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MODELLING AMBIENT CONDITIONS IN THE FATTENING ROOM AND CORRESPONDING PERFORMANCE OF PIGS WITH THERMIPIG MODEL

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ABSTRACT A mechanistic, dynamic and determinist model, called ThermiPig, has been developed by combining a growth model and a bioclimatic model. It allows for the prediction of the within-room thermal balance at the room level and its consequences on the daily and individual performance of group-housed pigs. As this research is part of the Pigsys ERA-Net project, co-funded under EU Horizon 2020 RI program (SuSan, www.era-susan.eu, Grant Agreement n°696231) by the French ANR (grant n°ANR-16-SUSN-0003-02), a survey was performed in different European countries by the partners of the project in order to describe different types of fattening rooms, feeding strategies and climatic conditions. Afterwards, the objective of the study was to use the results of the survey and to combine different characteristics of the fattening room (insulation, cooling and/or installed heater capacity when available, regulation rules of the climate control box) to simulate the corresponding impacts on (i) the thermal balance at room scale, (ii) growth performance, (iii) direct and indirect energy use, and (iv) nitrogen output in pigs. Simulations were performed over the whole fattening duration with each combination using 30 virtual batches of pigs, generated from an average animal growth profile. Based on outputs of the model, it is possible to evaluate the influence of insulation of walls or heater capacity under different climates or to optimize regulation rules of the climate box control of the ventilation system in terms of feed efficiency, margin on feed cost and nitrogen output.

Keywords: Pig, modelling, fattening room, climatic conditions, insulation, ventilation, performance, energy consumption.

INTRODUCTION Due to a poor insulation of the skin and limited sweating capacities, the pig is very sensitive to ambient temperature (Le Dividich et al., 1998). Like in other homeothermic animals, different mechanisms are involved in the thermoregulation and successively activated when the pig is exposed to ambient conditions outside its thermoneutral zone. Exposure to cold conditions is associated with an extra requirement in energy, which is met by an increase in feed intake (FI) when pigs are fed *ad libitum*, or a decrease in energy available for growth under restricted feeding conditions. In both situations, the feed conversion ratio increases as well as the indirect energy consumption (due to FI) and the feed cost. On the opposite, hot exposure induces a decrease in FI and growth rate (through average daily gain, ADG). In an all-in all-out system, it can compromise the final body weight (BW) at delivery to the slaughterhouse and consequently the income of the farmer.

When building new facilities, insulation, type of equipment and management rules are supposed to be adapted to the local climatic conditions. However, many pig farms have been designed many years ago. In a context of global warming, more frequent extremely episodes are observed, such as hot waves during late spring and summer or extremely cold episodes in winter. In EU and North America, the available equipment may become limiting, especially when pigs are heavy and produce a lot of heat. Independently of investment in new equipment, alternative management strategies in terms of feeding level, dietary formulation, regulation rules of the climate box control, could be interesting not only to mitigate the impact of outdoor climate on indoor conditions and the associated technical and economic performance at the farm level, but also to reduce the global impact of pig production, through a lower use of direct energy or improved efficiency of resources.

A dynamic model called ThermiPig has been developed that simulates the thermal balance at the fattening room scale based on the difference between the heat produced by the group of pigs and the heat lost due to fattening conditions (Brossard et al., 2019). It can be used to evaluate *in silico* the impacts of the factors mentioned above on the thermal balance of the fattening room and on the associated growth performance of pigs. The aim of the present study was to investigate, using ThermiPig, the return on performance, environmental impact, economy and overall energy consumption that can be expected from new equipment or changes in farmer’s practice, depending on the climatic conditions.

MATERIAL AND METHODS Simulations are performed with the ThermiPig model. This model is written in Python language and organised in three modules, corresponding to a growth model (InraPorc, van Milgen et al., 2008; Cadero et al., 2018), a bioclimatic model (ThermiSim, Marcon et al., 2016) and a coupling module developed in the PigSys Susan-Eranet project. Indoor temperature (T_{in}) is predicted with the model with an accuracy of 0.5°C (Brossard et al., 2019; Quiniou et al., 2021). Both static basic inputs and dynamic inputs are required to represent the room, the animals, the management rules, and the outdoor climatic conditions (Figure 1). In the present study, a single type of pigs and a single room are considered. But different level of insulation of the wall, rules of the climate box control of ventilation, feeding strategies and use of additional equipment are investigated under different climatic conditions.

