Optimization of ventilation rates for growing-finishing piggeries

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Abstract: A methodology to optimize the ventilation rates for growing-finishing piggeries having no heating or cooling systems and compare them with the current ASABE recommendations was developed. It was based on transient simulation and hourly climatic data of Heraklion in S. Greece coinciding with US climatic zone I and Kastoria in N. Greece coinciding with US climatic zone II. The ASABE (ASAE EP270.5 standard) values were not justifiable for both areas and during all seasons apparently resulting to higher potential heat stress for growing-finishing pigs. At the area of Heraklion they were up from 26% during summer to 87% during winter, resulting in 8393 annual hours out of the PS compared to 6504 (1.3 times more). Similarly, at Kastoria they were up from 34% during summer to 60% during fall resulting in 6417 annual hours outside the PS compared to 4310 (1.5 times more). The average seasonal optimum ventilation rates were proven to be more effective for Kastoria as they reduce the annual hours outside the PS by 32.8% compared to 22.5% for Heraklion.

Keywords: optimum ventilation rate, production space, growing-finishing piggery, ASABE standards, Greece

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1 Introduction

Appropriate ventilation rates aim, among others, at maintaining indoor air temperature and relative humidity at required levels depending on outside climatic conditions, production phase, animal weight, housing density, type of floor, feed energy content, etc. A fundamental concept to understand whether ventilation can be expected to provide a suitable indoor environment in terms of air temperature and relative humidity is the Production Space (PS) within which an animal remains productive up to or nearly up to its genetic potential (Albright, 1990). The PS of the growing-finishing pigs is defined by temperature limits coinciding with the lower and the upper critical temperatures of the thermoneutral zone, and relative humidity limits which are set equal to values recommended by CIGR (1984).

Current ventilation rate guidelines for swine are based on ASAE EP270.5 standard (ASABE, 1986), which make reference to data published in MWPS-1 (1983). A wealth of publications (Brown-Brandl et al., 2004; Brown-Brandl et al., 2011; Brown-Brandl et al., 2013; Hayes et al., 2013; Nienaber and Brown-Brandl, 2008) underlined the increase in heat and moisture production values that have occurred in modern pigs. Hayes (2015) stated that under central-Illinois weather conditions these production values illustrate the potential for under ventilation in commercial facilities. Very recently (ASABE 2017; personal communication) ASAE EP270.5 was seriously criticized as outdated with the need for a solid revision.

Lately much attention is given to the importance of improvement of energy efficiency of buildings, in order to reduce energy use. Overall, buildings are central to the EU's energy efficiency policy, as nearly 40% of final energy consumption and 36% of greenhouse gas emissions (GHG) is in houses, offices, shops and other buildings (European Commission, 2018). Installation of thermal insulation on the external walls and the roof is,

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among others, a feasible solution (Banhazi and Rutley, 2013; Hinkle and Stombaugh, 1983) to effectively control the piggery indoor climate. ASABE (1993) recommends minimum overall heat transmission coefficients depending on climatic zones within US.

The objective of this study is to optimize the ventilation rates and provide new guidelines for growing-finishing piggeries having no heating or cooling systems and located at Greek areas coinciding with US climatic zones I and II.

2 Materials and methods

A detailed transient simulation model of the piggery building (Figure 1) was developed within the TRNSYS (2006) program environment, which can be used for simulation of a wide variety of renewable and other energy systems. It was used to calculate, during winter, spring, summer and fall, the free floating inside temperature and relative humidity values aiming at allocating them in or out the PS.

