Comparison Between Simplified and Detailed Methods for the Calculation of Heating and Cooling Energy Needs of Livestock Housing: A Case Study

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Abstract

Climate control (heating, cooling, and ventilation) is an important aspect of animal production, since the zootechnical performance and the health of reared animals are strongly related to their comfort conditions. Currently, there are neither specific protocols nor commercial tools to estimate the energy use for climate control in a livestock housing.

In this work (in the context of a funded project called EPAnHaus) three different energy simulation methods (QS: quasi-steady-state method, SH: simple hourly dynamic method, DD: detailed dynamic method), in compliance with the ISO 13790 standard, are applied to a broiler house. The aim of the work is to verify which method is more suitable to be applied for the estimation of heating and cooling energy needs of the animal house. A study was carried out to make consistent boundary conditions between the analysed models.

In the comparison of the results, the variability of the boundary conditions is not represented in QS model, resulting in considerable overestimations of the heating energy needs in the colder months (January, February, and December), it does not consider the simultaneity of heating and cooling needs during some months (February and March). Dynamic models (SH and DD models) correctly describe the thermal behavior of the analyzed building, in particular the trend of heating and cooling loads during the production cycles, and the temperature trend during empty periods.

It should be noted that the energy need for cooling is only theoretical since usually free cooling is provided by increased ventilation instead of mechanical cooling. Further analysis and comparison with measured data may therefore be carried out once the performance and the energy use of ventilation fans in the house are modelled.

1. Introduction

The aim of animal rearing is to maximize reared animals' zootechnical performance to increase production (e.g., meat, milk, and eggs) and, at the same time, to guarantee the best life conditions for the animals as required by the EU directives on animal welfare (e.g., European Council Directive 2007/43/CE and 2008/120/EC).

In this context, the climate control of livestock houses plays an important role, because it allows to maintain the indoor environmental conditions within a range of acceptability in terms of temperature, humidity, and indoor air quality (IAQ).

The indoor air temperature in livestock houses must be kept within the range of nominal losses, a thermal neutral air temperature range in which the animal production level is acceptable (ASHRAE, 2005). Within said temperature range, animals use most of the energy gained by feed intake for both, their own growth and the production increase.

Humidity and contaminants are other important parameters that are controlled in livestock houses in order to guarantee optimal environmental conditions by ventilation. Non-optimal levels of moisture may increment the animals' heat stress and cause health problems. Contaminants production is an important issue in livestock (European Commission, 2015): the presence of microscopic particles, ammonia and sulphides coming from feed, bedding and faecal material, may cause health problems to both, the animals and the workers inside the houses. For this reason, a ventilation flow rate to grant the IAQ is always

present in these buildings and it generally reaches high values (e.g., 5-7 ach).

Temperature, humidity, and IAQ control are therefore indispensable for maintaining high production levels and for ensuring a high-quality environment. At the same time, they represent an energy use and a financial cost factor because they are carried out by mechanical systems (e.g. gas heaters and fans). Some values of energy use related to climate control can be found in the literature (Rossi et al., 2013; Costantino et al., 2016): in meat chicken (broilers) production, climate control uses 75.5 % of the global thermal energy needed by the house, and 96.3 % of the total electricity consumption. These percentages consider heating (86–137 kWh/m^{2}year of thermal energy) and ventilation (4–11 kWh/m^{2}year of electricity, for both cooling and IAQ control). In swine production, 47.7 % of total thermal energy and 69.2 % of the total electricity is used for climate control with 34–37 kWh/m^{2}year of electricity used for ventilation and local heating. In dairy cow production, the energy use for climate control is lower and only equal to 20.0 % of the total electricity used into a dairy house.

Many aspects such as the species and the stocking density must be considered to estimate the energy performance of a livestock house. Currently, there are neither specific protocols nor commercial tools that allow farmers and agricultural engineers to estimate the energy use for animal house climate control. Due to the estimated growth in the consumption of livestock products e.g. meat and milk (FAO, 2011) and the projected transference of new technologies to the animal production sector in the coming future (De Corato et al., 2014), an increase in energy needs is expected in the next years. For this reason, the correct estimation of energy use in livestock houses is essential to adopt appropriate energy efficiency strategies in this sector.