Characteristics of the fattening room A fattening room representative of the IFIP experimental facilities (Romillé, France) is used. Its dimensions, i.e. width, length, and height are 10.41 m x 11.61 m x 2.60 m, respectively. It has been designed for 96 fattening pigs housed in 16 pens with 0.7 m^2/pig on fully slatted-floor, extra corridors required for demonstration activities, and a suspended ceiling. The characteristics of this real room correspond to the reference values, and alternative ones are tested.

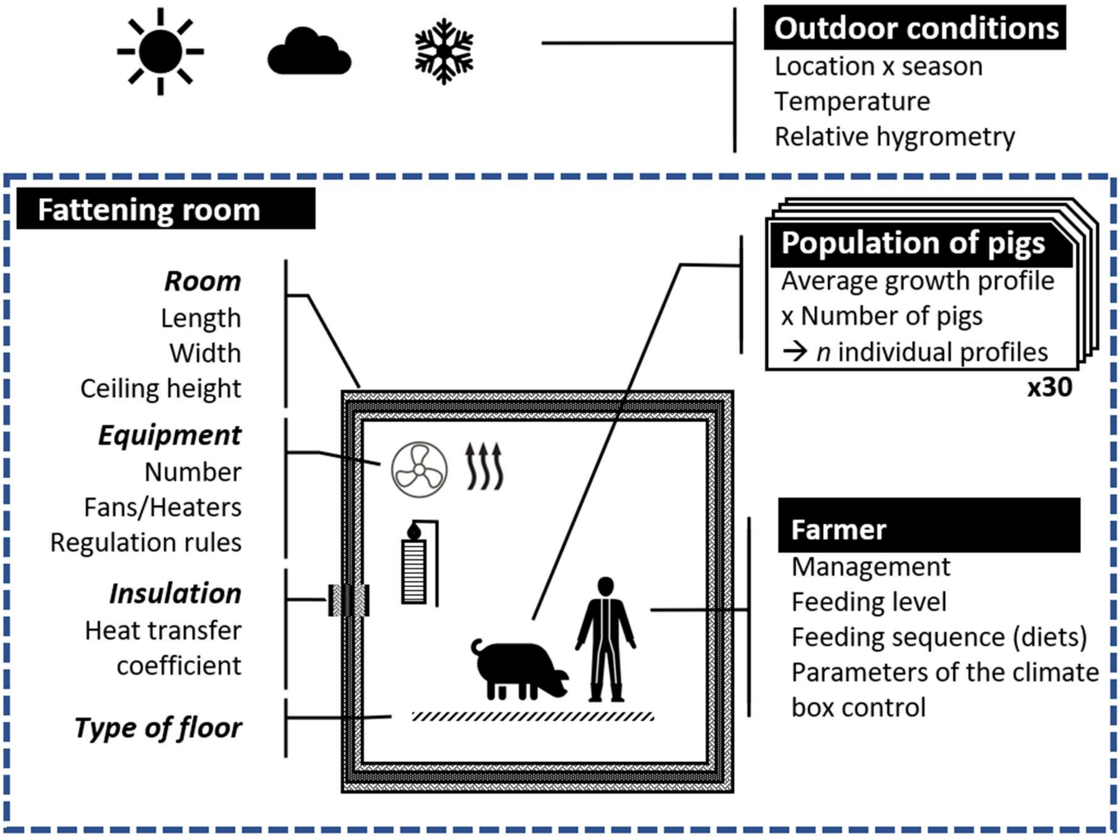

Figure 1. Inputs considered in the ThermiPig model to simulate the thermal balance at the room scale.

