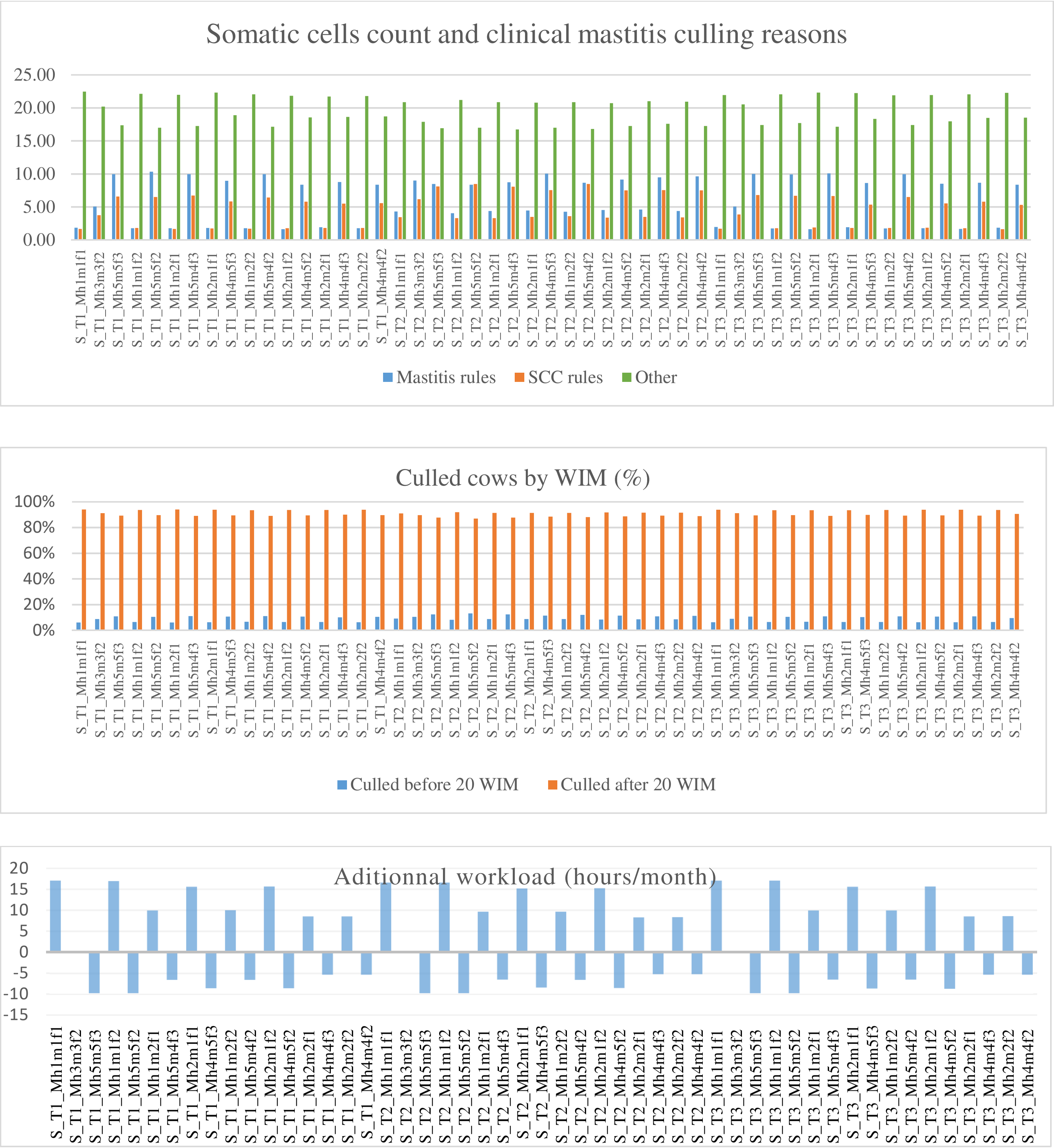


Figure 5a to 5c: (a) Average number of cows culled per year for SCC or clinical mastitis infection reasons per scenario (T and M, EVT fixed), (b) percentage of cows culled before and after 20 WIM (weeks in milk), and (c) median additional workload of farmers per scenario (T and M, EVT fixed)

Figure 6: Average expected utility (risk adjusted gross income) per year (€) for the 3 milk withdrawal strategies (E10m, E800, and E80T)

Table 1: Economic model calibration for prices, price variation coefficients, purchased and self-produced food nutritional values, and nutritional value variation coefficients

