# Bio-economic modelling of antimicrobial use and health management in French dairy production

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## Abstract

Calls for antimicrobial use (AMU) reduction in farms are growing. It is yet challenging for farmers to reduce AMU without reducing their economic performances. This paper proposes an original bio-economic framework for AMU management in French dairy farms. This framework combines a recursive economic optimization model with a biologic model that describes the effects of health management strategies on the dynamic of a dairy herd. An appealing feature of the newly developed model is that it allows testing win-win strategies in terms of health management: maximising risk-adjusted revenue while minimising AMU and workload. It can also be used to test incentives to encourage farmers to adopt virtuous strategies and practices. In the present paper, the bio-economic model is applied mainly to mastitis management, which represents the first reason for AMU in dairy production. The results identified selective dry-off strategy (dry-off with AM for at risk cows only) rather than the conventional systematic dry-off strategy (AM on all cows at dry-off) as being effective to lower AMU while maintaining famer's income.

**Key words :** Animal health, economics, bio-economic modelling, mathematical programming, mastitis

## Introduction

Food animal health have been challenged by various actors since decades, in part because of the stakes on public health (through zoonotic diseases), on society concerns (welfare, food quality, system sustainability…) and on the economics of farms and value chains. The intensification of the productions in many areas of the world, the globalisation of the agriculture and the agro-industry, the increase in certification demand from consumers and the right of the citizens to have a say on agriculture practices increase continuously the challenges agriculture and animal farming have to face. Many initiatives –high quality products, private certifications…- try to define animal health or production standards, in particular those that may be acceptable by stakeholders, but it appears as a complex and perhaps unachievable task. For instance, the average (high) mortality rate of dairy calves and cows – on average 10% yearly each for France– or the average dairy cow life time (or replacement turnover) appear as unacceptable by society but hard to change by farmers. Economic approaches on diseases management has been developed to help defining health standards and decision rationale. The two popular typical cases (with all intermediaries possible) of economics applied to animal health are (i) macro-economic analysis on mono-infectious epidemics or endemics and (ii) micro-economic analysis on multi-infectious and multifactorial (production) diseases. Micro-economics of production diseases is particularly challenging, especially for cattle production in most of the livestock systems, due to (i) the high complexity of the production function linked to an open production system with high diversity and difficulties to measure inputs/outputs, (ii) the long to very long time pattern (2 years to start milk production, half turnover of 5 years), and (iii) a series of daily decisions made on various topics by individuals or a small group of

farmers. With few exceptions, the economics applied to bovine health has been progressively developed on business-based models which “simply” apply a monetary translation on epidemiology modelling. Considering revenue as the only component of farmer’s utility does not seem still acceptable. Moreover, risk aversion, workload and anticipation of market changes appear as key criteria to be included in the economics approaches applied to animal health.
Overcoming these methodological limits and defining new methodological standards to economics applied to animal health is all the more needed than farm management and farmer’s situation is changing worldwide. These changes are for instance critical for EU cattle farmers. Since few decades, they face increasing price volatility of inputs and outputs. Their aspiration to reduced their labour time hold out the daily farm management. Lastly, the production constraints are continuously increasing due to society and public pressures. Among these new constraints, animal health management has been recently challenged by the antimicrobial use (AMU) in food animal production (Lhermie, Gröhn, & Raboisson, 2017). Antimicrobial resistance (AMR) is a global public health problem. As food animals are involved in AMR creation, calls for reduced antimicrobial use (AMU) on farms are growing. It is yet challenging for farmers to reduce AMU without reducing their economic performances and there is no clear evidence today on virtuous situations associated with lower AMU and satisfactory or higher income and utility levels. Disease prevention and curative alternatives of AM are the 2 key levers to reduce AMU in food animal production. Preventing diseases may face technical issues and leads to higher production risk since the efficacy of prevention is unreliable and focusing on disease prevention does not prevent curative treatment on a subpopulation. Field observations yet highlight that AMU reduction can be cost-effective, for example, when obtaining more outputs by using less or same levels of inputs (such as preventive tools and antimicrobials). Sustainability of such situation yet remain unclear, in particular since the utility of farmer may be limited in such virtuous AMU management situations, and the capability of farmer to deal with long term high risky disease management has to be assessed.

The present work aims at identifying the trade-offs between AMU and farm income in dairy cow production, using a recursive bio-economic model. It focuses on optimizing the farmer utility (risk-adjusted income) under constraints technical, biological, workload and AMU constraints. Mastitis was used as a case study since it represents the first reason for AMU in dairy production.

The remainder of the paper is structured as follows. We describe first the farmer’s decision making process and the biologic model. We then present and discuss the main results obtained, followed by some concluding remarks.

## Material and methods

A bio-economic model was developed to analyse the trade-offs between AMU and farm income in dairy cattle production. First, a biologic model defined on a cow-week basis and weekly probabilities of events, productions and diseases was implemented using R statistical software. This biological component aims at the dynamic representation of a dairy herd. It allows to formulate and simulate livestock management scenarios and build an input and output matrix for each scenario. The biologic model was then combined with an economic optimization model implemented using General Algebraic Modelling System (GAMS) software. The economic model aims at maximizing the farmer’s risk-adjusted income under budget, working time, AMU and animal welfare constraints.