Insulation The room is supposed to be in a row of rooms. Therefore, we assume that heat losses are due to the only one wall facing the outside and the ceiling. Thermal exchanges at the bottom of the slurry pit are considered negligible. The ground under the concrete slab of the building is supposed to be already warmed by the previous batch of pigs. The total heat transfer coefficient (HTC, $W.m^{-2}.°C^{-1}$) of walls depends on the thickness and thermal conductivity of the different materials used. The reference ($Wall_{Ref}$) corresponds to a 0.20 m thick monolithic terracotta brick paneling which overall HTC is 0.55 $W.m^{-2}.°C^{-1}$. It was compared to three options: a three-layer paneling ($Wall_{Op\ 1}$; overall thickness: 0.35 m; HTC: 0.27 $W.m^{-2}.°C^{-1}$), a 1-layer concrete panelling ($Wall_{Opt\ 2}$; overall thickness: 0.15 m; 11.33 $W.m^{-2}.°C^{-1}$) or a thicker monolithic terracotta brick paneling ($Wall_{Op\ 3}$; overall thickness: 0.30 m; HTC: 0.35 $W.m^{-2}.°C^{-1}$). The ceiling is insulated with 10 cm of glass wool (HTC = 0.32 $W.m^{-2}.°C^{-1}$).

Ventilation The room is equipped with two fans of 400 mm in diameter which are managed in a normal way by a climate box control. The minimum and maximum ventilation rates are fixed to 10 and 100%, respectively. The other regulation rules are detailed in Table 1 for the reference ($Ventil_{Ref}$) or the tested options ($Ventil_{Opt\ n}$).

Other equipment Heaters and pad cooling are not set up in the reference room but considered in simulations. The regulation of the heating system is based on a minimum and maximum heating rate of 0 and 100%, and three heating powers: 18.8, 37.6 or

50.0 W/pig. The initial and final setpoint temperatures of the heating system were fixed to 25 and 22°C, respectively, with an interval of 15 days to switch from initial to final T setpoint linearly. The temperature setpoint of the pad cooling system is fixed at 25°C outside, meaning that cooling starts only when outside temperature reaches 25°C.

Table 1. Description of the setpoint temperature curves considered in different regulation rules of ventilation.

Regulation rules	Reference	Option					
Rules	$Ventil_{Ref}$	1	2	3	4	5	6
Temperature (T) curve							
Initial T setpoint (°C)	24	24	24	20	20	18	18
Final T setpoint (°C)	22	17	17	17	17	15	15
Setpoint interval (d)[1]	15	77	77	77	77	77	77
Bandwidth (°C)[2]	6	6	10	6	10	6	10

[1]Number of days required to switch linearly from initial to final T. [2]Number of degrees between the T setpoint and the T at which ventilation rate reaches its maximal value.

Characteristics of the pigs Data collected in a previous study performed on crossbred (Large White × Landrace) × (Large White × Piétrain) pigs, in the reference room, were used to parameterize an average growth profile. Growth curve was described according to a Gompertz function with relevant information for the initial BW (30.2 kg at 70 days of age), the average protein deposition rate (138.4 g/d), the Gompertz coefficient of precocity (0.0162/d), and the age at 110 kg (158 d). A feed curve was also modelled with a gamma function of net energy (NE, MJ/d) intake with BW, with the criterion “a” adjusted to 4.805 and “b” to 0.0214/kg. The model is deterministic but can account for variability amongst individual pigs within the batch and amongst batches when each pig in the group is described by a specific growth profile. A generator of virtual pigs is used to create 30 populations of 96 individual animals, based on a generic covariance pattern amongst parameters of the average growth profile (Vautier et al., 2013). Thereafter, simulations were performed 30 times with ThermiPig, i.e. with 30 different groups of pigs. The limits of the thermoneutral zone were calculated on an individual and daily basis. Based on the reviews published by Verstegen and van der Hel (1974) and Holmes and Close (1977), the lower critical temperature for group-housed pigs on fully slatted floor was supposed to decrease linearly with BW (kg): LCT (°C) = 22.5 - 0.031 BW. The upper critical temperature was defined according to Renaudeau et al. (2011): UCT (°C) = 40.9- 4.4 × ln(1+BW).

Feeding strategy The feeding strategy depends on the feeding level (*ad libitum* or restricted feeding) and the feeding sequence, i.e. the number of diets and their characteristics. Simulations are performed in *ad libitum* (AL) feeding conditions with a 2-phase feeding strategy. A grower diet is supposed to be delivered up to 60 kg average BW at the group level, then a finisher diet. Both diets are formulated for 9.60 MJ of NE per kg and for 0.9 and 0.8 g of standardized ileal digestible lysine per MJ NE, respectively. The heat increment due to the ingestion, digestion and metabolic use of metabolizable energy (ME) contributes to the total heat produced by the pig (Noblet et al., 1994). The thermic effect of feed (TEF) can be described by the NE/ME ratio. Two sequences were investigated in *ad libitum* conditions with NE/ME ratio of 74.4 and 74.8%, respectively for the grower and finisher diets in the conventional (TEF+) sequence, and 75.8 and 76.3%

