ICT monitoring and mathematical modelling of dairy cows performances in hot climate conditions: a study case in Po valley (Italy)

Filippo Bonora[1], Matti Pastell[2], Stefano Benni[1*], Patrizia Tassinari[1], Daniele Torreggiani[1]

(1. *Department of Agricultural and Food Sciences, University of Bologna, Bologna, Italy*;
2. *Natural Resources Institute Finland (Luke) Green Technology, Helsinki, Finland*)

Abstract: Automatic Milking Systems (AMS) measure and record specific data about milk production and cow behaviour, providing farmers with useful real-time information for each animal. At the same time, indoor climatic conditions in terms of temperature and humidity within a dairy livestock barn represent a well-known crucial issue in farm building design and management, since these parameters can remarkably influence cows behaviour, milk yield and animal welfare.

The goal of the study is to develop and test an innovative procedure for the comprehensive analysis of AMS-generated multi-variable time-series, with a focus on the analysis of the relationship between milk production and indoor climatic conditions. The specific purpose of the study is to develop and test a mathematical computer procedure using AMS-generated data and environmental parameters, designed to provide a forecasting model based on the integration of milking data and temperature and humidity levels surveyed from local sensor grids, designed to model milk production scenarios and, specifically, yield trends depending on the expected environmental conditions.

For this purpose, a typical Italian farm with AMS has been adopted as a study case and internal climatic data of the barn have been analysed to understand the influence of high values of the Temperature Humidity Index (THI) on milk production in time. Then the correlation between yield variations and THI has been computed and characterized. Finally, external climatic data have been used to forecast the milk production in summertime. Once the model was validated, tests has led to predict milk yield with a relative error smaller than 2%.

This study represents a step of a research aimed to define integrated systems for cow monitoring and to develop guidelines for the optimization of barn layouts.

Keywords: Precision Livestock Farming; THI (Temperature Humidity Index); Productivity; Dairy Cow.

1. Introduction

The effects of the introduction of AMS for milking performance have been subject of several studies published in scientific literature. In particular, Gygax et al. (2007) have compared the functional aspects of automatic milking systems and milking parlours, Jacobs and Siegford (2012) have studied the impact of these systems on cow management, and Tremblay et al. (2016) have analysed factors associated with increased milk production for automatic milking systems.

Besides, indoor climatic conditions in terms of temperature and humidity within a dairy livestock barn represent another well-known crucial issue in farm building design and management, since these parameters can remarkably influence cows behaviour, milk yield and animal welfare. Many scholars have focused on the study of the relationship between production yield and THI (Temperature Humidity Index), a very common index used to assess and monitor the risk of heat stress for cows (Sousa, Canata, Leme, & Martello, 2016).

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***Corresponding Author**: **Stefano Benni**, Department of Agricultural and Food Sciences, University of Bologna, Bologna, Italy. Email: stefano.benni@unibo.it

It is well known that high THI values lead to increased stress levels causing reduction in milk production and reproduction (Allen, Hall, Collier, & Smith, 2015; Ghassemi Nejad et al., 2015; Pavani et al., 2015). In particular, Samal (2013) associated THI thresholds to significant levels of heat stress in cows:

- $72 < THI < 80$ causes a mild stress level, with increase in respiration rate and blood vessels dilatation;
- $80 \leq THI < 90$ causes a moderate stress level, with water consumption increase, body temperature growth and milk production decrease (from 1% to 20%);
- $90 \leq THI < 98$ causes a severe stress level, with high body temperature, panting, excessive saliva production and a marked decrease in reproduction and milk production;
- $THI \geq 98$ causes a very dangerous stress level with potential death.

Nevertheless, an analytical mathematical model of the correlation between THI and milk production has not been developed yet in the scientific literature. The expression of such a correlation in equation form is necessary in order to develop forecasting models, capable to assess milk production depending on expected environmental conditions. On the basis of this kind of prediction, it is possible to identify the most efficient design solution for cattle barns and related systems for indoor climate control, with the aim to maximize milk production and animal welfare in relation to construction costs and building management expenses.

Within these challenging research topic, the goal of the study is to develop and test innovative procedures for the comprehensive analysis of the relationship between milk production and climatic conditions in the hot season, with the aim to support livestock farm management and the definition of design scenarios. The specific goal of the study is to define and formulate a forecasting model based on the integration of milking data and parameters quantifying temperature and humidity conditions surveyed from local sensor grids, designed to model milk production scenarios and milk yield trends depending on the expected environmental conditions.

