Optimal financial insulation thickness of a broiler house

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Abstract: A common method for environmental control in livestock facilities is to use thermal insulation for exterior walls and roofs. In regions with cool winters increasing the insulation thickness decreases the heating requirements, however in regions with hot summers may lead to an unwanted increase of inside temperature, thus intensifying cooling loads. It is worth noting that financial thickness optimization of a broiler house external walls and gable roof insulation for different orientations has not been sufficiently addressed. Thus, a detailed transient simulation was used to model and calculate the annual heating and cooling loads of a broiler house. For that, hourly climatic data and all the heat and moisture gains and losses resulting from birds, heat flow through the building envelope, and mechanical ventilation were considered. An economic analysis based on the life cycle savings (LCS) method was performed for the walls and gable roofs for various insulation thicknesses and orientations. The comparison of the annual heating loads per unit area with that of similar energy audited broiler houses was satisfactory. The optimum insulation thickness of external walls and gable roof was found to be between 4.0 cm and 4.5 cm depending on their orientation, while the wall facing north offered the greatest economic benefit compared to other orientations. According to the results, the annual cooling load was 3.3 times higher than that of heating.

Keywords: broiler house, optimum insulation thickness, cooling load, heating load, NPV, Greece

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1 Introduction

Broilers are homeothermic animals trying to maintain their body temperature constant at 41°C (Da Silva and Maia, 2013; Yahav, 2014). Low temperatures result in impaired immune and digestive systems (Lee et al., 2003), whereas high temperatures reduce feed intake, growth rates and feed efficiency (Reece and Lott, 1983). The aim of controlling air temperature and relative humidity (De Oliveira et al., 2006) is to maximize breeding performance through ensuring optimal growth rate, feed efficiency, good health, and reduced mortality (Heier et al., 2002; Baarendse et al., 2006; Blahova et al., 2007; Akşit et al., 2008).

Broiler meat production covers almost 82% of meat needs in Greek (Greek Ministry of Agriculture and Food, 2016). Broiler meat is 150,695 t produced from 86,895×10^3 heads (FAOSTAT, 2017). Environment control in Greek broiler houses is a necessity, and for this reason, conventional means, namely fossil fuels for heating and evaporative pads for cooling are used (Martzopoulou, 2006). The operation of such systems leads to high and uneconomic energy costs and environmental pollution

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(Bokkers et al., 2009), thus Manolakos et al. (2019) investigated the use of heat pumps for precise environment control targeting to improve welfare and productivity. A practical environment control solution in livestock facilities was using thermal insulation of exterior walls and roof (Hinkle and Stombaugh, 1983; Banhazi and Rutley, 2013).

In regions with cool winters and hot summers, increasing the insulation thickness can decrease the heating requirements, but may also lead to unwanted increase of inside temperature and intensify cooling loads during hot periods (Axaopoulos et al., 2014). High levels of insulation can decrease thermal losses, increase the cost of insulation, and raise the capital cost of the building. Yu et al. (2009) and Ozel (2011) used the degree-day (or degree-hour) concept to determine the optimum wall insulation thicknesses in thicknesses of the insulation material. Beyond a certain point, the insulation cost will exceed the monetary benefits of the energy saved. Comparing the difference between the life cycle cost of a conventional heating system and the life cycle cost of the insulation plus auxiliary energy system, for several thicknesses and over the lifetime of the building, a maximum monetary benefit and the economically optimum thickness of insulation will be obtained.

Although it is well known that the installation of insulation reduces heat losses, the problem of optimizing the thickness of insulation of external walls and gable roof for different orientations of a broiler house has not been sufficiently addressed. The present study seeks to addresses this question by thoroughly simulating a broiler house.

2 Materials and methods

2.1 Simulation

A detailed transient simulation model of a broiler house accounting for the heat flow through the building shell, the sensible and latent heat loads of broilers and the mechanical ventilation heat losses was run. The following time-dependent equations were used to calculate the temperature and relative humidity inside the broiler house, and assuming the indoor air was perfectly mixed.