	Units	Values
Price_Vet1	€/intervention	20
Price_Vet2	€/intervention	35
Price_Vet3	€/intervention	45
Price_MilkP	€/kg	1.9
VarPrice_MilkP	-	10.53%
Price_CalvCcF	€/kg	0.3793
VarPrice_CalvCcF	-	14%
Price_Calfs	€/animal	80
VarPrice_Calfs	-	20%
Price_HeifersRTC	€/animal	1300
VarPrice_HeifersRTC	-	15.38%
Price_Soja	€/kg	0.2541
VarPrice_Soja	-	10.94%
Price_Cereal	€/kg	0.1834
VarPrice_Cereal	-	12.98%
Price_MeatC	€/kg carcass weight	2.5
NutrVal_Cereal_UFL	MFU per kg of food	1.03
NutrVal_Cereal_DMI	kg of dry matter per kg of food	0.862

NutrVal_Cereal_CP	-	10.8%
NutrVal_Soja_UFL	UFL per kg of food	1.08
NutrVal_Soja_DMI	kg of dry matter per kg of food	0.881
NutrVal_Soja_CP	-	35.4%
NutrVal_CornE_UFL	UFL per kg of food	0.35
NutrVal_CornE_DMI	kg of dry matter per kg of food	0.32
NutrVal_CornE_CP	-	2.87%
VarNutrVal_CornE_UFL	-	20%
VarNutrVal_CornE_DMI	-	20%
VarNutrVal_CornE_CP	-	20%
MilkPrice_Q1	€/kg of milk	[288.8 – 403.8]
Penalty_MilkQ2%Q1	€/kg of milk	3.1
Penalty_MilkQ3%Q1	€/kg of milk	9.2
Penalty_MilkQ4%Q1	€/kg of milk	15.3
Dev_MilkPrice	-	[2.3% - 7.7%]

Price_Vet denotes the price of veterinarian intervention by type (3 types were defined according to the treatment time); Price_MilkP: milk powder price; Price_CalvCcF: price of concentrated food for calves; Price_Calfs: 1-month-old male calf price; Price_HeifersRTC: price of heifers ready to calve; Price_Soja Soybean meal price; Price_Cereal: cereal-based concentrated food price; Price_MeatC: culled cow carcass weight price. Retrospective milk price analysis was performed to define the median price ranges (over 10 years) and their variations (Var parameters).

The Var parameters represent the coefficients of variation, computed as the ratio of the standard deviation to the mean for food and milk prices (cows and calves) and are defined based on experts for live animal prices and corn ensilage nutritional value variations. UFL: milk fodder unit, DMI: dry matter intake, and CP: crude protein.

Table 2: Strategies of systematic and selective treatments at dry off

	Description	Declination at the cow level of the 3 strategies
T1: Common practice	Systematic antibiotic treatment for all cows at dry off	Reference
T2: Simple selective antibiotic treatment	Selective antibiotic treatment for cows > 250,000 SCC/mL of milk last month at dry off[1,2]	Relative risk = 2 for clinical mastitis up to 14 WIM in cows not treated (< 250,000 SCC/mL of milk) compared to conventional treatment (Scherpenzeel, 2014)
T3: Combined selective antibiotic treatment	Selective antibiotic treatment of cows > 250,000 SCC/mL of milk last month at dry off[1] and teat sealant for the other cows at dry off[3]	Relative risk = 1 for cows treated with antibiotics at dry off and for cows that have had a teat sealant (Crispie, 2004)

[1]: only cows with somatic cell counts (SCC) > 250 000 cells/mL of milk are treated with antibiotics.

[2]: cows with SCC < 250 000 cells/mL of milk do not receive any treatment

[3]: cows with SCC < 250 000 cells/mL of milk receive teat sealants

Table 3: Farmer profiles regarding hygiene and feeding

	Mh: Management strategy for housing hygiene				Mm: Management strategy for milking hygiene			Mf: Management strategy for feeding practices	
Strategies	Straw /cow/ day at dry off (kg)	Straw [a]/cow/day in cubicles (kg)	Extra labour/cow for cleaning cubicles (kg)	Relative risk of clinical mastitis up to 13 WIM	Extra labour/cow/day (sec)	Extra cost/cow/ day for hygiene (€)	Relative risk of clinical mastitis up to 13 WIM	Cows with twice higher risk of SCK	Time saved per day for the whole herd (min)
Mh1m1f1	5	4 to 6	6	0.5	30	0.0452	0.5	5%	0
Mh1m2f1	5	4 to 6	6	0.5	15	0.02226	0.5	5%	0
Mh2m1f1	5	2 to 3	3	0.5	30	0.0452	0.5	5%	0
Mh2m2f1	5	2 to 3	3	0.5	15	0.02226	0.5	5%	0
Mh1m1f2	5	4 to 6	6	0.5	30	0.0452	0.5	15%	0
Mh1m2f2	5	4 to 6	6	0.5	15	0.02226	0.5	15%	0
Mh2m1f2	5	2 to 3	3	0.5	30	0.0452	0.5	15%	0
Mh2m2f2	5	2 to 3	3	0.5	15	0.02226	0.5	15%	0
Mh3m3f2	3	3 to 5	6	1	0	0	1	15%	0
Mh4m4f2	0	1.5 to 3	3 saved	1.5	7 saved	0	1.5	15%	0
Mh4m5f2	0	1.5 to 3	3 saved	1.5	15 saved	0	1.5	15%	0
Mh5m4f2	0	1.5 to 3	6 saved	2	7 saved	0	2	15%	0
Mh5m5f2	0	1.5 to 3	6 saved	2	15 saved	0	2	15%	0
Mh4m4f3	0	1.5 to 3	3 saved	1.5	7 saved	0	1.5	50%	30
Mh4m5f3	0	1.5 to 3	3 saved	1.5	15 saved	0	1.5	50%	30
Mh5m4f3	0	1.5 to 3	6 saved	2	7 saved	0	2	50%	30
Mh5m5f3	0	1.5 to 3	6 saved	2	15 saved	0	2	50%	30