for the TEF- sequence, respectively. The cumulated energy demand (1.8 nonrenewable fossil + nuclear) at plant was 4157.594, 3782.039, 6330.812 and 5732.601 MJ/ton, respectively for the four diets. It was calculated with the methodology of life cycle assessment from cradle to field gate, to storage agency, to mill gate or to French port depending on the ingredient (Wilfart et al., 2016) and used to assess the indirect energy consumption. In the context of feedstuff prices of December 2019 in Brittany (France), the feed prices were 246.00, 238.00, 229.42 and 220.28 €/ton, respectively.

Other inputs In addition to the maximum occupation time of the room, other inputs are considered in the model to run simulations at the batch level, such as the loss of pigs before the end of the fattening period or the strategy of delivery of pigs to the slaughterhouse. In the present study, the maximum duration of the fattening period is fixed to 119 days, with two deliveries to the slaughterhouse organized with a 7-day interval and an expected average body weight at delivery of 115 kg. Based on the overall mortality rate observed in the room during an *in vivo* study, this input is fixed to 5.2%, each death occurring randomly all along the whole fattening period.

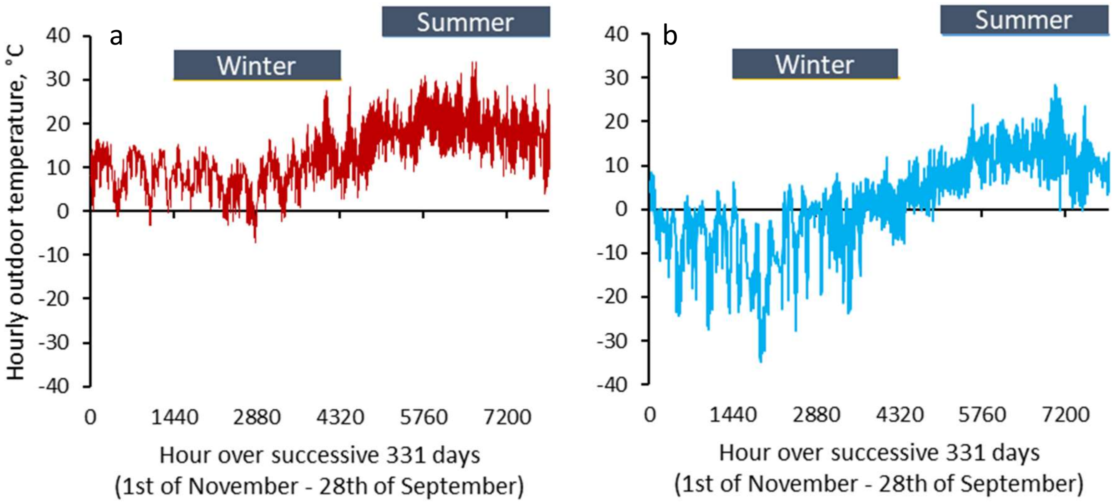

Figure 2. Hourly outdoor temperature in Western France (a) or Northern Sweden (b) for 330 successive days from November 1st and indication about seasonal conditions used in simulation.

Combination with local climatic conditions The aim of our study was to evaluate how the French room, supposed to be representative of a typical French pig room, would perform and, eventually, be inadequate under much colder winter conditions or warmer summer than presently observed in France. Data of hourly outdoor temperature (T_{out}) were collected at different locations and seasons over the year in Western France (FR) and upper Northern Sweden (SW) (Figure 2). The arrival of the batch of pigs was assumed to occur at different time, either on January 1st (month 1) or June 1st (month 6) corresponding to fattening at different seasons, i.e. winter and summer, respectively. The impact of cold was investigated, using datasets of hourly climatic data over 119 days labelled FR01 or SW01 when fattening started in month 1 in France or Sweden, respectively. The impact of warm weather was studied when fattening started on June 1st (month 6) under FR climate, labelled FR06. Hourly T_{out} is presented in Figure 2 over 331 days. Under the FR01 climate, the average daily T_{out} ranges between -3 and 19°C (-7 and 27°C for hourly T_{out}) in winter (Figure 2a). Average daily T_{out} ranges between -33 and 6°C under the SW01 climate in winter (Figure 2b). Corresponding hourly T_{out} ranges were -35 to 12°C. In summer, the hourly T_{out} ranges between 4 and 34°C in FR06 conditions, corresponding to average daily values ranging between 12 and 25°C (Figure 2a). The corresponding ranges in SW06 were between 0 and 28°C on an hourly basis, and between 6 and 18°C, on a daily basis (Figure 2b).