$$\left(\rho_{\mathrm{i}} V c_{\mathrm{p,i}}\right) \frac{\mathrm{d}T_{\mathrm{i}}}{\mathrm{d}t} = \dot{Q}_{\mathrm{surf}} + \dot{Q}_{\mathrm{s,p}} + \dot{Q}_{\mathrm{vent}} \quad (1)$$

$$(\rho_{\mathrm{i}} V) \frac{\mathrm{d}W_{\mathrm{i}}}{\mathrm{d}t} = \rho_{\mathrm{i}} \dot{m}_{\alpha}(W_{\mathrm{o}} - W_{\mathrm{i}}) + \dot{w}_{\mathrm{p}} \quad (2)$$

where, ρ_{i} is the density of inside air, kg m^{-3}, V is the volume of the inside air space, m^3, $c_{\mathrm{p,i}}$is the specific heat of air, J kg^{-1} °C^{-1}, T_{i} is the inside air temperature, °C, t is the time, s, $\dot{Q}_{\mathrm{surf}}$ is the heat flow through the walls, the roof and the floor, W, $\dot{Q}_{\mathrm{s,p}}$ is the sensible heat production, W, $\dot{Q}_{\mathrm{vent}}$ is the heat losses due to ventilation, W, $\dot{m}_{\alpha}$ is the ventilation air flow rate, m^3 s^{-1}, W_{o} is the outside air humidity ratio, kg kg^{-1}, W_{i} is the inside air humidity ratio, kg kg^{-1}, $\dot{w}_{\mathrm{p}}$ is the broiler water vapor production, kg s^{-1}.

The thermal behavior of the walls and roof was studied via TRNSYS (2006), with respecting to heating and cooling transmission load for different orientations. Conduction heat transfer was treated as one-dimensional and the thermophysical properties of the building materials were considered independent of their temperature. Each layer of the exterior wall was presumed to be homogeneous, the air adjacent to both wall sides was at a uniform temperature and the surface of both sides of the wall was also at a uniform temperature. Finally, the ground reflectance coefficient was set equal to 0.2 (Santamouris, 2006) throughout this study for comparison purposes and the solar absorptance of the outside surface of the walls and gable roofs was presumed to be 0.6 (Incropera and DeWitt, 1990).

Broilers mostly need high temperature and low relative humidity environment (Cobb, 2012). Their mass (M_{c}) at each day within a production cycle was given (Lohmann Meat, 2007) by the following polynomial equation:

$$M_{\mathrm{c}} = f_1 d^3 + f_2 d^2 + f_3 d + f_4 \quad (3)$$

where, f_1 = -0.000021164, f_2 = 0.0025608, f_3 = -0.0053002, f_4 = 0.070839, d_p is the day within a production cycle

Also, the desired inside temperature for each day of the production cycle was given by the following polynomial equation (Cobb, 2012):

$$T_{\mathrm{i}} = Ad_p^4 + Bd_p^3 + Cd_p^2 + Dd_p + E \tag{4}$$

where, A = -0.000003, B = 0.0004, C = - 0.0122, D = -0.3886, E = 34.032.

The indoor relative humidity for day-10 was set to vary between 40% and 60%, and for day-35 was between 50% and 70% (Costantino et al., 2018). From the above polynomials, it becomes evident that during the first growing days young birds of low mass need high inside temperatures and as birds' mass increases the inside temperature gradually decreases. This fact, along with the increasing birds' mass which rises their sensible loads, means that by the end of the growing period the cooling loads will be higher. On the contrary, during the first growing days, there will be a need for heating, depending on the time of the year.

The broiler sensible and latent heat loads were calculated based on the set of equations given in Sallvik and Pedersen (1999), whereas the calculation of $\dot{Q}_{\mathrm{surf}}$ was based on the heat conduction transfer functions method (Stephenson and Mitalas, 1971). Full details were provided in Axaopoulos et al. (2017) and Manolakos et al. (2019).

The mechanical ventilation rate $\dot{Q}_{\mathrm{vent}}$ was calculated for carbon dioxide (CO_2) concentration control (Pedersen and Sällvik, 2002).

$$\dot{Q}_{\mathrm{CO_2}} = \frac{v_i \cdot (M_{\mathrm{CO_2}})}{(CO_{2\mathrm{i}} - CO_{2\mathrm{o}})} \tag{5}$$

where, $\dot{Q}_{\mathrm{CO_2}}$ is the CO_2 concentration control ventilation rate, m^3 s^{-1}, v_i is the specific volume of the inside air, m^3 kg^{-1}, $M_{\mathrm{CO_2}}$ is the quantity (broiler mass dependent) of CO_2 produced within the building, kg s^{-1}, CO_{2i} is the maximum allowable CO_2 concentration of the inside air, kg kg^{-1}, CO_{2o} is the average CO_2 concentration of the outside air, kg kg^{-1}.

All the above equations were used in conjunction with the appropriate parameters and the hourly weather data, to determine the heat flux on the external wall surfaces and gable roof. Finally, the integration of the resulting heat flux during a time-period determined the heating or cooling load for that period.