The bio-economic model was calibrated based on literature review and experts' opinions. The model was run over 10 years and includes sequentially the most common potential decision and management strategies by the farmer.

*Economic model overview*

The economic model developed is a recursive mean-variance optimisation framework which assumes that farmers make their decisions in order to maximize their income while minimising the associated risk, under technical, biological, structural and AMU constraints. We assume that farmers are risk-minimisers since many studies have demonstrated that they are typically risk-averse (Hardaker, Huirne, Anderson, & Lien, 2004). This means that they are willing to sacrifice a part of their income to avoid facing risk. To incorporate risk-averse behaviour in farmers' decision making, we use a Markowitz-Freund mean-variance objective function (Hardaker, Huirne, Anderson, & Lien, 2004). Mathematically, the economic model can be formulated as follows (equations 1-8):

$$\max U = E\left[Z_{k,t}\right] - \tfrac{1}{2}\phi\sigma\left(Z_{k,t}\right) \tag{1}$$

$$Z_{k,t} = \textstyle\sum_l MilkProd_{l,t} \times MilkPrice_{l,k,t} + \sum_a\left(NS_{a,t} \times SalePrice_{a,k,t}\right) + \sum_a NE_{a,t} \times Csub_{a,t} + Dsub_t - \sum_{a,co}\left(N_{a,t} \times ConcQty_{co,t} \times ConcPrice_{co,k,t}\right) - \sum_{a,F}\left(N_{a,t} \times AMQty_{F,t} \times AMPrice_{F,t}\right) - \sum_{a,F}\left(N_{a,t} \times NAMQty_{F,t} \times NAMPrice_{F,t}\right) \tag{2}$$

$$E\left[Z_{k,t}\right] = \frac{\sum_k Z_{k,t}}{K} \tag{3}$$

$$\sigma\left(Z_{k,t}\right) = \sqrt{\frac{\left(Z_{k,t} - E\left[Z_{k,t}\right]\right)^2}{K}} \tag{4}$$

Equation (1) denotes objective function of farmers where **E** denotes expected values, **k** represents the state of nature which is defined here as the possible level of price; $\boldsymbol{Z_{k,t}}$ stands for the income 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 the income. Equation (2) indicates how the income is computed. In this expression, $\boldsymbol{MilkProd_{l,t}}$ denotes the milk of type ***l*** sold at time ***t***; the type of milk is linked to number of cellules in case mastitis, $\boldsymbol{MilkPrice_{l,k,t}}$ represents the price of the milk of the type ***l*** sold in state of nature ***k*** at time ***t*** ; $\boldsymbol{NS_{a,t}}$ denotes the number of animals of type ***a*** (dairy cows, heifers and calves) sold at time ***t***; $\boldsymbol{SalePrice_{a,k,t}}$ is the price of animals of type ***a*** sold in the state of nature ***k*** at time ***t***. The sale price of the cull cows includes a slaughter premium. $\boldsymbol{Csub_{a,t}}$ denotes subsidies given to farmers and which are coupled to the type of animal and $\boldsymbol{NE_{a,t}}$ represents the numbers of animals of type ***a*** eligible for coupled subsidies ; $\boldsymbol{Dsub_t}$ represents subsidies given to farmers which are decoupled to production decisions. $\boldsymbol{ConcQty_{co,t}}$ indicates the quantity of each type of concentrated feed ***co*** (soybean meal, wheat, and milk powder) used at time ***t***; $\boldsymbol{ConcPrice_{co,k,t}}$ stands for the prices of each type of concentrated feed in the state of nature ***k*** at time ***t***. $\boldsymbol{N_{a,t}}$ stands for the number of animals of type ***a*** at time ***t***; $\boldsymbol{AMQty_{F,t}}$ indicates the quantity of antimicrobial drugs of type ***F*** used at time t; $\boldsymbol{NAMQty_{F,t}}$ indicates the quantity of non-antimicrobial drugs of type ***F*** used at time ***t***. Equations (3) and (4) indicate how the expected value of the income and its standard deviation are computed.

*Constraints*

The equation (1) was estimated with the outcomes of the biologic models and under the following technical, biological, structural and AMU constraints. First, the feeding constraints (Equation 5) were built so as to the sum of forage unit requirements (FUR) by animal category ***a*** and period ***p*** remains lower than or equal to the number of forage units available per period ***p***, per crop ***c*** and concentrated feed ***co***.

$$\sum_a \left(N_{a,t} \times FUR_{a,p}\right) \leq \sum_c \left(X_{c,t} \times FU_{c,p}\right) + \sum_{co} \left(ConcQty_{co,p,t} \times FU_{co,p,t}\right) \tag{5}$$

The feeding system was based on 3 main components: corn silage, energetic crop such a barley or wheat, and nitrogen corrective feed such a soybean meal. Because the present model was herd centred and not farm centred, the quantity and production cost of corn silage was not available and it was assumed that the quantity of corn silage to feed the herd was available each year (fixed herd size). Its energetic value yet changes yearly due to weather grow conditions, and this changes have to be compensated by changes in crop selling or purchase. A constraint for protein (PDIN, PDIE) requirements is defined similarly to equation (5).