2. Materials and methods

2.1. Study cases

Two dairy farms, indicated as farm A and farm B, have been considered as study cases for the research:

- farm A is equipped with AMS and has been adopted as training and validation case for the forecasting model of milk production;
- farm B is equipped with a conventional milking parlour and has been adopted as test case for the forecasting model.

Both farms are located in the plain area of the metropolitan district of Bologna (Emilia-Romagna Region, Italy). Farm A is placed in the municipality of Budrio, about 15 km northeast of Bologna (WGS84 coordinates 44°33'32.7"N 11°31'09.7"E, 25 m a.s.l.). The barn (whose layout is shown in Figure 1) is a 51 m long and 23 m wide rectangular building with steel frame structure and double pitched roof of insulated metal panels. It has SW-NE-oriented longitudinal axis with ridge height of 8.52 m and gutter heights of 4.95 m on the NW side and 6.65 on the SE side. The barn consists of a hay storage area on the SE side, a resting area in the central part of the building, and a feeding area and a feed delivery lane on the NW side. The resting area, whose floor is partially slatted, hosts 78 cubicles with straw bedding where about 65 Friesian lactating cows are housed; two blocks of head-to-head rows are located in its central part, and another row runs along the entire length of the resting area. The milk-room is located on the SW side of the building, next to the offices and technical plant rooms. Ventilation is controlled by three high volume low speed (HVLS) fans with five horizontal blades which are activated by a temperature-humidity sensor situated in the middle of the barn. Cow milking is performed by means of a robotic milking system (marked in the right part of Figure 1) “Astronaut A3 Next” by Lely (Maassluis, The Netherlands). The robot is programmed to assure a number of daily visits for each cow depending on the cow productivity and its expected optimal milk yield per visit, with a minimum and a maximum number of daily visits as constraints. Temperature and humidity sensors within the barn are located in the central cubicle rows, at a height of 1 metre from the ground (indicated as circles in Figure 1).

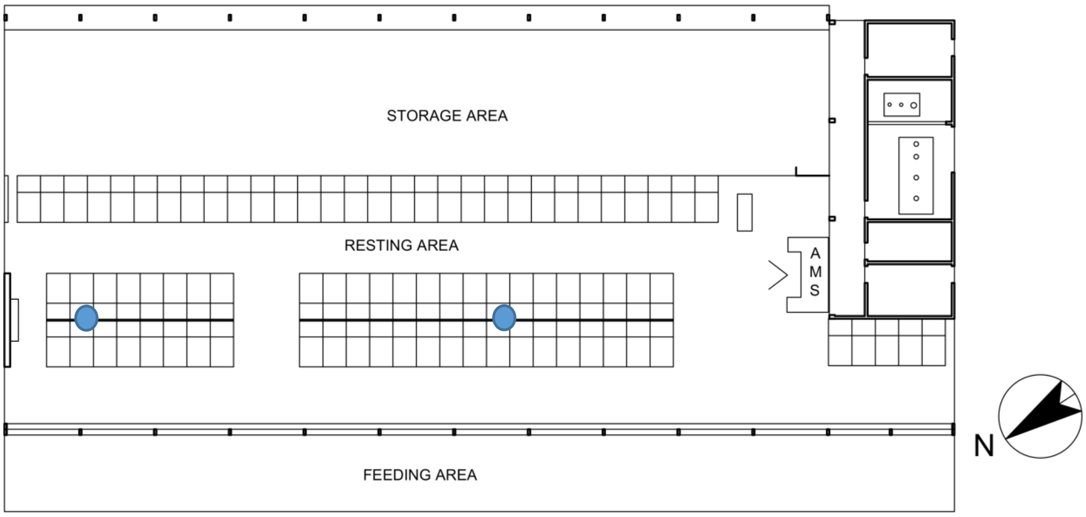

Figure 1. Farm A. Plan layout of the barn. Circles represent the locations of T-RH sensors.