1.1 The Aim of the Work

Given this picture, a project called EPAnHaus has been funded to develop a certification scheme of energy use for climate control in animal houses through modelling and simulation, and measurements. In the present work, three different simulation methods, namely quasi-steady-state (QS), simple hourly dynamic (SH), and detailed dynamic (DD) are applied to a case study. The main purpose is to identify which method is more suitable to be used at the energy performance certification stage for determining the energy needs for the heating and cooling of a livestock house. The case study refers to a house for broiler production.

In the present work, we analyze the consistency options of the boundary conditions and assumptions made during the modelling stage, and compare the outputs of each simulation model. In this way, it is possible to understand which models can correctly describe the boundary conditions and the thermal behavior of the analyzed building.

2. Simulation

2.1 The Case Study

2.1.1 Broiler Production

In the present work three different simulation models are applied to a broiler house to estimate its heating and cooling energy needs. Humidity control is not taken into account.

The broiler house was chosen for the case study because of its interesting features from an engineering point of view.

First, broilers are bred in a closed enclosure. Another interesting element is that broilers are reared in high stocking densities, generally between 33 and 42 kg_{meat}/m^2, which means an animal presence between 15-23 birds/m^2, depending on the final live weight. These high values entail considerable heat and vapor production that strongly affect the indoor environment. For example, the flock analysed in this work (about 34,400 birds) has a maximum sensible heat emission of 385 kW and it can produce 170 kg of water in 24 hours by breathing and by faecal material. The data for the estimation of heat and vapor emission by broilers can be determined by animal physiology and homeothermy manuals (Esmay et al., 1986).

An additional feature that makes broiler production interesting is that the climate conditions that must

be kept in the house are not steady during the duration of the production cycle (batch). Conditions, like the heating set point, the cooling set point, and the IAQ ventilation flow rate vary as a function of the broiler age and weight. As shown in Fig. 1, the two-set point temperatures are negatively related to the age (older broilers need lower temperatures than younger ones), while the IAQ flow rate is positively related to the age (older broilers produce more contaminants due to their greater weight).

For this reason (high internal gains and variable set point temperatures) in broiler houses heating may be needed also in the hot season and cooling in the cold one.

In this work, a flock of 34,440 birds is considered. The considered stocking density for the flock is 16.5 birds/m², with a batch duration of 39 days. At day 1 of the batch, few-day-aged chicks are carried in the house. Between two consecutive batches, a sanitary empty period of 13 days is considered, in which there are no animals in the houses and the climate of the house is not controlled. Given these assumptions, each year, 7 completes batches can be carried out.

Using performance objectives tables by feed companies (Lohmann Meat, 2007), the live weight of the birds for each day of the batch can be considered. At the start of the batch chicks of 0.042 kg are considered, while at day 39, broilers have a final live weight of 2.5 kg, as shown in Fig.1.

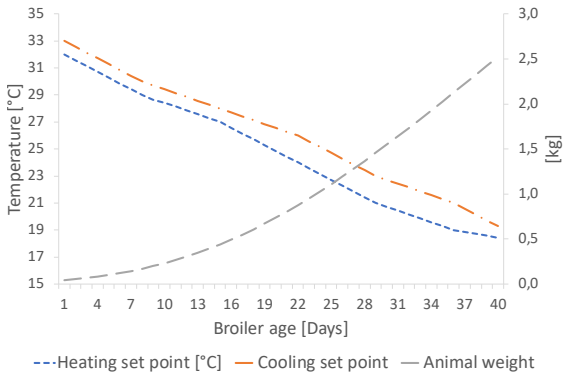

Fig. 1 – Animal weight and air set point temperatures for the batch duration

Data about set point temperatures and minimum IAQ ventilation flow rate come from guides for the management of broiler houses (Cobb, 2008). In Fig 1 the heating set point and cooling set point trends are shown.

2.1.2 The reference broiler house

Broiler production is generally carried out in low insulated buildings, with a width of 10-15 m and a length that can be greater than 100 m.