2.2 Economic analysis

Determination of the most profitable insulation thickness of walls and roofs is based on a simple economic analysis, namely the life cycle savings (LCS) method (Duffie and Beckman, 2006), which can be used to find the economically optimum design of a given system. The appraisal requires the synthesis of both the energy performance results and several economic parameters. Performance data were calculated using the simulation model above and a set of presumed economic parameters.

The net present value (*NPV*) was used to perform a comparative economic analysis for a 20-year period (*N*). The *NPV* is the sum of the net cash flow of all costs and benefits (LS_j), discounted at a discount rate (d) and is given by the following equation:

$$NPV = \sum_{j=0}^{N} \frac{LS_j}{(1+d)^{\mathrm{j}}} \tag{6}$$

where, j is the year of economic analysis.

The payback period was calculated using its discounted form including the time value of money (Duffie and Beckman, 2006), hence it was more reliable for finding the payback period. In this case it is the time required for the discounted cumulative energy savings to equal the initial investment cost. By means of the appropriate equations and a spreadsheet (Axaopoulos et al., 2017), the *NPV* was calculated for different external walls and gable roofs insulation thicknesses and orientations. For each orientation, the insulation thickness corresponding to the highest positive *NPV* value is optimum.

2.3 Case study

Aiming at validating the transient simulation model, a broiler house located at Kavala (40°59'N, 24°36'E) in northern Greece was used as a case study. Hourly solar irradiance on horizontal surface, ambient temperature and relative humidity values for this area were used (Meteonorm, 2004). The required performance data have been calculated using the simulation model above. The building data and broiler data was shown in Table 1, and a set of presumed economic parameters pertinent to Greece was shown in Table 2. Insulation cost was calculated at the time of construction in Table 2.

The growing period lasts 35 days. Afterwards the broiler house was evacuated for 15 days devoted to cleaning and disinfection. Ten thousand birds were grown per production period, occupying one third of the broiler house from day-1 to day-10 and the whole house from day-11 to day-35.

Table 1 Building data and broiler data used in the simulation

Building and broiler data	Description
Type of building	Enclosed facility
Orientation	East-West
Building width (m)	13.61
Building length (m)	45.7
Building height gutter (m)	3.55
Walls, Gable roof	Sandwich panels
	Galvanized steel
	Polyurethane foam
Roof inclination (°)	9
Floor materials composition	8 cm sawdust litter
	2 cm concrete coating
	15 cm concrete
	2 cm waterproof
	25 cm soil
Type of ventilation	Mechanical
	13 axial fans
	5 centrifugal fans
	10 wall flange-openings
Total number of broilers	10000
Broiler mass (kg)	0.325 – 2.2
Inside temperatures required (°C)	18.0 – 34.0

Table 2 Presumed economic parameters

Parameter	Value
Insulation cost(€ m^{-3})	325
Domestic electricity price (€ kWh_e^{-1})	0.11
Cost of heating energy(€ kWh_{th}^{-1})	0.21
Domestic electricity inflation rate(%)	4
Propane price inflation rate(%)	4
Bank loan interest rate(%)	7
Loan lifetime	10 years
Economic analysis	20 years
Discount rate(%)	3.0
COP (evaporative cooling)	7
Boiler efficiency	0.91

3 Results and discussion

The change in external climatic conditions, coupled with the daily increase in bird mass, leads to a daily change of the broiler house energy needs, thus the required high inside temperature during the initial 10 days need heating. Subsequently, the gradual increase in bird mass improved their sensible heat loads and decreased the required inside temperature (Figure 1), resulting in an increased cooling load.

The values of the heating and cooling loads per growing period depend, among others, on the climatic conditions and consequently on the corresponding time-period of the year and hour of the day. Figure 2 showed the change of heating and cooling loads compared with the outside temperature for a growing period during the cooler part of the year (1st January to 4th February). It showed that even then the broiler house required cooling, besides heating. The gradual decrease in outside temperature resulted in an increase of the heating load, while the heating loads peaks were evident at the lower values of the outside temperature. On the contrary, along with the outside temperature rose, the increase of birds' sensible load led to low heating loads. And in fact, there were hours during the day, which also required cooling loads. During the last days of the growing period (high sensible loads) and because of the wide range of outside temperature fluctuation (day-night), there was a cooling load during the day and a heating load during the night.

Figure 3 was like Figure 2 but referred to a growing period during the hotter part of the year (25th July-29th August). The cooling load is very high as although during the first days of the growing period (i.e. low bird sensible heat loads) some heating loads are required, despite the high outside temperature and the need for elevated inside temperature. Subsequently, as expected, due to the high outside temperature and the gradual increase of the birds' sensible load, the cooling load appeared high and continuous for 24 hours. It is worth mentioning that the cooling load during this growing period is 53.5 times higher than the corresponding heating load.