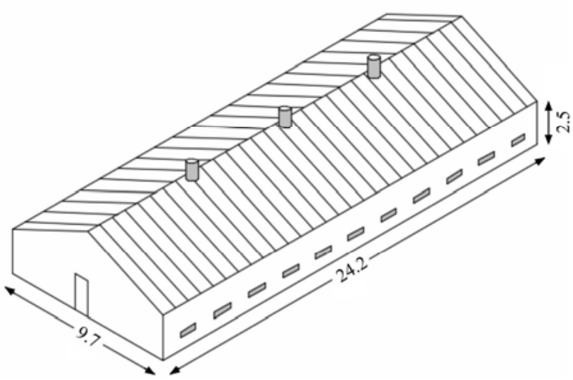

Figure 1 Growing-finishing piggery building

Following recommendations (Nienaber et al., 1987; Hillmann et al., 2004; Huynh et al., 2005) the thermoneutral zone of growing-finishing pigs was set between 10°C and 18.8°C. The matching (CIGR, 1984) lower and upper relative humidity values for the lower critical temperature were set to 50% and 80%, and for the upper critical temperature to 50% and 70%. The heat flow through the building surfaces, the sensible and latent heat loads of pigs and the ventilation heat losses were considered. Table 1 tabulates building and animal data.

Two areas (Figure 2) were selected, namely Heraklion in South Greece (35°19'N, 25°8'E) coinciding with US climatic zone I and Kastoria in North Greece (40°31'N, 21°15'E) coinciding with US climatic zone II. Their approximate distance is 690 km, the heating degree days are 708 and 2575, respectively, and the corresponding cooling degree days are 1182 and 606. Figure 3 depicts the annual ambient temperature and relative humidity values for both areas.

Table 1 Building and animal data used in the simulation

Type of building	Growing-finishing piggery (no heating or cooling)
Orientation	East-West
Building dimensions (m)	
Width	9.7
Length	24.2
Height	2.5-4.8
Walls[#]	Polyurethane foam sandwich panels
Gable roof[#]	Polyurethane foam sandwich panels
Floor	Concrete slats
Type of ventilation	Mechanical (3 chimney fans with 11 wall flange inlets at each N-S side wall)
Total number of animals	300
Weight per animal (kg)	50
Feed level	3 × level of maintenance

Note: [#]: Overall coefficients of heat transmission based on ASABE (1993) recommendations.

Figure 2 Areas under consideration

The following time-dependent equations were used to calculate the temperature and relative humidity inside the pig building, assuming the indoor air is perfectly mixed:

$$(\rho_i V c_{p,i})\frac{dT_i}{dt} = \dot{Q}_{surf} + \dot{Q}_s + \dot{Q}_{vent} \tag{1}$$

$$(\rho_i V)\frac{dW_i}{dt} = \rho_i \dot{m}_a (W_o - W_i) + \dot{w}_p \tag{2}$$

where, ρ_i is the density of inside air in kg m^{-3}; V is the volume of the inside air space in m^3; $c_{p,i}$ is the specific heat of air in J kg^{-1} °C^{-1}; T_i is the inside air temperature in

°C; t is the time in s; $\dot{Q}_{surf}$ is the heat flow through the building surfaces in W; $\dot{Q}_s$ is the pig sensible heat production in W; $\dot{Q}_{vent}$ is the heat losses due to ventilation in W; $\dot{m}_a$ is the ventilation air flow rate in m^3 s^{-1}; W_o is the outside air humidity ratio in kg H_2O kg dry air^{-1}; W_i is the inside air humidity ratio in kg H_2O kg dry air^{-1}; $\dot{w}_p$ is the pig water vapor production in kg s^{-1}.