The reference building used as the case study is in Parma, in the North of Italy. The building is a gable roof broiler house built with a steel structure and prefabricated sandwich panels. It is 15 m wide and 140 m long, with the longer axis aligned on the east-west direction. The total useful floor for the broiler production is 2087 m². At the ridge level the house has a height of 5 m and it decreases to 3 m at the eave level.

The house walls and the roof are prefabricated sandwich panels made up of a double layer of pre-painted steel sheets. Between the two metal sheets a 0.04-m thick high-density spread polyurethane layer (λ = 0.028 W/(m K)) is interposed as a thermal insulation layer.

The floor is a reinforced concrete screed above a waterproofing sheet and a thermal insulation layer of cellular glass granules (λ = 0.08 W/(m K)). The thickness of the thermal insulation layer is 0.15 m, while the concrete screed has a thickness of 0.20 m. The internal heat capacity of the opaque elements was calculated according to the ISO 13786 standard (ISO, 2007).

The analysed broiler house has a guillotine opening system for the windows. They are made of metal frames and polycarbonate alveolar panels.

Table 3 – Thermo-physical proprieties of the building envelope

Element	U-value [W/(m² K)]	κ_i [kJ/(m² K)]	α [-]
Walls	0.63	4.8	0.3
Roof	0.64	4.9	0.6
Floor	0.45	67.9	/
Windows	3.6	/	/

All data used for the building envelope come from commercial products. The thermo-physical proprieties of the envelope are presented in Table 1.

2.2 Calculation Methods

Three different calculation methods based on the ISO 13790 standard (ISO, 2008) were adopted to create three different energy calculation models. The used methods are:

- a monthly quasi-steady-state calculation method (QS);
- a simple hourly dynamic calculation method (SH);
- a detailed (hourly) dynamic simulation method (DD).

They differ because of the chosen time step, the dynamic parameters considered, and the different details of the requested input data.

The adopted methods are described in the following sections.

2.2.1 The quasi-steady-state (QS) model

The quasi-steady-state calculation method (ISO, 2008) is based on the monthly balance of heat losses (transmission and ventilation) and heat gains (solar and internal), assessed in monthly average conditions (Corrado et al., 2007). The dynamic effects on the net energy needs for space heating and space cooling are taken into account by introducing a utilization factor for the mismatch between transmission *plus* ventilation heat losses and solar *plus* internal heat gains leading to heating/cooling loads. The utilisation factor depends on the time constant of the building, the ratio of heat gains to heat losses, and the occupancy/system management schedules.

The energy need for space heating and cooling for each month is calculated as:

$$Q_{\mathrm{H,nd}} = Q_{\mathrm{H,ht}} - \eta_{\mathrm{H,gn}} \cdot Q_{\mathrm{gn}} \quad (1)$$

$$Q_{\mathrm{C,nd}} = Q_{\mathrm{gn}} - \eta_{\mathrm{C,ls}} \cdot Q_{\mathrm{C,ht}} \quad (2)$$

where, $Q_{\mathrm{H/C,nd}}$ is the energy need for space heating/cooling, $Q_{\mathrm{H/C,ht}}$ are the total heat losses (transmission *plus* ventilation), Q_{gn} are the total heat gains (internal *plus* solar), $\eta_{\mathrm{H,gn}}$ is the utilization factor of heat gains, and $\eta_{\mathrm{C,ls}}$ is the utilization factor of heat losses.

The actual lengths of the heating and the cooling seasons are determined on the basis of the limit value of the dimensionless heat-balance ratio for the heating mode and the cooling mode respectively. The limit value is expressed as a function of a dimensionless numerical parameter depending on the time constant of the building.