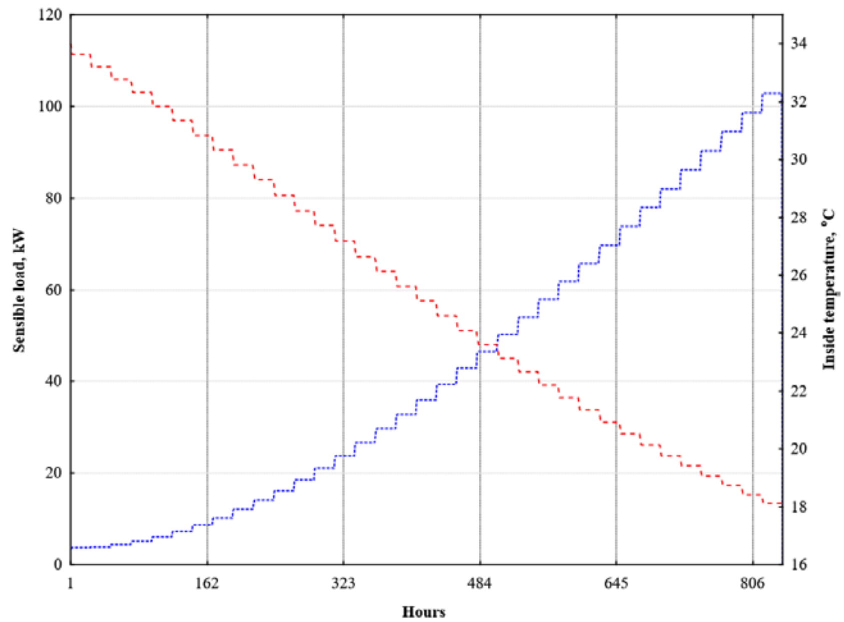

Figure 1 Sensible load and inside temperature (. . . . sensible load, - - - - inside temperature)

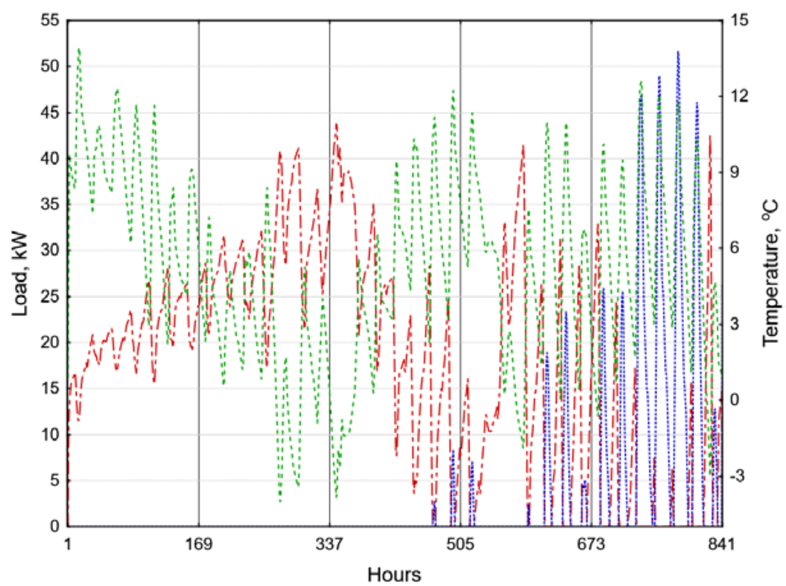

Figure 2 Growing period during the cooler part of the year (-.-.-.-. outside temperature, - - - - heating loads, ... cooling loads)