The second farm (farm B, WGS84 coordinates 44°42'59.2"N 11°27'04.9"E, 17 m a.s.l.) is located in the municipality of San Pietro in Casale, about 25 km north of Bologna, same topography of the building A site. This farm has the capacity to host 270 lactating cows and the barn is arranged into three sectors (Figure 2), located into three adjacent barns built in different periods: the milking parlour and the milk room, built in the 2000s are in the NW side of the building. The milking parlour is 2x15 herringbone and the herd milk production is recorded daily. Beside this area towards SE, a coeval barn with an effective systems of natural and forced ventilation hosts 90 cows in the first three months of lactation. Beside towards SE, 110 cows in the intermediate lactating period (4 months) are reared in a masonry barn built in 1986 and in an adjacent shelter with steel structure and double metal sheet roof. The third and last sector on the SE side is for 70 cows in the last three lactating months and is in a barn built in the 1990s. The second sector (Figure 3) has shown the greater problems of ventilation and cooling, and has been monitored for this study and for a broader research in collaboration with the farm. It has concrete floor with scrapers; two rows of cubicles and the feeding alley are inside the masonry building and all cubicles have straw bedding. This area has eaves height of 4.20 m, ridge height of 6.25 m, with 45% pitch slope. Three sensors of ambient temperature and humidity have been positioned at 2.2 m from the ground respectively at the centre of the indoor resting area, at the centre of the outdoor cubicles row and in the middle of the feeding alley.

Figure 2. Farm B. Plan layout of the barn. Circles represent the locations of T-RH sensors.

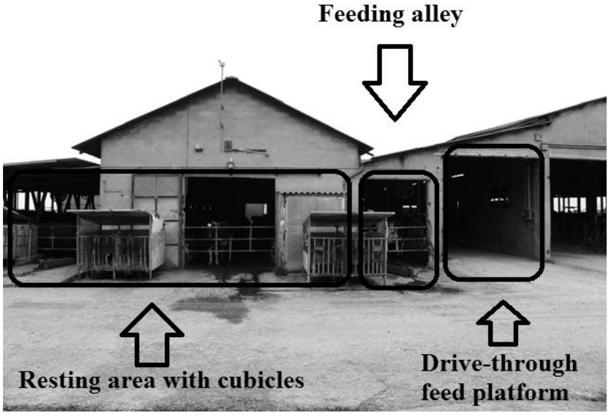

Figure 3. The analysed sectors of farm B.

2.2. Data acquisition and preliminary data analysis

Internal temperature and relative humidity (RH) have been measured and recorded in both farms by two PCE-HT71 stand-alone-data-logger, which have resolution of 0.1°C and 0.1% RH, with accuracy of ± 0.5 °C and 3% RH. The data-loggers have been set to measure and record temperature, humidity and dew point every 30 minutes. External climate data for farm A have been recorded by a PCE-FWS20 weather station - installed besides the barn- measuring temperature, humidity, rain amount and rate, solar radiation, wind speed and wind directions every 30 minutes. They are collected from June 2014 to September 2015. Climate data concerning farm B (from June 2015 to August 2015) have been acquired from a weather station of the Environmental Service ARPAE of the Emilia-Romagna Region, located 7 km from the barn, with no difference in topographic conditions.

Milk production data of farm A have been recorded by the AMS at each cow passage, in terms of the following parameters:

- Cow identification number (*Cin*);
- Date and time of the cow passage (*tcp*);
- Milk yield (*My*);
- Days of lactation (*Ld*);
- Concentrate intake (*Fi*), feed supplementation with additional concentrates. Total daily amount is calculated by the AMS based on milk yield and day of lactation;
- Cow body weight (*Cw*);
- Parity (*Pa*).

Since milking with AMS is voluntary, milking events and data acquisition frequency and time distribution are highly variable, so that the datasets cannot be compared directly on a regular basis. To allow a comparison of synchronous data of the parameters recorded by AMS, milk production data of farm A have been interpolated over synchronous 6-hour time steps (12 am - 6 am, 6 am - 12 pm, 12 pm - 6 pm, 6 pm - 12 am), by calculating the average hourly rate of milk production (L_h) for each cow according to Equation 1, where *tcp* is expressed in h:

$$L_h(tcp_{\mathrm{i}}) = \frac{My_i - My_{i-1}}{tcp_i - tcp_{i-1}} \qquad \text{(Eq. 1)}$$

Then, interpolating L_h over 6 h time spans, we have obtained a straight line of milk production for each cow. Further aggregation of four time steps has provided synchronous daily production data. Before interpolation and data aggregation, rows with null milk yield or feed intake data have been deleted, since they corresponded to unsuccessful milking sessions (e.g. in case of stressed or uncomfortable cow kicking in the machine, or insufficient time interval since last milking) which would have led to biased values. Similarly, milking events under 4 hour interval for the same cow have been aggregated to allow a smoother distribution of data.