2.2.2 The simple hourly dynamic (SH) model

The simple hourly dynamic model is described in Annex C to the ISO 13790 standard (ISO, 2008). It consists in a simplification of the heat transfer between outdoor and indoor environment based on a similarity between the thermal behavior of the analyzed building and a resistance – capacitance network made of 5 resistances and 1 capacitance (5R1C). The schematics of the model is reported in Fig. 2 where:

- θ_{air}: indoor air temperature
- θ_{s}: temperature given by the mix of mean radiant and indoor air temperature
- θ_{m}: temperature of the capacitive mass node
- θ_{e}: outdoor air temperature
- θ_{sup}: supply air temperature
- H_{ve}: ventilation heat transfer coefficient
- $H_{\mathrm{tr,is}}$: heat transmission coefficient
- $H_{\mathrm{tr,w}}$: transmission heat transfer coefficient through windows
- $H_{\mathrm{tr,op}}$: transmission heat transfer coefficient through opaque components
- C_{m}: building fabric heat capacity
- Φ_{ia}, Φ_{st}, Φ_{m}: internal and solar heat gains
- $\Phi_{\mathrm{H/C,need}}$: heating or cooling heat load.

The indoor air temperature (θ_{air}) is calculated as:

$$\theta_{\mathrm{air}} = \frac{H_{\mathrm{tr,is}} \cdot \theta_{\mathrm{s}} + H_{\mathrm{ve}} \cdot \theta_{\mathrm{sup}} + \Phi_{\mathrm{ia}} + \Phi_{\mathrm{H/C,nd}}}{H_{\mathrm{tr,is}} + H_{\mathrm{ve}}} \quad (3)$$

The heating/cooling energy need during the analyzed period ($Q_{\mathrm{H/C,need}}$) is obtained by summing the $\Phi_{\mathrm{H/C,need}}$ per each time step adopted by the model (1 hour).

This model was applied to a calculation tool for the estimation of the heating and cooling energy need of a broiler house, as shown in Fabrizio et al. (2015).

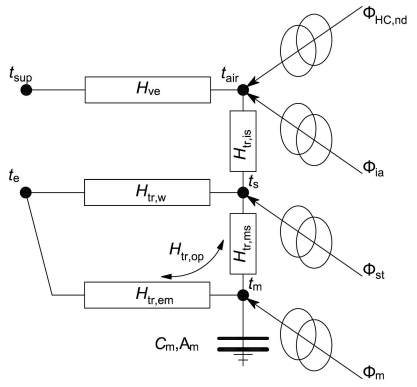

Fig. 2 – Schematic representation of the simple hourly method (ISO, 2008)

2.2.3 The detailed dynamic (DD) model

The detailed dynamic model was created in the EnergyPlus software tool (Filippi et al., 2012).

The building thermal zone calculation method of EnergyPlus is the air heat balance model. It is based on the assumptions that the air in the thermal zone has, by default, a uniform temperature, the temperature of each surface is uniform, the long-wave and short wave radiation is uniform, the surface irradiation is diffusive, and the heat conduction through the surfaces is one-dimensional. The air heat balance, neglecting the heat transfer due to infiltration and to inter-zone air mixing, can be written as:

$$C_z \frac{d\theta_z}{d\tau} = \sum_{i=1}^{N} Q_{c,i} + \sum_{i=1}^{N_{surface}} h_i A_i (\theta_{si} - \theta_z) + \dot{m}_v c_p (\theta_e - \theta_z) + \dot{Q}_{sys} \quad (4)$$

where, N is the number of convective internal loads $Q_{c,i}$, $h_i \cdot A_i \cdot (\theta_{si} - \theta_z)$ is the convective heat transfer from the zone i-surface at temperature θ_{si} to the zone air at temperature θ_z, while $c_p \cdot (\theta_e - \theta_z)$ is the heat transfer due to ventilation with the outside air, and $\dot{Q}_{sys}$ is the system output. The capacitance C_z takes into account the contribution of the zone air as well as that of the thermal masses assumed to be in equilibrium with the zone air. In order to determine the building net energy need under ideal conditions and to make the result independent from the system features, the so-called "Ideal Loads Air System", which can be operated with infinite heating and cooling capacity, was applied.

A time step of fifteen minutes was adopted in the simulation.

Some examples of application of this tool to animal houses can be found in literature (Fabrizio, 2014).

2.3 Consistency Options

In order to compare the net energy needs obtained with different methods, the modelling procedures should be made consistent, as shown in Corrado et al. (2015) and Ballarini et al. (2011). In the following, the consistency options applied to the models are presented.