Second, the labour constraints (Equation 6) were considered as the sum of working time per type of animals ***a*** at time ***t*** , $WorkingTime_a \times N_{a,t}$, plus sum of working time per strategy of disease management, $WorkingTime_s \times ND_{a,t}$, plus the time allocated to administrative ($AdmWork$) tasks must be lower than the labour available in annual working unit (AWU). $ND_{a,t}$ represents the number of animals treated at time t.

$$\sum_a \left(WorkingTime_a \times N_{a,t}\right) + \sum_s \left(WorkingTime_s \times ND_{a,t}\right) + AdmWork \leq AvailableLabor \tag{6}$$

The constraint labour time was implemented according to a monthly smooth rolling function considering monthly farmer's extra time available for health preventive and curative management (in addition to average working time) as a fixed time value per week plus saved time on the previous weeks (below the average working time). This function allows to reproduce in a close way the behaviour of farmers and their labour time flexibility on moderate to long time patterns.

Third, the cash constraint was defined by Equation (7). It links years to each other and allows unused income of a given year to be used in the next year. More precisely, equation (7) indicates that each year the available cash from the past year ($CASH_{t-1}$) and the revenue generated ($REV_t$) are used for disease management ($DM_t$), operational expenses ($OperCost_t$), household expenses ($HExp_t$) or saved ($CASH_t$). This equation ensures, in part, the ″recursivity″ of the model.

$$CASH_{t-1} + REV_t = DM_t + OperCost_t + HExp_t + CASH_t \tag{7}$$

Fourth, the constraint on AMU was built on the number of treatments at herd level. The number of animals treated at time t ($NAtrt_t$) must be lower than the total number of animals ($NAtot_t$) minus the number of animals treated until $t-1$ ($\sum_{t=1}^{t-1} NAtrt$).

$$NAtrt_t \leq NAtot_t - \sum_{t=1}^{t-1} NAtrt \tag{8}$$

*Biologic model overview*

The biologic model simulated herd's population, cow reproduction, milk production and health on the basis of cow-week events defined by a matrix of probabilities. It aims to be as exhaustive as possible to represent all the practical cow-related events of the farm, including production and diseases. The diseases included lame, dystocia, milk fever, placental retention, puerperal metritis, purulent vaginal discharge, subclinical endometritis, abomasum displacement, subclinical ketosis and clinical ketosis. They represent the high majority of disorders observed in dairy herds, except accident issue (broken leg …). The model included all the categories of animals from birth to death or culling and all the physiological states of animals (dry, in milk, open for insemination, in calf…). The events were defined for each cow and each week mechanistically, based on basic incidence risks, cow specific risk factors and intra-herd inter-cow contamination risks. Culling rules were applied on all cows each week, with series of criteria including udder health, lame, pregnancy status and milk production, alone and in combination, so as to create a set of rules with increasing aggressively in culling decision, applied in accordance to the herd density (i.e., the number of cows to be culled so as to maintain the herd size). The rules were builds according the observations made in the field so as to mimic the usual famer behaviour. Importantly, the present model only focus on functional decisions at this stage and investment decisions were not considered. It means that all structural characteristics of the farms are considered as constraints, from a biology (barn size and number of cows in milk) and economic (decisions to be made within the present farm structures) point of view.

The bio-economic model is obtained by combined the economic model and biologic one. More precisely, the links between the biologic and the economic model are built by including the technical matrix of inputs-outputs provided by the biologic model into the economic model described in the previous sub-section.

### *Calibration*

The biologic model developed here deals with quantitative data and facts with scientific backing. Input model parameters were defined thanks to a large literature overview as shown in Tableau 1**Erreur ! Source du renvoi introuvable.**. The calibration of the economic models was based on market prices in France[1].