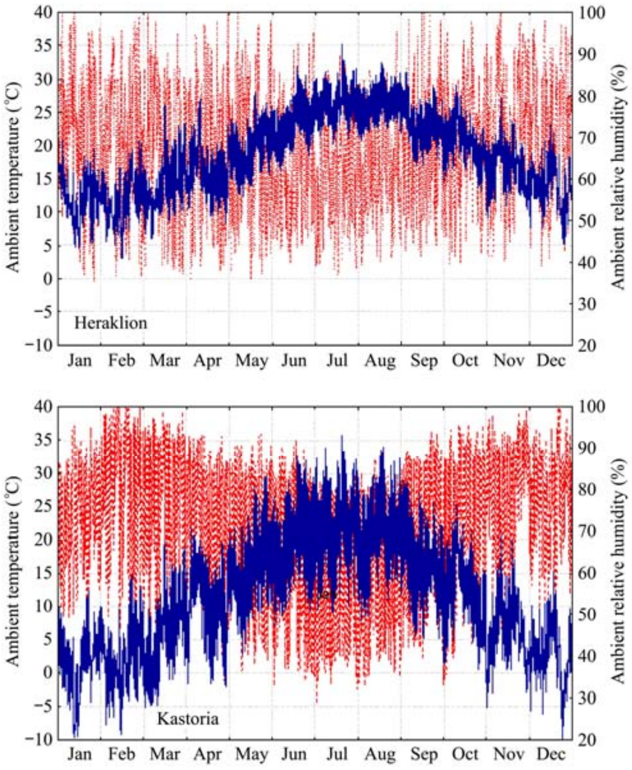

Figure 3 Annual ambient temperature (solid lines) and relative humidity values (dashed lines) at Heraklion and Kastoria

The dynamic thermal modelling of external walls was run using TRNSYS (2006). The conduction heat transfer through an opaque building surface, such as an external wall, is the combined effect of the convective heat that the surface at both side of the wall is exchanging with the air, and the radiant heat exchanges with other surfaces to which it is exposed. The calculation of $\dot{Q}_{surf}$ was based on the heat conduction transfer functions method (Stephenson and Mitalas, 1971), which uses the following time series Equations (3) and (4) to calculate the heat flux (W m^{-2}) at the inside ($q_{s,i}$) and outside ($q_{s,o}$) surfaces, respectively (TRNSYS, 2004):

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{bs}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{cs}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{ds}} d_s^k T_{s,i}^k \tag{3}$$

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{as}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{bs}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{ds}} d_s^k T_{s,o}^k \tag{4}$$

where, a_s, b_s, c_s in W m^{-2} K^{-1} and d_s (dimensionless) are the coefficients of the time series equations and n_{as}, n_{bs}, n_{cs}, n_{ds} are the numbers of their terms, respectively. $T_{s,o}$ and $T_{s,i}$ are the outside and inside surface temperature, respectively. The superscript k refers to the term in the time series. A value of k equal to zero represents the current time interval, whereas k equals to one is the previous time interval and so on. The coefficients of the time series equations are determined by the program only once at the beginning of the simulation using the material layers properties of the wall. The transfer functions method has been validated experimentally and adopted by ASHRAE (1989) and is considered as one of the most accurate methods for the calculation of a time-variable heat load (Giaconia and Orioli, 2000).

For the outside surface temperature of the time series equations, the sol-air temperature ($T_{sol\text{-}air}$) referring to the combined effect of the incident solar irradiance, outdoor air temperature and convective heat exchange with the outdoor air has been used (ASHRAE, 1989):

$$T_{sol-air} = T_a + \frac{\alpha I_T}{h_{o,c}} + \frac{\varepsilon \Delta R}{h_{o,c}} \tag{5}$$

where, T_a is the outdoor air temperature in °C; α is the solar absorptance of the outside surface; I_T is total solar irradiance incident on the surface in W m^{-2}; $h_{o,c}$ is the combined convective and radiative heat transfer coefficient on the outside surface in W m^{-2} K^{-1}; ε is the hemispherical emittance of the surface and ΔR is the difference between the long-wave radiation incident on the surface from the sky and surroundings and the radiation emitted by a blackbody at outdoor air temperature in W m^{-2}. In Equation (5) the value of (ΔR) was considered (ASHRAE, 1989) zero for vertical surfaces because the radiant heat loss to the sky compensates the heat gain from the ground, whereas ($\alpha/h_{0,c}$) ratio value was taken equal to 0.026 as recommended (ASHRAE, 1989) for light colored surfaces.