[a]: *Straw distributed in cubicles ranges from a low value if herd density < 90% and a high value if herd density > 110%*

Table 4: Farmer behaviour related to market constraints (milk withdrawal strategies)

Strategies	Declination
E10m: No milk withdrawal	A cow's milk is removed from the milk tank when it contains more than 10,000,000 SCC/ml of milk.
E800: Strict cow threshold (SCC) milk withdrawal strategy	A cow's milk is removed from the milk tank when it contains more than 800,000 SCC/ml of milk.
E800T: Mixed cow and tank threshold (SCC) milk withdrawal strategy	A cow's milk is removed from the milk tank when it contains more than 800,000 SCC/ml of milk only if the milk tank is at more than 300,000 SCC/ml of milk.

Table 5: Optimal scenario selection when optimizing the objective function (F) with no additional workload constraints or antimicrobial use constraints.

Year	Maximize F	Maximize F under a zero additional workload constraint	Maximize F under an antimicrobial reduction constraint
Median year	T3_Mh1m2f1_E10m	T3_Mh4m4f2_E800T	T3_Mh1m2f1_E10m
1	T2_Mh2m2f1_E800T	T3_Mh4m5f2_E10m	T2_Mh2m2f1_E800T
2	T2_Mh1m2f1_E800T	T3_Mh4m4f2_E10m	T2_Mh1m2f1_E800T
3	T2_Mh1m2f1_E800T	T3_Mh4m4f3_E10m	T2_Mh1m2f1_E800T
4	T2_Mh2m2f2_E800T	T3_Mh4m4f2_E800T	T2_Mh2m2f2_E800T
5	T2_Mh2m1f1_E10m	T1_Mh4m5f2_E10m	T2_Mh2m1f1_E10m
6	T3_Mh1m1f2_E10m	T3_Mh4m5f3_E800T	T3_Mh1m1f2_E10m
7	T3_Mh1m1f1_E800T	T1_Mh4m4f2_E10m	T3_Mh1m1f1_E800T
8	T3_Mh2m2f1_E10m	T1_Mh4m4f3_E10m	T3_Mh2m2f1_E10m
9	T3_Mh2m2f1_E10m	T1_Mh4m5f3_E10m	T3_Mh2m2f1_E10m
10	T3_Mh1m2f1_E800T	T1_Mh4m4f2_E800T	T3_Mh1m2f1_E800T

T: treatment strategy at dry off, T1: systematic treatment, T2: selective treatment without sealant, and T3: selective antimicrobial treatment with teat sealant application for low SCC cows. M: global herd management scenarios, Mm: milking hygiene, and Mf: food practices. E: for milk withdrawal scenarios, i.e., if the farmer withdraws a cow's milk according to a 10,000,000 SCC/ml threshold (E10m), 800,000 SCC/ml threshold (E800) or 800,000 SCC/ml threshold if the bulk tank SCC level is higher than 300,00 SCC/ml (E800T).