**Tableau 1 : biological model input parameters**

| Parameters | Sources |
|---|---|
| Diseases risks and effects | Enting, Kooij, Dijkhuizen, Huirne, & Noordhuizen-Stassen, 1997; D. Raboisson, Mounié, Khenifar, & Maigné, 2015 ;D. Raboisson, Mounié, & Maigné, 2014; Didier Raboisson & Barbier, 2017 ; Ostergaard & Gröhn, 1999 ; Ettema & Østergaard, 2006; Gröhn et al., 2003; Østergaard, Sørensen, & Houe, 2003 ;Manhani, 2015 |
| Mastitis (clinical and sublinical) risks and effects | Cha et al., 2014; de Haas, Barkema, & Veerkamp, 2002; Gröhn et al., 2003; Østergaard, Chagunda, Friggens, Bennedsgaard, & Klaas, 2005; D. Raboisson et al., 2014 |
| Lactation | Meadows, Rajala-Schultz, & Frazer, 2005 ; Rutten et al., 2016 ; Wood,1967; |
| Body weight and food needs | Friggens, Ingvartsen, & Emmans, 2004; Giordano, Kalantari, Fricke, Wiltbank, & Cabrera, 2012 ; Van Arendonk, 1985 |
| Heifers growth and reproduction | De Vries, 2006; Groenendaal, Galligan, & Mulder, 2004; Gröhn et al., 2003; Inchaisri, Jorritsma, Vos, van der Weijden, & Hogeveen, 2010; Mohd Nor, Steeneveld, Mourits, & Hogeveen, 2015; Wathes, Pollott, Johnson, Richardson, & Cooke, 2014 ; Taylor, 2001); Margerison, 2005 ; Phong, 2016 ; Mannani, 2015; Khun, 2006. |
| Reproduction parameters | Cabrera, 2010; de Vries, 2004; De Vries, 2006; J. Ettema, Østergaard, & Kristensen, 2010; Giordano et al., 2012; Groenendaal et al., 2004; Inchaisri et al., 2010; Inchaisri, Jorritsma, Vos, van der Weijden, & Hogeveen, 2011; Kalantari & Cabrera, 2012; Kristensen, Østergaard, Krogh, & Enevoldsen, 2008; Meadows et al., 2005; Mohd Nor et al., 2015; D. Raboisson et al., 2014; Rutten et al., 2016; Rutten, Steeneveld, Inchaisri, & Hogeveen, 2014; Santos et al., 2004; Wathes et al., 2014 ; Østergaard et al., 2005, 2003 ; Shahinfar, 2015; Laport, 1994; Mannani, 2015 ; Phong, 2016; Opsomer, 1999 |
| Culling rules | Cha et al., 2014; Kristensen et al., 2008; Mohd Nor et al., 2015; Østergaard et al., 2005; Rutten et al., 2014 ; Phong , 2016; Mahnani, 2015 ; Dechow, 2008 ; Sorensen, 1992. |

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[1] https://investir.lesechos.fr/cours/matiere-premiere-tourteaux-de-soja-chicago-futures,wmpcb,sm,sm,opid.html

*Scenarios*

Biological scenarios and health management strategies were defined thanks to experts' opinion and literature overview. The retained scenarios (i) are in accordance with regulation in France (drug authorized), (ii) match with in the field common practices and (iii) have a given efficacy defined thanks to evidence based medicine principles. Because each biological scenario included specific non-medical farm practices in addition to drug use, the scenario underlies farmer's state of mind and drug choice as well as over farm management, leading to consider "health management strategy" adopted by farmer instead of biological scenarios alone. In other words, it means the different situations proposed here correspond to farmer's strategies under technical constraints. The 9 scenarios were defined as a combination of 3 scenarios representing technical strategies related to clinical mastitis management at dry-off (common practices and 2 alternatives) and 3 scenarios representing animal health management (common, deteriorated and adequate practices). Details are reported in Tables 2 and 3.

**Table 2 : Technical scenarios definition**

| | Description | Risk | Reference |
|---|---|---|---|
| T1: Common practice | systematic treatment at dry-off | reference risk | |
| T2: Alternative practice # 1 at dry-off | selective antimicrobial treatment at dry-off for cows > 150 000 SCC[1] | odd ratio for clinical mastitis up to 100 DIM = 2 | (Scherpenzeel et al., 2014) |
| T3: Alternative practice # 2 at dry-off | selective antimicrobial treatment at dry-off for cows > 150 000 SCC AND an internal teat sealer for other cows | odd ratio for clinical mastitis up to 100 DIM = 1.05 | (Crispie, Flynn, Ross, Hill, & Meaney, 2004) |

[1]:SCC: milk Somatic Cell Counts: indicator of udder health in dairy production

**Table 3 : Management scenarios definition**

| | Cleanliness at dry off | Cleanliness of in milk cows | Milking practices costs | Diet practices |
|---|---|---|---|---|
| M1 "Good" management scenario | 5 kg of straw per cow per day | - 4 to 6 kg of straw per place per day<br>- +0.20 min extra time per place<br>- odd ratio= 0.5 for probability of clinical mastitis on 4 first week in milk<br>- odd ratio= 0.5 for probability of clinical mastitis for second and third cases on 8 first week in milk | - extra time per cow: + 1 min<br>- extra cost per cow per day: + 0.0452 € | 5 % of cows with risk factor for subclinical ketosis (change in practices during dry off) |
| M2: "Usual" management scenario | 3 kg of straw per cow per day | - 3 ~ 5 kg of straw per place per day | reference practices | 15 % of cows with risk factor for subclinical ketosis (change in practices during dry off) |
| M3: "deteriorated" management scenario | no straw | - 1.5 ~ 3 kg of straw per place per day<br>- odd ratio= 2 for probability of clinical mastitis for second and third cases on 8 first week in milk<br>- odd ratio= 2 for probability of clinical mastitis on 4 first week in milk<br>- 0.20 min saved time per place. | - 0.5 min saved time per cow | 50 % of cows with risk factor for subclinical ketosis (change in practices during dry off)<br>- 30 min saved per day for a 100 cows herd. |