Calculations and statistical analyses Depending on outdoor thermal conditions and condition of simulation, the model simulates the thermal balance at the room scale and the consequence of resulting T_{in} on performance of individual pigs. Thereafter it is possible to calculate the average or cumulated daily characteristics of pigs at the group scale (n = 30) and the overall performance from the beginning of the fattening period to the first delivery to the slaughterhouse or to the end of the fattening period.

Calculations Each day the model generates outputs either at room scale (T_{in}, energy consumed by the equipment…) or at pig scale (feed intake, BW, N retention…).

Growth performance Results obtained daily on each pig delivered to the slaughterhouse are used to calculate the individual average growth performance, i.e. daily feed intake (DFI), ADG, feed conversion ratio (FCR), nitrogen (N) balance and carcass leanness.

Environmental impact The amount of individual N intake is calculated from the individual intake of each diet, and the corresponding crude protein content, divided by 6.25. The N retention is assessed according to the simplified balance method proposed by Dourmad et al. (2016), i.e. as the difference between the final and the initial body protein content divided by 6.25. The efficiency of N retention is calculated as the ratio between N retention and N intake. The amount of N output per pig is obtained by difference between N intake and N retention. The daily intake of the different diets and the amount of N output per pig (even when they die before the end) are cumulated at the batch scale over the fattening period. The total energy consumption per batch expressed in international standard energy unit is obtained from the demand of energy due to total feed intake (in MJ, obtained from cumulated amount of feed intake and their cumulated energy demand per ton), and the electricity (direct energy) consumed by equipment (kWh) multiplied by 13.3 MJ/kWh (corresponding to the electricity French energy mix produced from nuclear and fossil energies, assessed with the SimaPro® LCA software). The results are divided by 96, i.e. the number of pigs at the beginning of the fattening period.

Economic performance The margin on feed cost is calculated per pig as the difference between the carcass value and the cost of feed intake. At slaughter, the economic value of the carcass is calculated for each pig, based on the French payment grid that takes into account the hot carcass weight and the carcass leanness (http://www.uniporc-ouest.com/, 30 March 2015). The price observed on average in December 2019 in Brittany (France, (http://www.marche-porc-breton.com/pdf/ntm/ntm1219.pdf) is used as the reference (1.496 €/kg). The cost of feed intake is calculated from the amount of each diet and its price based on the price of feedstuffs (available at Rennes, France) in December 2019, including 20 €/ton of delivery costs at the farm gate. The price of electricity used by equipment is fixed to 0.09 €/kWh (French average cost).

Statistical analyses Results obtained on average for each batch and each simulation are submitted to an analysis of variance (proc GLM, SAS, v9.4, Inst. Inc. Cary, NC) with the factors studied as the main effects and the batch as a random effect.

RESULTS AND DISCUSSION

Impact of room insulation Variation in T_{in} all along the fattening period was first simulated with different wall conductivities under the FR01 or SW01 climate, with similar regulation rule ($Ventil_{Ref}$) and feeding sequence (TEF-).

Under mild winter There are only small differences between simulated T_{in} for the highest insulations tested (i.e., $Wall_{Ref}$, $Wall_{Opt\ 1}$ and $Wall_{Opt\ 3}$), and T_{in} remains within the expected range of values parameterized in the climate box control of ventilation from the beginning of fattening to the first delivery to slaughterhouse (Figure 3a). With $Wall_{Opt\ 2}$, insulation is not high enough to prevent T_{in} from dropping below the minimal T setpoint especially at the beginning of the fattening period, when pigs are light, or just after the first delivery. The increase in T_{in} during the last hours of the fattening period is related to an increase in T_{out} that occurs when pigs are heavy and produce a lot of heat.