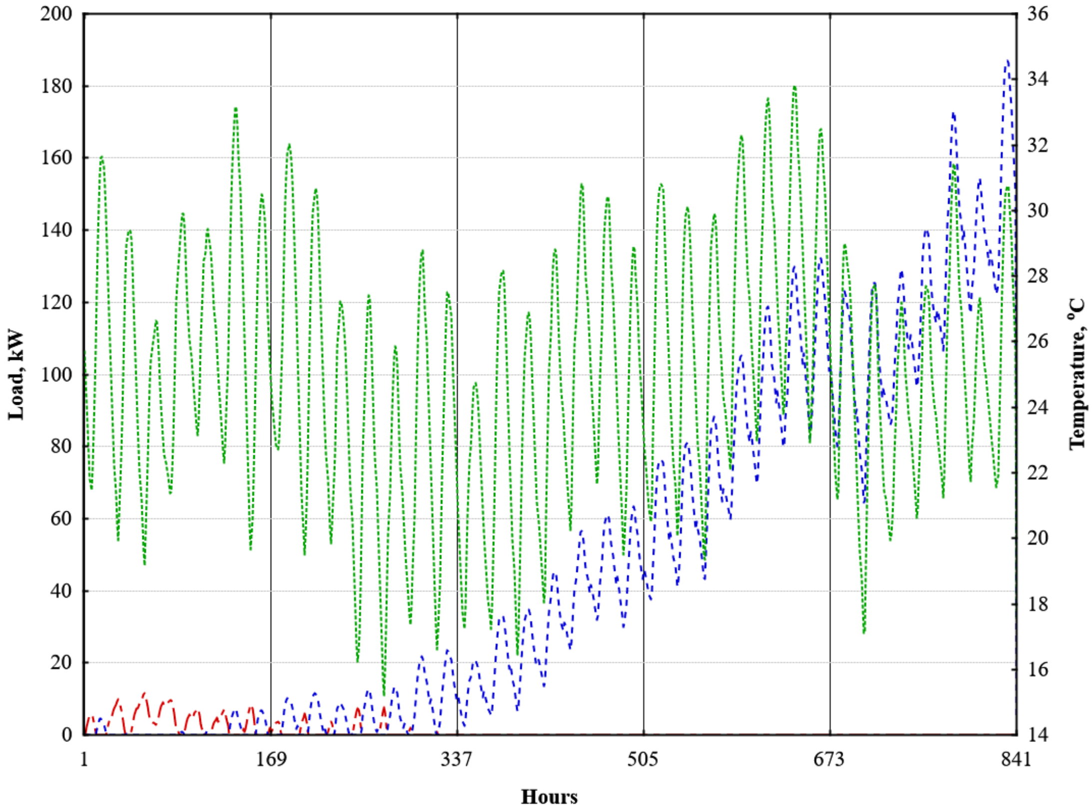

Figure 3 Growing period during the hotter part of the year (. . . . outside temperature, -.-.-.-. heating loads, - - - - cooling loads)

The annual thermal study of the broiler house showed that during all growing periods throughout the year, there was a requirement for heating and cooling loads with the latter being 3.3 times higher. The low relative differences between inside and outside temperatures, especially during the hot months, and the increased cooling load would favour the use of a heat pump and a well-adjustable mechanical ventilation system for more efficient regulation of the inside microclimate. The variation of the heating and cooling loads per square meter of surface area for four different insulation thicknesses was shown in Figure 4.

It is evident that increasing the insulation thickness reduces the heating load and increases the cooling load. However, the cost of insulation increases with thickness, therefore there is a point which denotes the optimum insulation thickness and beyond which the cost of the insulation exceeds the monetary benefits of the energy saved.

For insulation thicknesses of 4 cm the annual heating load per unit area was 68.24 kWh m^{-2}. This value is only 0.8% higher than the energy audit value (67.7 kWh m^{-2}) recorded by Baxevanou et al. (2017), presenting results from fifteen insulated broiler houses at the Ioannina region. Both Kavala and Ioannina are classified as climatic Zone C of the Greek territory (Heating Degrees Days, at 18.3 °C, for Ioannina are 2037, whereas for Kavala are 1996).

Because the optimum insulation thickness for each wall was different, Figures 5 and Figure 6 were presented below. They referred to the heating and cooling transmission load per square meter of wall and roof area, respectively. It showed that when the thickness of the insulation increased the heating and cooling transmission load per square meter of the wall area decreased, for all walls and roofs orientations. It is worth noting that the heating and cooling transmission load refer to the shell of the broiler house and not to its entire load.

During winter (i.e. heating period) the north-facing wall had the highest heating transmission load (Figure 5), due to the negligible solar heat gain. On the contrary, the south-facing wall had the lowest heating load per unit area than all other orientations because of the high solar heat gain. Throughout the winter months the sun rises and sets to the south of east-west line, therefore the surface is exposed more hours to solar radiation. In conclusion, the south-facing wall seems to be the most advantageous compared to any other wall orientation.