Normality of average milk production data for each cow in farm A has been tested both graphically and by means of the Jarque-Bera test (Jarque & Bera, 1980) for fixed time steps. The test was performed on synchronous data and it proved that their distributions can be considered as normal, with a significance level of rejection of null hypothesis fixed at 5%.

2.3 Effect of climatic conditions and forecasting model

As already mentioned, several studies have investigated the influence of climatic conditions on milk production. In particular, Bohmanova, Misztal, Tsuruta, Norman, and Lawlor (2008) analysed the duration of the time lag between heat stress and production loss. This research found that in USA the climatic conditions 3 day before the considered milking show stronger correlation with the variability of milk production than those of 1 or 2 days before.

The time lag of maximum correlation between heat stress and milk productivity has been computed for the study case of farm A through the analysis of correlation (Bravais-Pearson coefficient) of the following two variables in the 2015 summer time step (July 1st - September 14th):

- Exponential Moving average of daily THI values (*ITHI*, internal THI), computed as the exponential moving average of the daily mean of THI values recorded inside the barn every 30 min between 12 pm and 6 pm. This time interval has been chosen as it proved to be period of the day when THI most significantly exceeds the heat stress threshold;

- Simple moving average of the difference of daily values of milk production of the herd (*SMy*) with a certain forward time lag from the days considered for the computation of the variable *ITHI*; such time difference (in days) has been defined through correlation analysis.

Then, a model for forecasting the milk yield of the herd has been implemented by means of a stepwise multilinear regression where data about outdoor climatic conditions - i.e. wind speed w (m/s), relative humidity rh (%), temperature T (°C), and time D (positive integers as Julian date, e.g. 1= 1st January, 32 = 1st February) along the study period - are assumed as the predictive terms, while the milk yield of the herd (*My*) represents the dependent variable. These variables are selected to underline how much the environmental conditions affect the milk production.

The data recorded in farm A in summer-autumn 2014 (from June to December) have been used as the training set (196 daily data, derived from a dataset of 1860 milking records and 9408 temperature records), while the data of farm A recorded in summer 2015 (from June to August) have been adopted as the validation set (74 daily data from a dataset of 13270 milking records and 3552 temperature records). Finally, the data of summer 2015 (from June to August) of farm B have been used as the test set (74 daily data from a dataset of 148 milking records and 1776 temperature records).

The starting Equation of the model is the multi-linear relationship expressed by Eq. 2 for the generic time *t* for a generic cow, with coefficients $a_0 \ldots a_4$:

$$My(t) = a_0 + a_1 * w(t) + a_2 * rh(t) + a_3 * T(t) + a_4 * D(t) \qquad \text{(Eq. 2)}$$

It is well known that milk yield for a cow varies with time according to a lactation curve, as well as the main behavioural parameters representative of animal welfare (Maselyne et al., 2017). In this case the whole herd production has been considered, which at a generic time *t* is the sum of the values at that moment of the lactation curve functions of every cow, which are randomly asynchronous. *My*(*t*) cannot thus be considered depending on a conventional lactation curve, while the multi-linear expression has been adopted. For the same reason, the variable ‘day of lactation’ has not been considered directly as an independent variable because it is different for each cow; at the same time the effect of time, including the variation of the day of lactation of every cow, is globally accounted for in Equation 2 by the term $a_4 * D(t)$.

Feeding ratio has been kept unchanged during the study period, while the supplemental feed provided in the AMS box is provided in quantities depending on lactation period and milk production, with coefficients which are uniform for all cows. As lactation periods of the single cows in the considered farms are asynchronous, the global feed intake of the herd cannot be recognized as a function depending on *t*, thus it has not been included in the model as an independent variable.

3. Results and discussion

The effects of climatic conditions on milk production have been analysed by testing the correlation of the two vectors *ITHI* and *SMy* with different time lags (from 1 to 7 days of difference) between *THI* value and milk yield recorded in farm A: the maximum correlation (in absolute value) is for lag of 5 days (Figure 4). For this specific lag, we have obtained a Bravais-Pearson coefficient ρ = -0.7, with significance level of correlation of 0.05. Therefore, there is a strong negative correlation between THI and milk yield (Figure 5).