For the external walls and roof the incident total solar irradiance on the external surface was calculated using hourly solar radiation data for the cities of Heraklion and Kastoria, and the well-known equations from solar geometry (Axaopoulos, 2011). At each time step, the solar incidence angle and the solar zenith angle were calculated from the solar position coordinates (i.e. solar altitude angle, solar azimuth angle) along with the surface orientation and slope. Then, the heat flow through building surfaces was calculated in conjunction with the appropriate parameters and the hourly climatic data (i.e. ambient air temperature and relative humidity, solar irradiance on horizontal surface). At the same time, a procedure was used to account for the combined effects of the convective heat transfer from the internal surface to the inside air and the radiant energy gain at the surface.

The total heat production Φ_{tot} (W) per growing pig at 20°C, the total heat production Φ^*_{tot} (W) at temperatures other than 20°C, the sensible heat production at house level Φ^*_{sen} (W) and the latent heat production at house level Φ^*_{lat} (W) were calculated based on the equations given in Blanes and Pedersen (2005). Φ^*_{sen} (W) was multiplied by the number of pigs housed in the piggery and used as $\dot{Q}_S$ (W) in Equation 1, whereas Φ^*_{lat} (W) was also multiplied by the number of housed pigs, resulting in the total latent heat production value. This value was then converted to water vapour production ($\dot{W}_p$, kg s^{-1}) using the latent heat of water evaporation (h_{fg}, J kg^{-1}), which was calculated from the expression: $(2501–2.42\cdot T_i)\times10^3$.

At each time step the value from Equation (6) was substituted into Equation (1), in order to calculate the heat flow through ventilation.

$$\dot{Q}_{vent} = \rho_i \dot{m}_a c_{p,i} (T_a - T_i) \qquad (6)$$

A simulation-based optimization methodology that combines simulation of the thermal behavior of the piggery facility with the generic optimization program GenOpt (Wetter, 2009) was used. GenOpt (Wetter, 2009) allows the optimization of given design variables, minimizing an objective function that is being evaluated by the simulation software. It automatically determines the values of variables, generates appropriate input files for the simulation program, runs TRNSYS with these files, saves simulation results including the value of objective function, and finally determines the new set of input variables in order to restart the simulation. The process is repeated until the optimum solution has been detected. The optimization methodology adopted used a single objective function approach and took into account the ventilation rate as a continuous variable, so as to minimize the total annual hours outside the production space.

3 Results and discussion

Table 2 presents the ASABE single ventilation rate values, weather type and production phase dependent, with the optimized ones (i.e. seasonal range) along with the resulting time outside the PS. It is worth noting that a single ventilation rate value cannot be used to cover the needs within a whole season. A strong proof are the ambient temperature differences of 15°C (5°C to 20°C) for Heraklion and 25°C (–10°C to 15°C) for Kastoria during winter and the respective summer temperature differences of 20°C (15°C-35°C) and 25°C (15°C-35°C).

Table 2 Ventilation rates and time outside the production space

	Ventilation rates, m^3 h^{-1} per pig				Time outside the production space, h			
	Heraklion		Kastoria		Heraklion		Kastoria	
	ASABE	Optimized	ASABE	Optimized	ASABE	Optimized	ASABE	Optimized
Season								
Winter$^{@}$	11.9	22.7-25.6	11.9	65.3-130.6	2160	965	2139	274
Spring#	40.8	41.2-120.7	40.8	93.7-201.6	1879	1434	1242	1131
Summer$^{\$}$	127.4	161.9-238.6	127.4	119.3-220.1	2205	2205	1825	1798
Fall$^{\%}$	40.8	38.3-161.9	40.8	115.0-156.2	2149	1900	1211	1108

Note: @: 1st December-28th February; #:1st March-31st May; $:1st June-31st August; %:1st September-30th November.