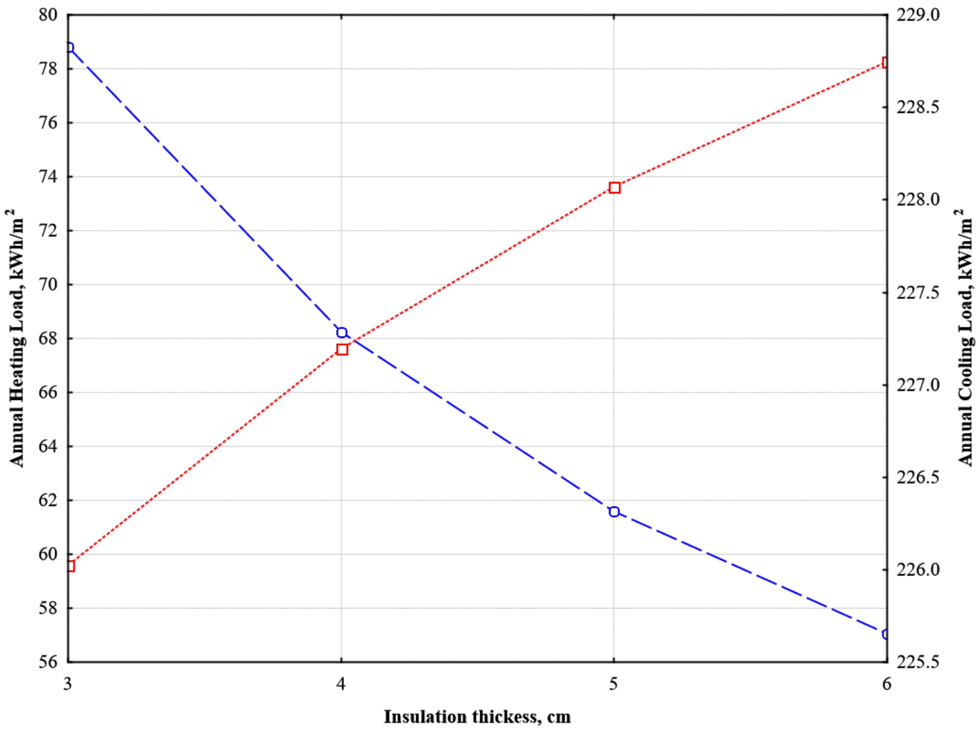

Figure 4 Annual heating and cooling loads per unit area for different insulation thicknesses (- - - - heating, ... cooling)

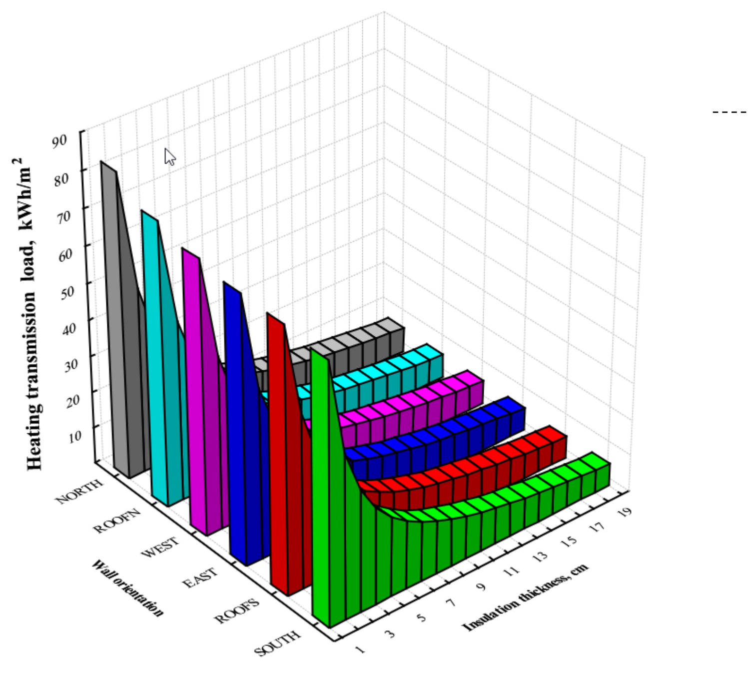

Figure 5 Heating transmission load per unit area

Throughout the cooling season (Figure 6) the roof facing south and the roof facing north had the highest and the lowest cooling load, respectively. The thermal behavior of the roof facing south was due to the high sol-air temperature on its external surface, the sun high altitude and the high ambient temperature during this period. In summer months (i.e. longer day length) the solar irradiance stroke the north facing wall for a few hours in the early morning and late afternoon, while its intensity, compared to all other orientations, was quite low. The required inside temperature range (Table 1) resulted in higher heating transmission load values compared to those of the cooling transmission load (Figure 5 and Figure 6).