Differences observed or not between the different types of wall insulation are due to their respective HTC. As the HTC of a homogeneous material depends directly on the thickness of the material (e, m) and the thermal conductivity (ʎ, in $W.m^{-1}.°C^{-1}$) according to an asymptotic function (HTC = ʎ / e), any extra centimeter of insulation is more effective when thickness is small. Insulation is expected to improve significantly when an insulation layer is added to a concrete wall ($Wall_{Ref}$ or $Wall_{Op\ 1}$ vs. $Wall_{Op\ 2}$) whereas 5 additional cm have a limited impact when the wall is already insulated ($Wall_{Op\ 3}$ vs. $Wall_{Ref}$).

As the surface of the wall that exchanges heat with outside is 27 m^2 and the HTC of $Wall_{Ref}$ is 0.55 $W.m^{-2}.°C^{-1}$, the heat loss through the wall is around 0.15 W/°C per pig (96 pigs in the room). If heat loss through the ceiling is also considered (0.40 W/C° per pig), 0.55 W/C° per pig is lost across the structure of the room with this type of insulation. This value is very low compared to heat loss due to air renewal, which can be estimated to 2.72 W/°C per pig when the minimum air flow rate is 8 m^3/h (recommended value for a 30-kg pig), with a 0.34 $W.m^{-3}.°C^{-1}$ volumetric heat capacity of moist air at 20°C and standard air pressure. The limited contribution of insulation to total heat loss already reported by The Pigsite (2010) and Harmon et al. (2010, 2012) explains why differences in T_{in} are so small amongst $Wall_{Ref}$, $Wall_{Opt\ 1}$ and $Wall_{Opt\ 3}$ that they can be considered as comparable.

Under very cold winter When the coldest T_{out} are observed at the beginning of the fattening period, the highest insulations (i.e. low HTC) help to regulate T_{in} (Figure 3b). However, not enough heat is produced by the animal to balance the heat lost through the wall and due to air renewal even when ventilation rate is minimal (Figure 3B). Hence, with a T setpoint that decreases from 24 to 22°C over the first 15 days (i.e., over the first 360 hourly data) in the $\text{Ventil}_{\text{Ref}}$ rules, Figure 3b illustrates that expectations are not met without any other source of heat when T_{out} is extremely cold. Subsequently, T_{in} decreases at the beginning of the fattening period when pigs are light and do not produce a lot of heat. After the first delivery to the slaughterhouse when the number of pigs in the room decrease in T_{in} is limited compared to what is observed at the beginning of the period due to the higher amount of heat produced at this stage by each pig. Then T_{in} remains close to or above LCT, which is assumed to be close to 19°C around 100 kg BW when pigs are housed on fully slatted floor (Quiniou et al., 2021).