## Results

*Main results of the Biological model*

The biologic model should correctly represent changes in management strategies and farmer's practices, and *ex-post* evaluations of the technical indicator of the herd performances were done so as to validate the biologic models. Such *ex-post* validation of the biological models included the likelihood of the output parameters, the agreement with values observed in the field, and the expected differences in the outcomes for the differences strategies and scenarios (antibiotic exposure, diseases prevalence, input required…). For instance, the biological results show that cows' AM exposure at dry-off is reduced by nearly 50% for the selective treatment scenarios (Table 1), and scenarios with "deteriorated" management procedures (M3) have the highest prevalence of clinical mastitis (Figure 2, Annex). It is also noted that the selective treatment associated with an internal teat sealer (T3) makes it possible to control the clinical mastitis infections as well as the systematic treatment strategy at dry-off (T1). The lowest production levels are those corresponding to "deteriorated" management scenarios (Figure 3 Annex). Compared to the "usual" management strategy (M2), the adoption of an adequate management strategy (M1) requires the farmer to spend on average 64 hours more of labour per month whereas the deteriorated strategy (M3) allows him to save an average of 35 hours of labour per month (see figure 4, Annex). The cow culling because of udder health disorder (clinical mastitis and high SCC) represent an important part of the causes of reform for the scenarios with lowest levels of mastitis infections control (Figure , Annex).

*Main results of the bio-economic model*

The certain equivalent of the income (Income_CE) for the different scenarios (Figure 1) highly varied according to years. This is the results of the variability in the combination of input and output prices, and the variations appear almost independent of the scenarios.

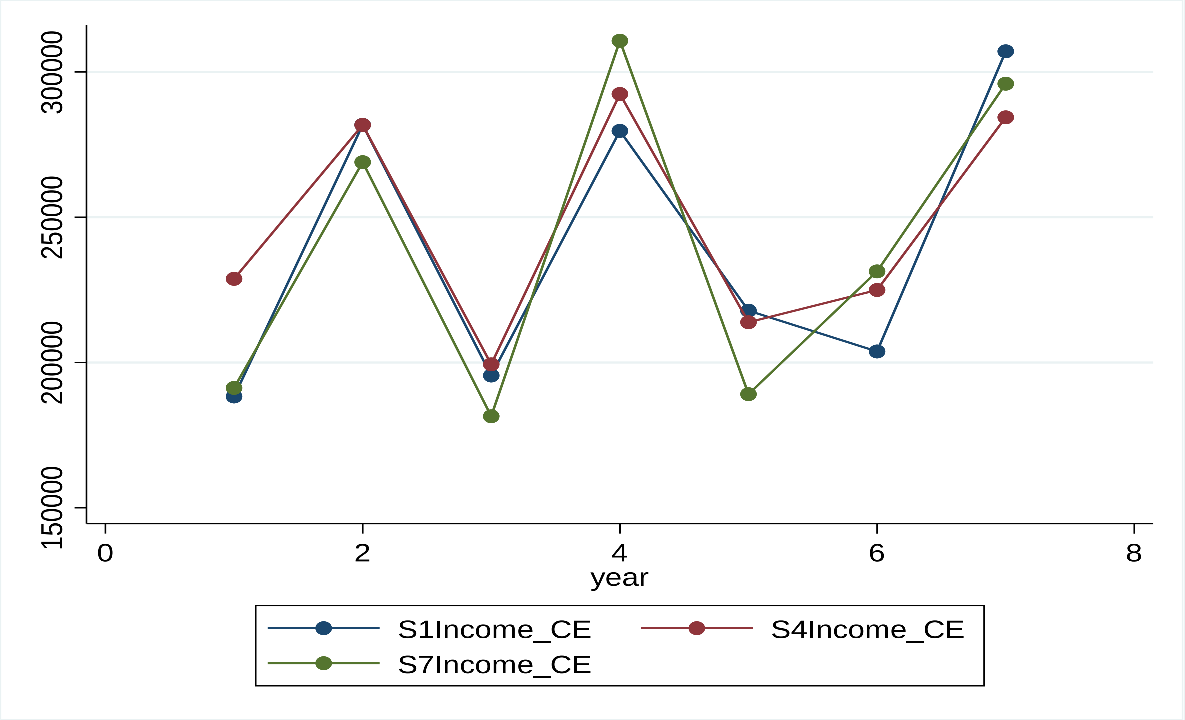
When proposing the 9 biological management scenarios as "activities" among the choices for optimisation and maximising the farmer's expected utility, the model identified the T1M1 strategy as the optimal strategy.