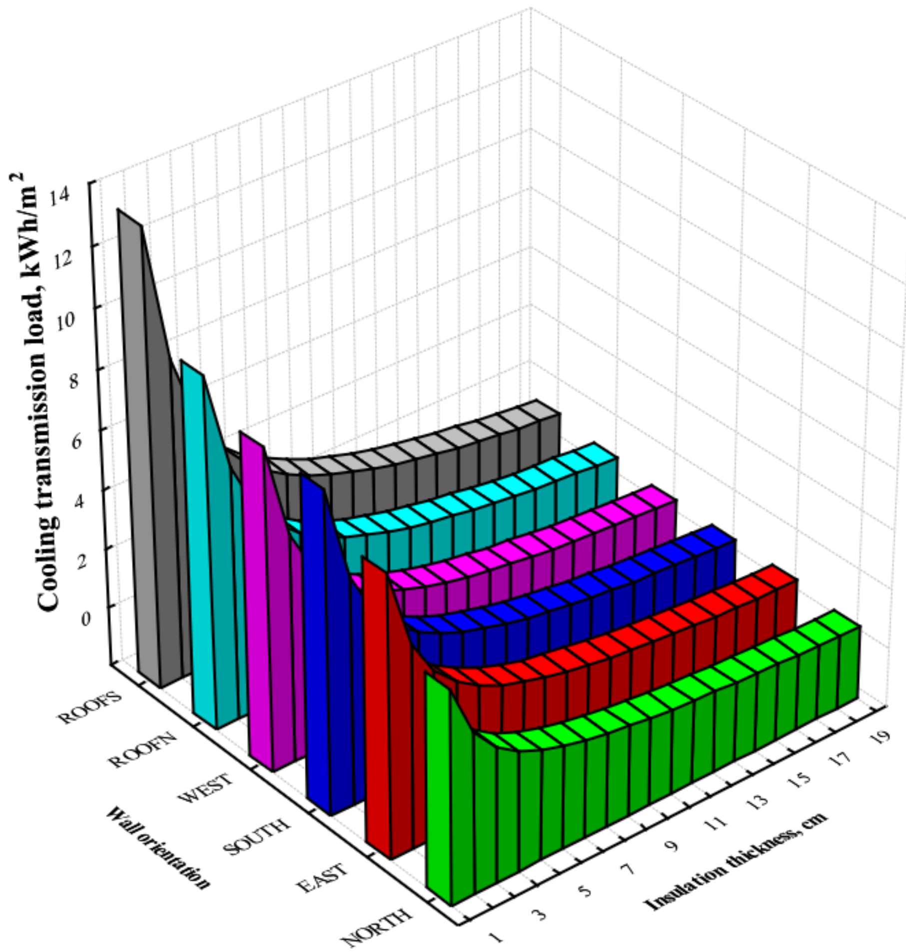

Figure 6 Cooling transmission load per unit area

Figure 5 and Figure 6 demonstrated that the heating and cooling transmission load depend, among others, on the insulation thickness. For example, the heating transmission load of the roof of 4 cm insulation thickness facing south was 4.13 times higher than the cooling transmission load of the roof having the same orientation. Similarly, the heating transmission load for the wall facing north was 13.02 times higher than the cooling transmission load for the wall facing north. For all other orientations the values fall in between.

Figure 7 presented the results of the economic analysis, showing that with increasing insulation thickness *NPV*s increased in all orientations. However, beyond a certain point (i.e. optimum insulation thickness) the *NPVs* declined, due to the increasing cost of insulation and the increasing fuel savings. Compared to all other orientations, the wall facing north had the greatest economic benefit for all insulation thicknesses. The economically optimal insulation thickness for all walls and gable roofs were shown in Table 3.