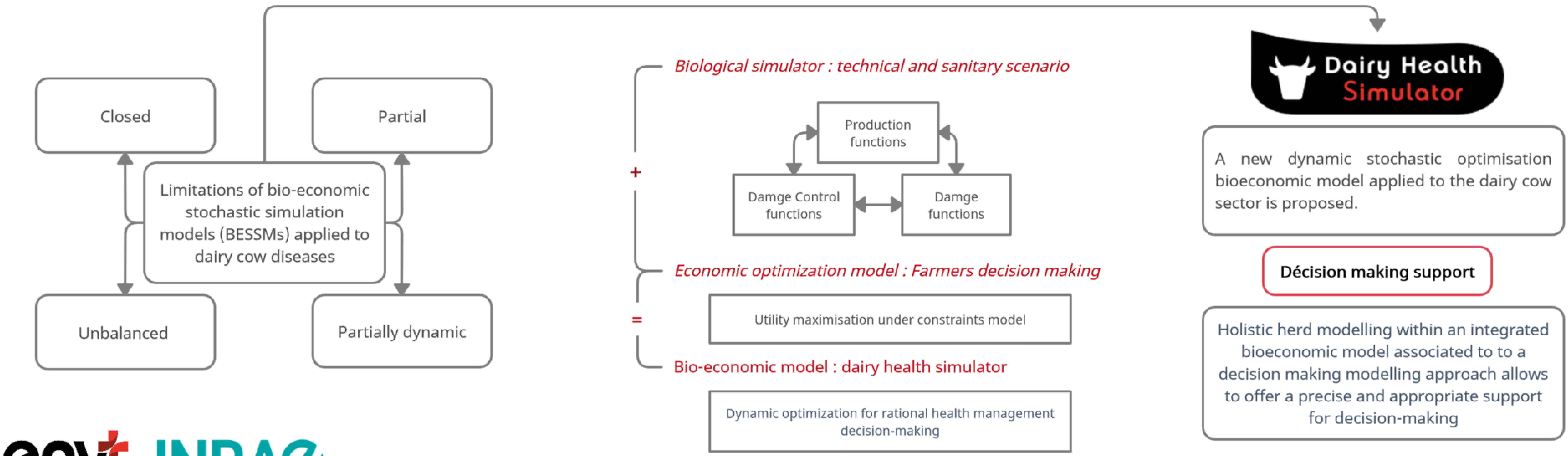
Table 6: Risk-adjusted income (U) and opportunity costs (OPPCOST) for the three technical strategies

	T1	T2	T3	E10m	E800	E800T
U_ ALL	283,313	277,746	283,629	283,153	278,729	282,806
U_M_{good} SCENARIOS	286,560	274,935	287,058	287,169	285,806	287,034
U_$M_{deteriorated}$ SCENARIOS	279,851	268,592	280,023	279,260	272,002	278,870
U T1 SCENARIOS				284,271	281,422	284,246
U T2 SCENARIOS				280,579	273,206	279,454
U T3 SCENARIOS				284,608	281,559	284,719
OPPCOST_ALL	-316	-5,882	0	0	-4,423	-346
OPPCOST M_{good} SCENARIOS	-498	-12,123	0	0	-1,362	-135
OPPCOST $M_{deteriorated}$ SCENARIOS	-172	-11,431	0	0	-7,258	-389
OPPCOST T1 SCENARIOS	0	-2,850	-26	0	-2,850	-26
OPPCOST T2 SCENARIOS	0	-7,372	-1,125	0	-7,372	-1,125
OPPCOST T3 SCENARIOS	-112	-3,160	0	-112	-3,160	0

M_{good}: good management strategies (m1h1, m2h1, m1h2 and m2h2), and $M_{deteriorated}$: deteriorated management strategies (m4h4, m5h4, m4h5 and m5h5). For example, U_ M_{good} SCENARIOS: the median utility among all good management strategies for the three treatments with dry-off strategies, namely, T1, T2 and T3. OPPCOST T1 SCENARIOS: the median opportunity cost among all systematic treatments with the dry-off strategy (T1) for the three milk withdrawal strategies (E), namely, E10 m, E800 and E800T.

Table 7: Link between conceptual concerns highlighted for BESSMs and the solutions proposed in the new BESOM proposed

		Solutions proposed and implemented in the model described			
		Multi-criteria optimization	Opportunity cost reasoning	Risk aversion and farmer behaviour	Sequential consideration
Concerns highlighted in BESSM	Partial	Multi-functionality of agriculture			
	Unbalanced	Societal constraints	Centred on resource allocation (economic question)	Economic functions (risk aversion)	Linking the biological and economic parts of the model
	Closed	Broad range of technical solutions proposed	Adequacy between economic questions and answers	Broad range of economic solutions proposed	
	Partly dynamic			Option value at time t for intangible animal characteristics	Time preference; dynamic process



Limitations of bio-economic stochastic simulation models (BESSMs) applied to dairy cow diseases

Closed

Partial

Unbalanced

Partially dynamic

Biological simulator : technical and sanitary scenario

Production functions

Damge Control functions

Damge functions

+

Economic optimization model : Farmers decision making

Utility maximisation under constraints model

=

Bio-economic model : dairy health simulator

Dynamic optimization for rational health management decision-making

Dairy Health Simulator

A new dynamic stochastic optimisation bioeconomic model applied to the dairy cow sector is proposed.

Décision making support

Holistic herd modelling within an integrated bioeconomic model associated to to a decision making modelling approach allows to offer a precise and appropriate support for decision-making