When running the model optimizing farmer's expected utility and imposing a reduction cow's exposure to antimicrobial inputs by 20%, the results identified management strategies that optimize a low AMU without lowering farmer's utility: the selective dry-off strategy (T3M1=S7) was identified as the optimal strategy, combining low AMU and stabilized incomes. This strategy yet failed to increase the income compared to the conventional systematic approach. A trend to have a higher variability in the revenue (Figure 1) was yet observed for this scenario.

Economic results are rather interesting. In fact, they show that strategies exist (S4, S7) that minimize the use of antibiotics while maintaining farmer's income at a similar level to that corresponding to an intensive use of antibiotics (S1).

**Table 1 : Antimicrobial treatments at dry-off**

| Scenarios | average number of AM treatments at dry-off | Average exposure to AM at dry-off |
|---|---|---|
| T1M1 (S1) | 615 | 100% |
| T1M2 (S2) | 590 | 100% |
| T1M3 (S3) | 538 | 100% |
| T2M1 (S4) | 336 | 56% |
| T2M2 (S5) | 327 | 55% |
| T2M3 (S6) | 270 | 50% |
| T3M1 (S7) | 336 | 56% |
| T3M2 (S8) | 332 | 54% |
| T3M3 (S9) | 353 | 57% |



S1 is the combination of T1 and M1; S4 is the combination of T2 and M1 ; S7 is the combination of T3 and M1

**Figure 1 :Yearly simulated production net value (Euros)**

The overview of the scenarios showed that:

- Scenarios of "good" management of livestock (M1 scenarios) are more time expensive and generates additional expenses (for straw and hygiene consumables purchases) but that they reduce the incidence of clinical mastitis in livestock. And conversely for the scenarios of "deteriorated" management.
- The systematic treatment scenarios (T1 scenarios) are the scenarios that expose the most cows at dry off to antibiotic treatment but also those who better prevent clinical mastitis for in milk cows.
- The selective treatment scenarios at dry off associated to the administration of an internal teat sealer (T3 scenarios) prevent clinical mastitis as well as systematic treatment scenarios.

> However, the simple selective treatment (T2 scenarios) makes it possible to reduce the AMU but exposes the cows to the risk of clinical mastitis and exposes the dairy farmer to the economic losses that this generates in production levels. For the simple selective treatment scenarios, mastitis infections historic and high level of somatic cells count are the main reasons for culling.

## Discussion

The present model represents a high improvement in the methods commonly used in economics of animal health, since most of bio-economic models in this area are primarily biological process models with a monetary component added. The optimization process, the utility function linked to the sequential decision-making and the adjustment made for multi-diseases are major improvements that helps to better understand, predict and influence health decision making in the farms. Such a method is all the more needed that we focus on moderate size farms with a familial component, and on long term production process, where health and disease prevention have consequences in future outcomes.

The biological model has been developed within a mechanistic point of view. Each animal face on a weekly base a basic risk of outcome, which is adjusted by risks linked to it history and to the characteristics of other cows within the herd. This mechanistic characteristic of the biological model allowed to represent the herd population with a holistic approach and to limit ex-ante assumption on herd dynamics. It also importantly deals with the partial approach often observed in economic models applied to animal health. For instance, models focusing on one disease are often built with a residual function for culling and death, defining a voluntary culling rate or a disease of interest independently to mortality rate. Such approach lead to high *a priori* in the model calibration and is likely to substantially influence the results. On the contrary, because the present model included all except very few diseases and production events, culling and death were only considered consecutive to disease or specific combination of cow characteristics. Moreover, the mechanistic approach leads to reduce dramatically the issue of partial characteristics of disease modelling. The assumption of ″separability″ of the biologic event is likely to be a high assumption that has to be rejected. The present model allows on the contrary to account for interactions between diseases, production and structural condition of the farm. These two points represent a high improvement in the biologic function.

The calibration of the biologic and economic models also aims to closely represent the conditions within which farms operate. In particular, “smooth functions” were used so as to allow to represent the balance that often occurs in the farms and to avoid drastic decision based on marginal technical indicators. These smooth functions were based on (i) the progressivity in the rules and threshold criteria and (ii) the time rolling. For instance, the culling rules were adjusted by the barn density, with criteria allowing more aggressive culling rules when the density increases above 1 (number of cows exceed the number of places available) compared to from 0.9 to 1, and specific rules were applied when the density increased above 1.1. Yet, these 3 thresholds were modulated by the duration the herd within a density classes. Time rolling rules were also used to the labour function. It is hard work to define the basic daily activities for a farmer, due to the large difference in farmers’ habits and working convention and in farm equipment. Author’s experience also highlights that farmers’ willingness to increase their labour time also highly differs, but farmers are used to adapt their labour time on a short time pattern to absorb punctual extra labour. A time rolling function allowing more extra time to diseases management in cases of moderate labour to be done on previous weeks seems appropriate to deal with this issue.