Markedly the ASABE values are not justifiable for both areas and during all seasons. At the area of Heraklion they are lower from 26% during summer (127.4 m^3 h^{-1} per pig vs. 172.3 m^3 h^{-1} per pig) up to 87% during winter (11.9 m^3 h^{-1} per pig vs. 89.5 m^3 h^{-1} per pig), resulting in 8393 annual hours out of the PS compared to 6504 (1.3 times more). Similarly, at Kastoria they are lower from 34% during summer (127.4 m^3 h^{-1} per pig vs. 193.1 m^3 h^{-1} per pig) up to 60% during fall (40.8 m^3 h^{-1} per pig vs. 102.2 m^3 h^{-1} per pig) resulting in 6417 annual hours outside the PS compared to 4310 (1.5 times more). The average seasonal optimum ventilation rates are proven to be more effective for Kastoria as they reduce the annual hours outside the PS by 32.8% compared to 22.5% for Heraklion.

A seasonal comparison (Table 2) clearly demonstrates that the largest difference occurs during winter at Kastoria when using the ASABE values results in 7.8 times more hours out of the PS, namely 2139 vs. 274. Notably, the low ambient temperatures (Figure 3) in Kastoria combined with a seasonal average optimum ventilation rate twice as much the ASABE (24.1 $m^3 h^{-1}$ per pig vs. 11.9 $m^3 h^{-1}$ per pig) result in increased thermal losses of the piggery, thus reducing its internal temperature within the thermoneutral zone.

Throughout spring, a season during which in southern Greece the ambient temperature starts to rise earlier than in northern Greece, the seasonal average optimum ventilation rates compared to the ASABE values reduce the hours out of the PS for the Heraklion area much more than the Kastoria area, namely 23.7% vs. 9%. The reason is that the difference between the ASABE ventilation rate value (40.8 $m^3 h^{-1}$ per pig) from the seasonal average optimum ventilation value for Heraklion (144.4 $m^3 h^{-1}$ per pig) is much larger than that of Kastoria (70.5 $m^3 h^{-1}$ per pig).

During summer, the solar heat gain through the roof, the animal heat loads and the high ambient temperatures in Heraklion result in almost all hours (99.9%) being out of the PS despite the increased optimal ventilation rate. On the contrary, at the area of Kastoria using either ventilation rate results in a smaller percentage of hours outside the PS, namely 83% for the ASABE values and 81% for the optimized values. For both the ASABE and the seasonal average optimized ventilation rates a large number of points outside the PS was due to the low ambient relative humidity values (Figure 3).

For the duration of fall, the ambient temperature in northern Greece starts to decline in early September whereas it remains high in southern Greece until the end of the season, the seasonal average optimum ventilation rate reduces the number of hours out of the PS for Heraklion slightly more than that of Kastoria (i.e. 11.6% vs. 8.5%) when compared to the ASABE standards. Due to ambient climatic conditions (Figure 2) when the seasonal average optimum ventilation rates are used in Kastoria the hours out of the PS are much less (i.e. 33.7%) than those of Heraklion.

4 Conclusions

A methodology to optimize the ventilation rates for growing-finishing piggeries having no heating or cooling systems and compare them with the current ASABE (ASAE EP270.5 standard) recommendations was developed. It was based on transient simulation and hourly climatic data. During the winter the ASABE ventilation rate values resulted in almost all hours being out of the PS for both climatic zones, whereas using the optimal ventilation rates a very small percentage of hours remained outside the PS. In climatic zone II (i.e. area of Kastoria) with the lowest ambient temperature, optimal ventilation rates significantly reduced the annual hours out of the PS, compared to those of climate zone I (i.e. area of Heraklion). On the contrary, during spring and fall, the optimal ventilation rates resulted in more hours outside the PS in climatic zone I. Compared to the current ASABE recommendations use of the optimal ventilation rates at two different climatic zones significantly reduced the annual number of hours outside the PS and apparently the potential heat stress of growing-finishing pigs.