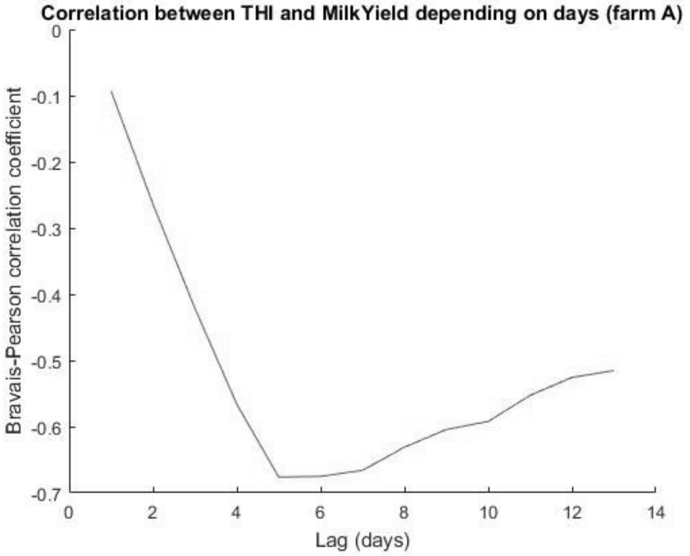

Figure 4. Correlation *THI*/Milk Yield in farm *A*: Bravais-Pearson coefficients between *ITHI* and *SMy* are reported on the vertical axis; the time lags (days) between the occurrence of the measured THI and the production of the milk yield considered are on the horizontal axis. There is a clear minimum for lag of 5 days.

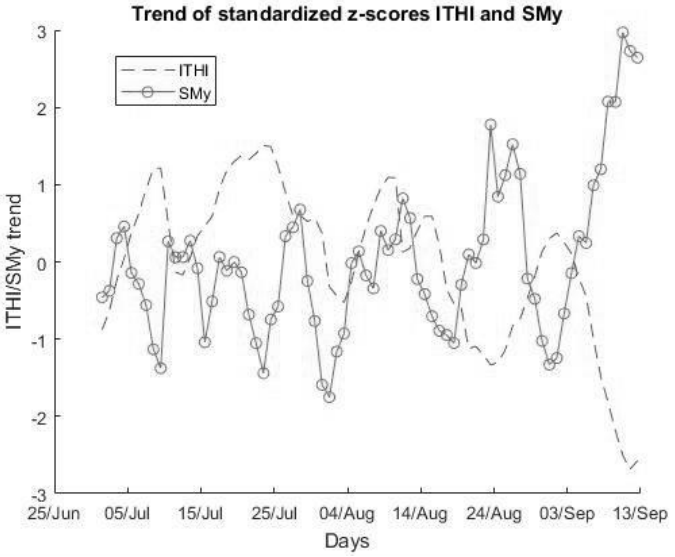

Figure 5. Correlation = -0.7 in farm A. Here, we plot *ITHI* and *SMy* with lag = 5 days. The trends of the two curves are clearly opposite.

Then, we have checked the same results in the previous summer (2014) and we obtained a correlation with ρ = -0.5. Therefore, we could state that in farm A not only the milk production is affected significantly by THI, but also the reduction in milk production appears dependent on the high levels of THI recorded five days before. This result differs from that of the study by Bohmanova et al. (2008), which was carried out considering the average values of manifold barns in the USA. The difference may be due to the different geographic and environmental conditions and to the specific features of the Italian study case considered.

A further test has been carried out on farm B, where THI and production data analysed are referred to the same time period, when about 230 Friesian cows were housed in the barn under investigation. The results show also that in this case a significant correlation exists for time lag of 5 days, as ρ is - 0.6.

This correlation connection has confirmed the opportunity to develop a predictive model of milk yield for a generic cow depending on THI. After the training phase, the model expressed by Equation 2 has provided the p-values displayed in Table 1. The p-value is the probability of finding the observed, or more extreme, results under the assumption of null hypothesis. In a stepwise regression, the null hypothesis is that the parameter would have a coefficient equal to zero if it is computed in the model. Based on such values, we have selected only T and D as variables to forecast milk yield in farm A.