The present model focuses on the herd and did not include the whole farm. This trade-off was done due to the high complexity in diseases modelling and the high number of scenarios already investigated. As a consequence, the present model fails to consider how investment may interact with health management, also structural constraints (barn, milking machine…) are known to represent risk factors for diseases. On the contrary, the model assumes given structural conditions of the farm for the whole simulation. Another consequence of this choice is the fact that the outcome of the model is an income that does not exactly correspond to a gross margin. Calculating the gross margin would require assumptions at least on the on farms food production system and exhaustive treatments costs. The present situation did not prevent to account for weather hazard on the feeding system, for instance by changing the quality of corn silage. Altogether, we are convinced the variation on the income calculated here is well correlated with the variation of the gross margin of the simulated herd.

The present results clearly highlight that the selective dry-off strategy is effective to lower AMU while maintaining famer's income at a satisfactory level. There is yet today no economic evidence for the farmer to prefer selective dry-off strategy. The use of selective dry-off strategy has yet a bad reputation on the field, and farmers are reluctant to this strategy because of the high level of hygiene required during the administration, leading otherwise to a higher risk of mastitis and general complication. The securisation of the biologic process through antibiotics is only partly accounted for in the present work, and further scenarios are needed to investigate the risk faced by farmers by using selective strategy. The trends to higher variability in the results reported here for the selective dry-off strategy could be in accordance with these limits.

## Concluding remarks

The present work helps in defining strategies that improve the use of AM without disturbing the farm profitability.

The present tool can also be used as a tool to test political incentives to help farmers in the adoption of virtuous strategies and practices. The results reported here clearly demonstrated how economic approach may help in defining the trade-off between AMU and farm profitability. Other case studies are provided for lame and reproductive issues.

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# Appendix

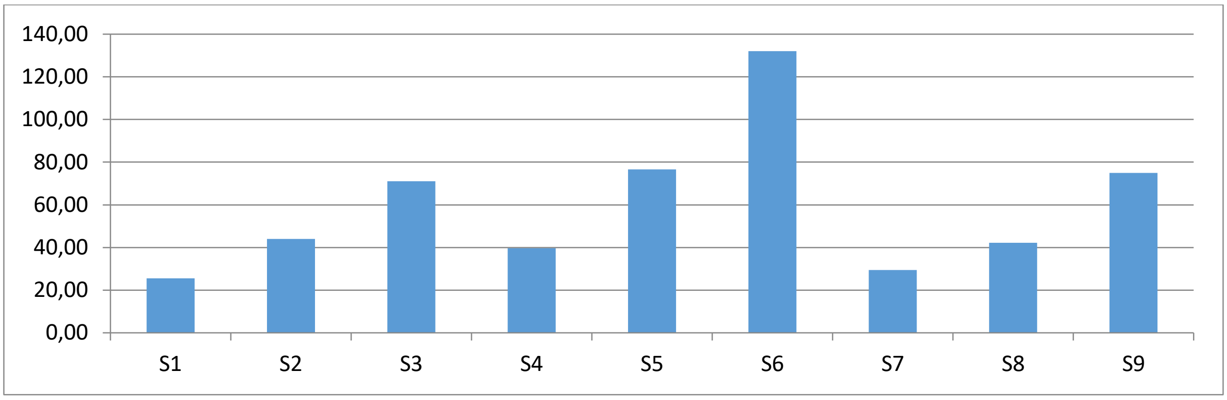

Figure 2 : Average clinical mastitis prevalence per scenario (cases/year)

S1 is the combination of T1 and M1. S2 is the combination of T1 and M2. S3 is the combination of T1 and M3. S4 is the combination of T2 and M1. S5 is the combination of T2 and M2. S6 is the combination of T2 and M3. S7 is the combination of T3 and M1. S8 is the combination of T3 and M2. S9 is the combination of T3 and M3.

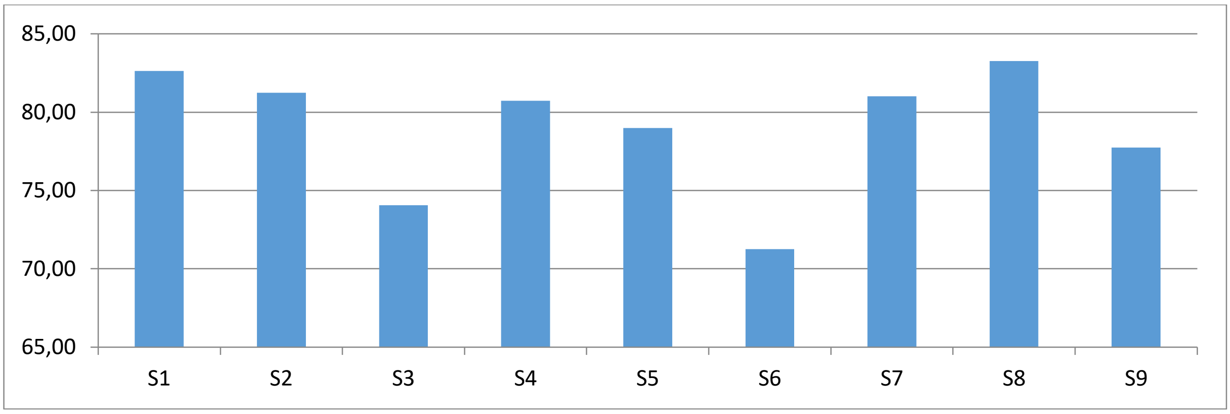

Figure 3 : Average milk yield (ton/year)

S1 is the combination of T1 and M1. S2 is the combination of T1 and M2. S3 is the combination of T1 and M3. S4 is the combination of T2 and M1. S5 is the combination of T2 and M2. S6 is the combination of T2 and M3. S7 is the combination of T3 and M1. S8 is the combination of T3 and M2. S9 is the combination of T3 and M3.