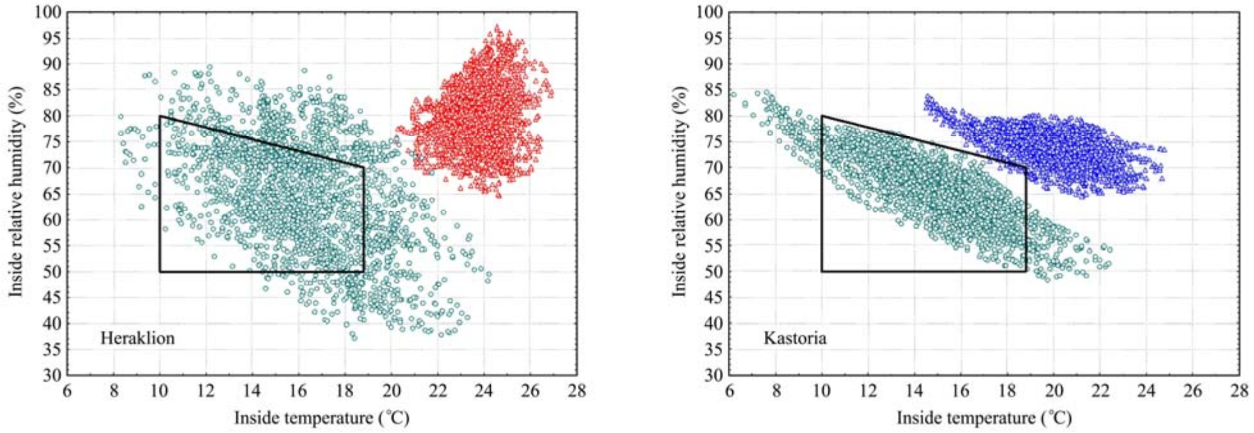

Figure 4 Hours outside the production space at Heraklion and Kastoria during winter (ASABE values: triangles; optimized values: circles)

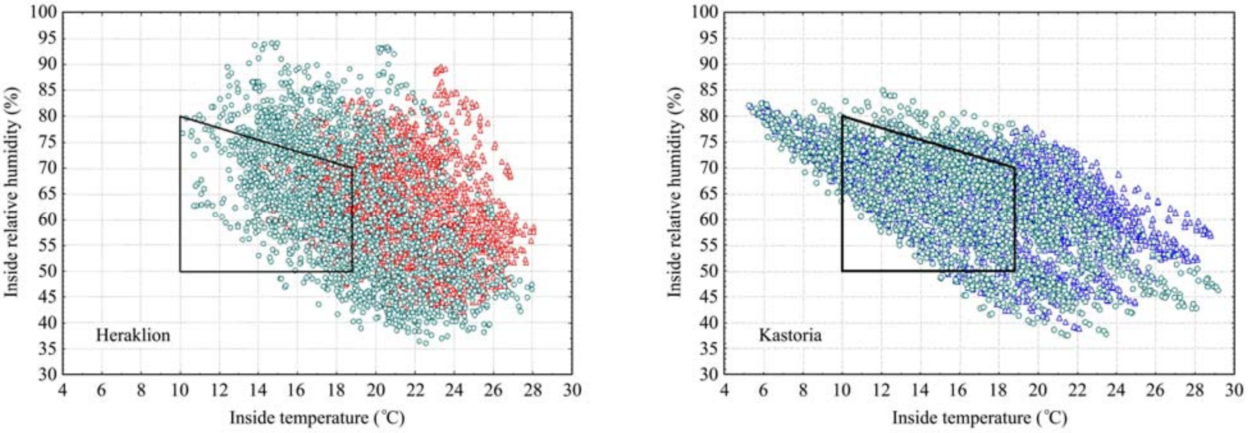

Figure 5 Hours outside the production space at Heraklion and Kastoria during spring (ASABE values: triangles; optimized values: circles)