- The hourly weather data (outdoor air temperature, solar radiation) used in the DD simulation come from a data set known as IWEC (International Weather for Energy Calculations). The same data were applied in the SH model. The monthly average values were considered in the QS model.
- Hourly schedules of heating and cooling set point temperatures, internal heat sources (sensible heat emission of broilers), and ventilation flow rate were assumed in the hourly methods (DD and SH), while monthly averages of the same quantities were used in the QS model.
- In EnergyPlus, the opaque and transparent building components were modelled by defining the detailed thermo-physical parameters of their materials (e.g., thermal conductivity, density, specific heat capacity, spectral features). The resulting thermal transmittance values of the envelope components and the total solar energy transmittance of glazing were applied to the SH and the QS model.

3. Discussion and Result Analysis

3.1 Numerical Results

The yearly energy needs for heating and for cooling estimated by the three models are reported in Table 2. From the table, it is possible to notice that the total heating energy need of the QS model is the highest value. By contrast, the SH total cooling energy need is the highest one, while the value obtained through the QS model is the lowest. For

both heating and cooling energy needs, the results of DD fall within the values obtained by the QS and SH models.

Focusing on the total heating energy needs, the differences between the outputs of the three models appear to be not negligible. Table 2 shows that, assuming the DD model value as a reference, the value estimated by the SH model is smaller by 17.0 kWh/m² (-17 %). The yearly heating need value estimated by the QS model is greater than DD by 66.9 kWh/m² (+66 %).

By contrast, when looking at yearly energy need values for cooling, all values are quite similar. Considering the detailed dynamic model (DD) result as reference, the QS model result is lower by 18.2 kWh/m² (-9 %), while the SH model value is greater by 6.7 kWh/m² (+3 %).

Table 2 – Yearly energy needs for heating and cooling (outputs of the models)

Energy use	QS model	SH model	DD model
Heating [kWh/m²]	168.1	84.2	101.2
Cooling [kWh/m²]	187.5	205.7	199.0

The significant difference that exists especially between the heating values of the QS model and of the DD and SH models can be explained by analyzing the monthly energy needs, as shown by Fig. 3.

In colder months, the energy needs for heating, estimated by the QS model, are greatly overestimated, in particular in January, February and December. Another interesting element is that the QS model is not able to consider the simultaneity of a heating and a cooling energy need in the same month, except for those months in which heating and cooling seasons (or vice versa) change, as it occurs in October. Since it does not contemplate this aspect, the QS model does not consider important shares of energy needs, such as the cooling needs in February and in April.

For these reasons, the use of the QS model cannot be recommended for this type of application.

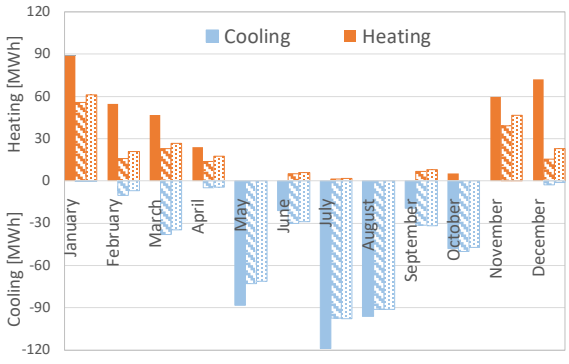

Fig. 3 – Monthly heating and cooling energy needs; (QS model: full color columns; SH model: striped columns; DD model: dotted columns)

In Fig. 4 the trends of heating and cooling loads estimated by the two dynamic models (SH and DD models) are shown during a complete batch carried out between February and April. In the first part of the chart (batch start) neither heating nor cooling loads occur because the birds are not inside the building, therefore the air temperature fluctuates in free-range conditions. When the young chicks arrive at the broiler house, there is a heating load peak which is estimated differently in the two models, while later, the trends of loads in both models appear quite close.