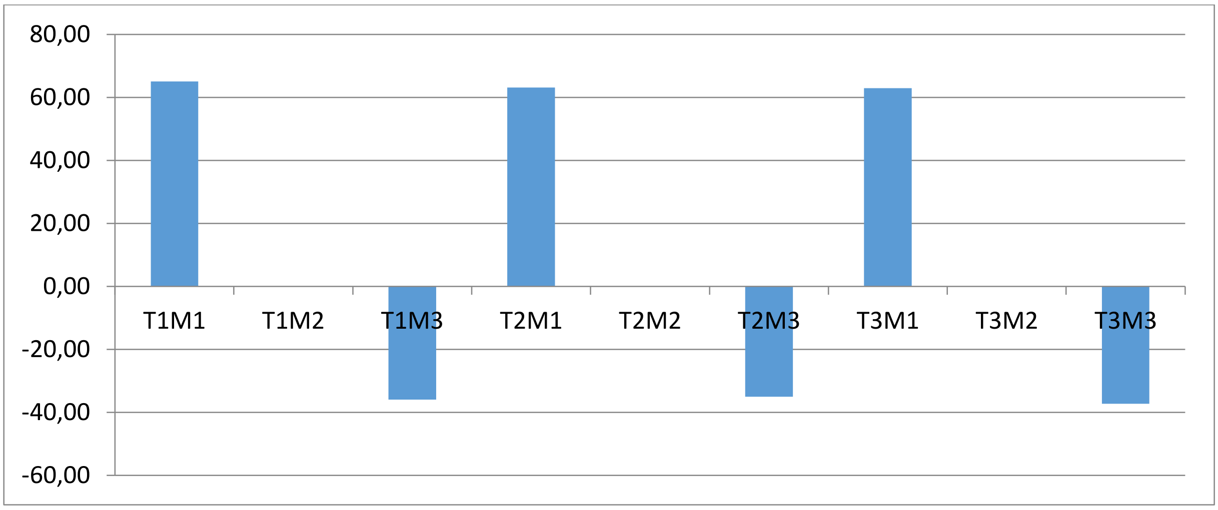

Figure 4 : Workload in hours per scenario per month

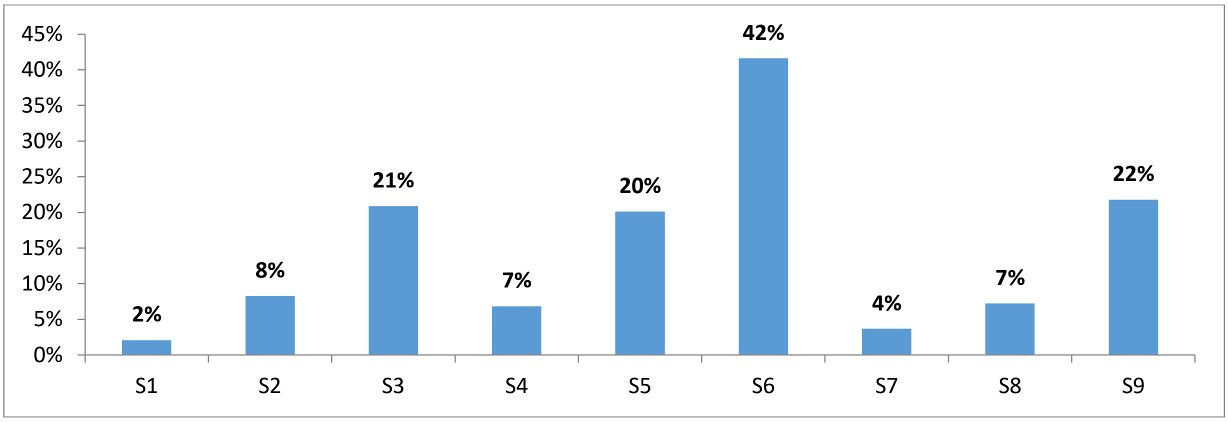

**Figure 5 : % mastitis infection and high SCC in culling reasons per scenario**

S1 is the combination of T1 and M1. S2 is the combination of T1 and M2. S3 is the combination of T1 and M3. S4 is the combination of T2 and M1. S5 is the combination of T2 and M2. S6 is the combination of T2 and M3. S7 is the combination of T3 and M1. S8 is the combination of T3 and M2. S9 is the combination of T3 and M3.