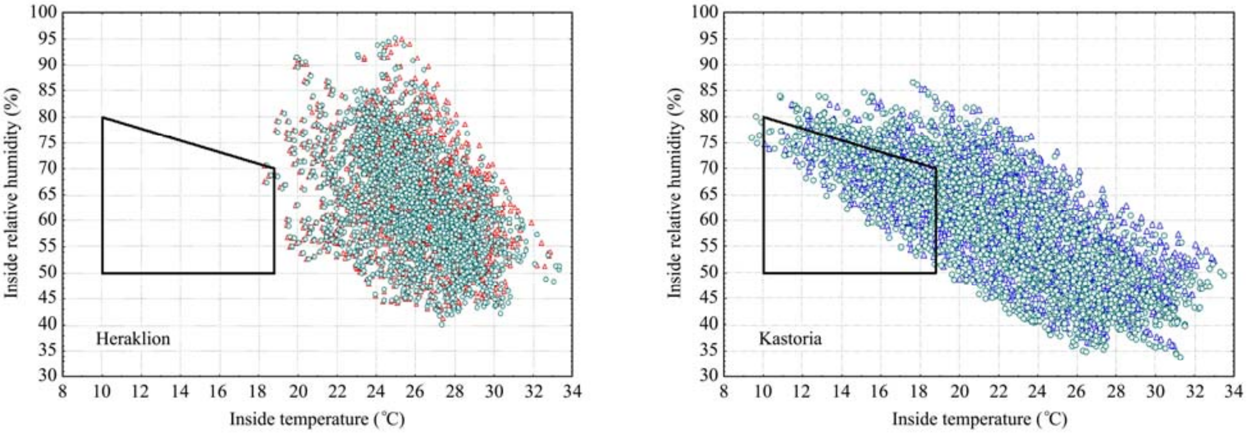

Figure 6 Hours outside the production space at Heraklion and Kastoria during summer (ASABE values: triangles; optimized values: circles)

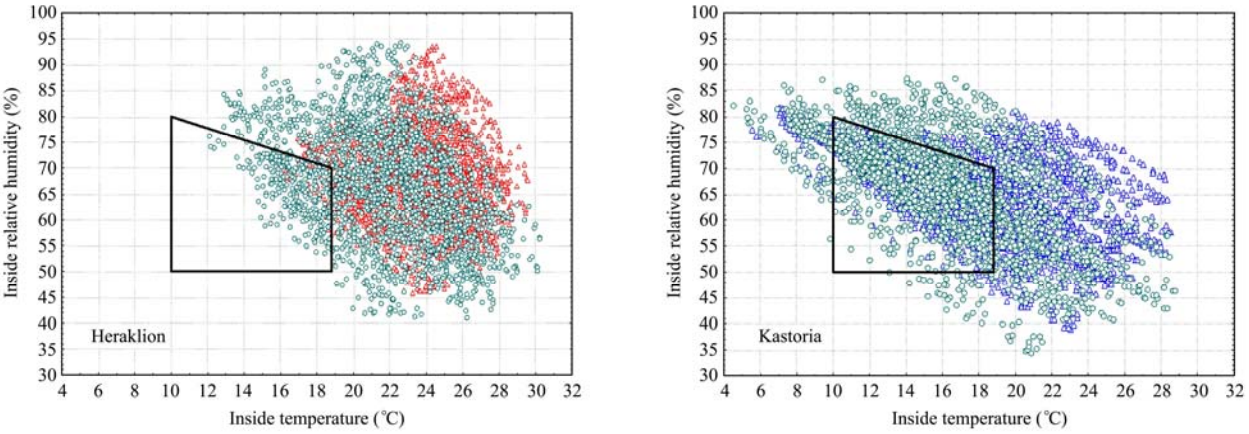

Figure 7 Hours outside the production space at Heraklion and Kastoria during fall (ASABE values: triangles; optimized values: circles)

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