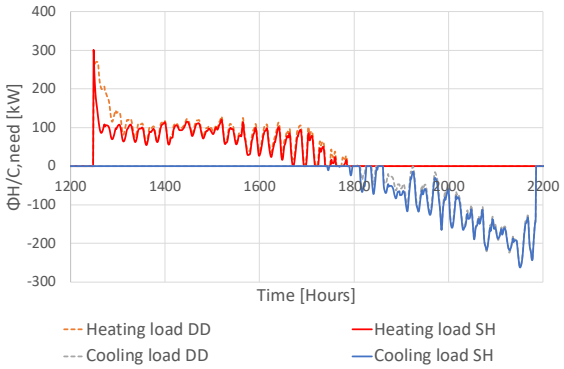

Fig. 4 – Hourly heating and cooling need during a batch (February–April)

While the animals grow, the heating load decreases, as shown in Fig. 4, as a function of the decrease in the heating set point temperature, and the cooling load increases during the last part of the batch. The RMSE between the two-load profiles, calculated over the 936 h of the batch, is equal to 22.0 kW for the heating load and to 8.1 kW for the cooling load. Not considering the first days in the calculation of

the heating load, the RMSE between the two trends decreases to 7.3 kW.

In Fig. 5 the indoor air temperature trends estimated by the SH and DD models are shown for the last days of the batch of Fig. 4, and for the following empty period. In the first part of the chart both estimated indoor air temperatures (obtained through the SH and DD models) correspond to the cooling set point. When the batch ends, the broiler house is empty, no set point temperature is requested and the indoor air temperature fluctuates in a free running condition. Both models present very close air temperature trends after some days, while just after the system shut off, the temperature decay in the DD model takes a few days when compared to the decay in the SH model that takes place in a few hours. This may be due to a difference in the heat capacity estimation of the floor in the two models.

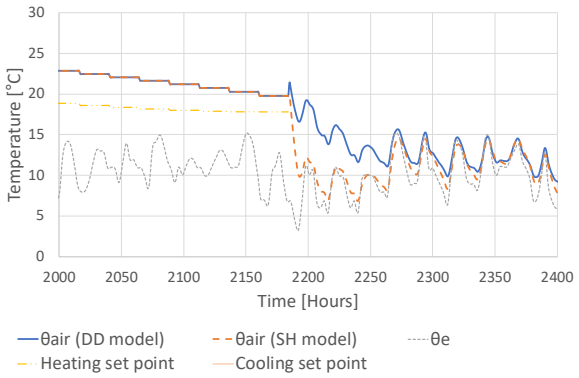

Fig. 5 – Temperature trends at the end of the batch of Fig. 4 and during the following empty period (free running conditions)

4. Conclusion

In the present paper, three simulation models for the estimation of the energy needs of a broiler house are compared.

The results show that the simple hourly dynamic method (SH) and the detailed (hourly) dynamic simulation method (DD) give similar results for heating and cooling energy needs, with a difference between 9 % and 17 %. The monthly quasi-steady-state method does seem not to be suitable for the energy analysis of such house because it considerably overestimates the heating energy need values and it is not able to correctly consider the variation of boundary conditions (e.g., set point temperature and internal heat gains).

It should be noticed that the cooling energy need is only theoretical; in fact only free cooling techniques based on the house's tunnel ventilation are applied. Therefore, a direct comparison with the measured data cannot be made at this stage, but it should be made once the electricity use for ventilation in free cooling mode is also estimated.

The presented methodology may also be used for estimating the energy consumptions of other livestock houses for animal species commonly reared in intensive breeding, such as swine and laying hens.

Acknowledgement

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Nomenclature

Symbols

C	Effective heat capacity (kJ/K)
H	Heat transfer coefficient (W/K)
Q	Thermal energy (Wh)
U	Thermal transmittance (W/(m² K))
α	Solar absorption coefficient (-)
η	Utilization factor (-)
θ	Temperature (°C)
λ	Thermal conductivity (W/(m K))
κ	Areal heat capacity (kJ/(m² K))
Φ	Heat flow rate (W)

Subscripts/Superscripts

a	Air
C	Space cooling
e	External, exterior
gn	Heat gains
H	Space heating
ht	Heat transfer
i	Internal (temperature)
ls	Losses

m	Mass-related
nd	Need (energy)
op	Opaque
tr	Transmission (heat transfer)
sup	Supply (of air)
ve	Ventilation (heat transfer)
w	Windows

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