Table 1. Statistics for forecasting (test phase). p-value and Status ("In" means considered in the final model; "Out" means not considered in the final model) for each variable.

Variable	p-value	Status
Temperature	$8.01 \cdot 10^{-13}$	In
Relative humidity	$1.48 \cdot 10^{-01}$	Out
Wind speed	$1.93 \cdot 10^{-01}$	Out
Day	$1.20 \cdot 10^{-25}$	In

The relationship expressed by equation 2 has thus become:

$$My(t) = 41.2 - 0.37 * T(t) - 0.07 * D(t) \qquad \text{(Eq. 3)}$$

It describes the relation between milk production of a generic cow (*My*) and temperature (*T*) in a specific time period (*t*) in the summertime (*D*) and it could be used for prevision purpose.

We considered a moving average over 5 days (Figures 6 and 7), following the above correlation results concerning the time lag of milk loss due to heat stress. We have then computed the mean error and the standard deviation of the error of milk yield foreseen by the model, respectively equal to 1.7% and 3.7%. Therefore, in case an uncertainty range of 2% is considered acceptable, this analysis represents a successful validation test.

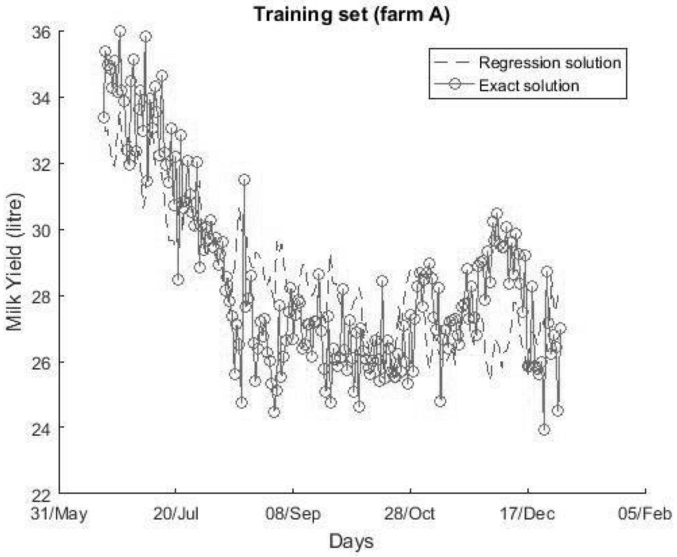

Figure 6. Training phase in farm A. This plot shows the training phase (June 19th - December 31st 2014) with regression and exact curve of daily milk yield for a generic cow in the analysed barn.

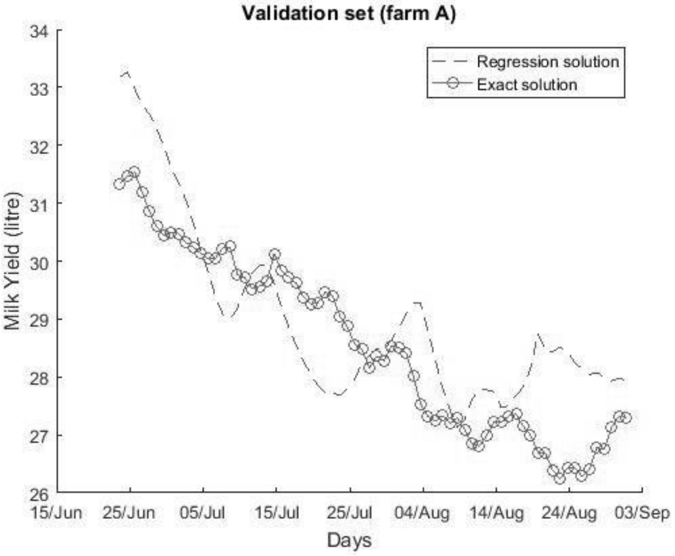

Figure 7. Validation phase in farm A. The plot displays the trend of regression and real data of the daily mean of the milk yield for a generic cow in the barn in summer 2015.

We have used farm B (Test set) to test our model: we have applied Equation 4 to the new climatic data of farm B in 2015 with the same time lag as farm A and we have forecasted the milk yield of the whole summer. We have decided to use the same time lag because our aim was to apply only one model for both of the farms. The results are illustrated in Figure 8, which shows a substantial agreement of theoretic results with measured data. Mean error is 1.7% with a standard deviation of 4.7%; therefore, the test has confirmed the reliability of the model, with a mean error below 2%. It is important to underline that the goal of this study was not to define a daily prediction, but the trend irrespectively of short-term fluctuations. Table 2 summarizes the statistics of the analysis performed.