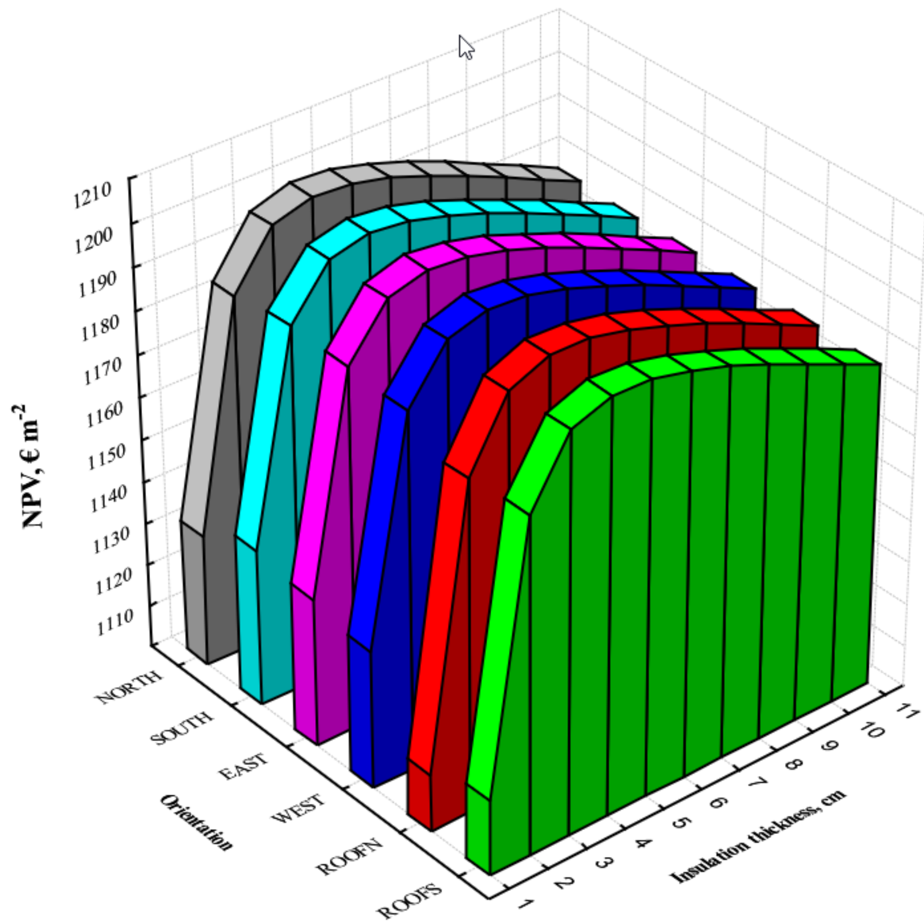

Figure 7 *NPVs* for different orientations and insulation thicknesses

Table 3 Optimum insulation thickness for the external walls and the gable roofs

Orientation	Optimum insulation thickness (cm)
South Wall	4.0
West Wall	4.2
North Wall	4.2
East Wall	4.1
South Roof	4.4
North Roof	4.5

4 Conclusions

The financial optimum insulation thickness of the external walls and the gable roofs of a broiler house was calculated based on a transient simulation model and an LCS economic analysis both using the appropriate parameters. Comparison of the annual heating load per unit area with that of an identical poultry energy audit was satisfactory indicating the validity of the simulation model developed. Increasing the thickness of the insulation can decrease the heating and cooling transmission load per square meter of the area for all walls and roofs. The wall facing north showed the highest heating and the smallest cooling transmission load per square meter of the area respectively, whereas the south roof had the maximum cooling transmission load per unit area. The optimum insulation thickness for all walls and roofs was from 4.0 cm to 4.5 cm depending on their orientation and the north-facing wall offered the greatest economic benefit compared to other orientations. The increased value of the desired inside temperature during the growing period early days, combined with the low birds' sensible loads (i.e. young birds), resulted in a heating load, the value of which depended on the time of year. Over the course of the growing days, the birds' mass increased along with their sensible loads, resulting in an inside temperature rising much higher than desired. As a result, there was a cooling load increasing too much during the hot period. The thermo-hygrometric requirements of the broiler house during the day-35 growing periods, combined with the prevailing external climatic conditions of the area, appear to favour the use of heat pump and mechanical ventilation to regulate the internal microclimate. Use of insulation material to a broiler house is critical, otherwise it will have a negative impact on its energy behavior as well as on the thermal comfort of the birds.

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Nomenclature

CO_{2i} maximum allowable CO_2 concentration of the inside air, kg CO_2 kg dry air^{-1}
CO_{2o} average CO_2 concentration of the outside air, kg CO_2 kg dry air^{-1}
$c_{p,i}$ specific heat of air, J kg^{-1} °C^{-1}
d discount rate, %
d_p day within a production cycle
j year
LSj net cash flow of all costs and benefits, €
M_c broiler mass, kg
M_{CO2} quantity of CO_2 produced within the building, kg CO_2 s^{-1}
m_α ventilation air flow rate, m^3 s^{-1}
N period of economic analysis, years
NPV Net Present Value, €
Q_{sp} sensible heat production, W
Q_{surf} heat flow through the walls, roof and the floor, W
Q_{vent} heat losses due to ventilation, W
$Q_{v(CO2)}$ CO_2 concentration control ventilation rate, m^3 s^{-1}
T_i inside air temperature, °C
t time, s
V volume of the inside air space, m^3
v_i specific volume of the inside air, m^3 kg^{-1}
W_i inside air humidity ratio, kg H_2O kg dry air^{-1}
W_o outside air humidity ratio, kg H_2O kg dry air^{-1}
$\dot{w}_p$ broiler water vapor production, kg s^{-1}