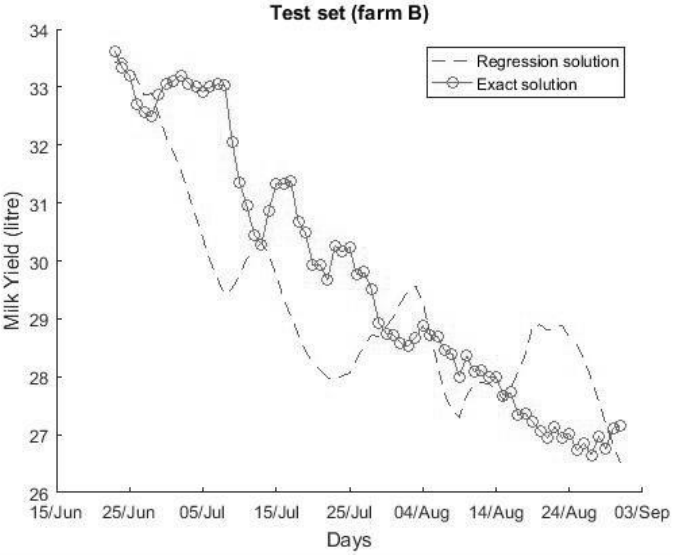

Figure 8. Test phase in farm B. This plot show the test phase: after training and validation, the model has been tested with summer 2015 data in a different farm (B).

Table 2. Statistics about forecasting (RMSEP: Root Mean Square Error of Prediction; MAE: Mean Absolute Error).

Phase	R^2	RMSEP (ld^{-1})	MAE (ld^{-1})
Training (farm A, 2014)	0.51	1.95	1.58
Validation (farm A, 2015)	0.47	1.14	0.96

Testing (farm B, 2015)	0.58	1.45	1.16

4 Conclusions

A mathematical approach to data analysis of dairy farms has been developed, by the formulation of this model.

A quantitative analysis of the effects of high THI levels on milk yield reduction has been performed through correlation. A strong negative correlation between THI and milk yield was found and mathematically modelled with the identification of a proper time lag between THI conditions and the consequent production recorded. The occurrence of THI levels above the heat stress threshold during the afternoon proved to be strongly correlated with milk production loss.

A model capable of forecasting milk yield in a farm in the warm season has been performed through a multi-linear correlation approach. The model defined has been applied and tested on two farms with different herd size and milking systems, and it proved reliable within a predefined acceptable interval of variability.

The forecasting model can be applied to assess the potential milk loss due to heat stress in a given climatic context, and therefore it represents a tool suitable for a direct assessment of the expected benefit that can be achieved through proper investments for the control of the indoor climate of a dairy barn. It also could be implemented to study milk yield trends depending on the expected environmental conditions. Thus it can be used also to predict milk production variation due to global climate change

Further ongoing developments of the research consist in the application of the models to other farms in different geographic contexts and under different climatic and farming conditions to widen the applicability rage of the model. Moreover, the response of single animals is the subject of future development through more sophisticated mathematical approaches. Finally, innovations in the definition of spatial layouts are expected from the analysis of the implications of the climatic conditions on the various parameters describing cows behaviour, with consequent benefits for the design of dairy barns.

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Nomenclature

Symbol	Description	Unit of Measurement
ρ	Bravais-Pearson Coefficient	//
a_0, a_1, a_2, a_3, a_4	Coefficients Regression	//
AMS	Automatic Milking System	//
D	Time	Positive Integers
Hsd	Heat Stress Degree	//
ITHI	Exponential Moving Average of Daily Internal THI	//
MAE	Mean Absolute Error	Percentage (%)
My	Daily Milk Yield for a Generic Cow	Litre (l)
SMy	Simple Moving Average of the Difference between Two Daily Milk Production	Litre (l)
rh	Relative Humidity	Percentage (%)
RMSEP	Root Mean Square Error of Prediction	Percentage (%)
T	Temperature	Celsius (°C)
t	Time Period	DD-MM-YYYY
tcp	Date and Time of the Cow Passage	Hour (h)
w	Wind Speed	Metre / Second (m/s)