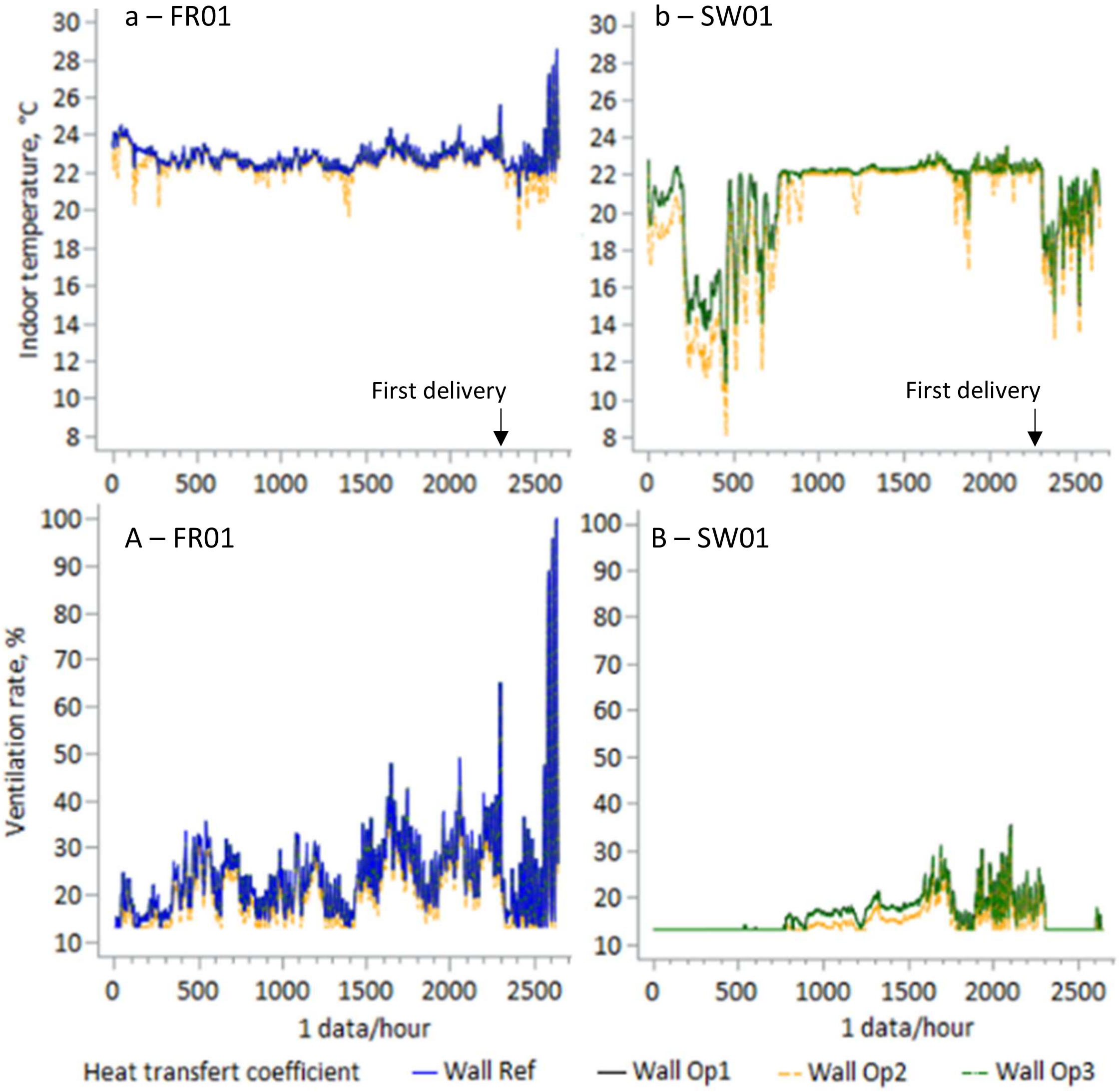

Figure 3. Effect of the heat transfer coefficient (HTC) of walls[1] on the hourly indoor temperature (a, b) and the ventilation rate (A, B) all along the fattening period either under the FR01[2] (a, A) or the SW01[3] (b, B) climate.

[1]Simulations performed with the same ventilation rules ($\text{Ventil}_{\text{Ref}}$) and feeding strategy (TEF-), without heating power, and with different HTC for Wall_{Ref}, $\text{Wall}_{\text{Op 1}}$, $\text{Wall}_{\text{Op 2}}$, and $\text{Wall}_{\text{Op 3}}$: 0.55, 0.27, 11.33 and 0.35 $W.m^{-2}.°C^{-1}$, respectively. [2]Lines obtained with Wall_{Ref}, $\text{Wall}_{\text{Op 1}}$ and $\text{Wall}_{\text{Op 3}}$ under FR01 climate and with $\text{Wall}_{\text{Op 1}}$ and $\text{Wall}_{\text{Op 3}}$ under SW01 climate are confounded. [3]Wall_{Ref} was not simulated under the SW01 climate.

Comparison of multicriteria performance As T_{in} regulation was similar with $Wall_{Op\,1}$ and $Wall_{Op\,3}$ under both climates, only results obtained with $Wall_{Op\,3}$ (monolithic brick) and $Wall_{Op\,2}$ (concrete paneling) are compared statistically in Table 2. Even when exposure to cold conditions occurs during a limited number of days at the beginning of the fattening period under the SW01 climate, it influences significantly all components of the performance, depending on the insulation level. The significant interaction observed between the climate and the wall insulation agrees with the differences in T_{in} observed between both options in Figure 3ab. With the highest insulation ($Wall_{Op\,3}$), lower DFI and FCR, feed cost and indirect energy utilization are obtained under both climates than with $Wall_{Op\,2}$ ($P < 0.001$). The difference is more important under SW01 than under FR01, with DFI reduced by 11 vs. 7 g/d, FCR reduced by 33 vs. 5 g/kg of BW gain, feed cost reduced by 49 vs. 10 c€/pig, and indirect energy reduced by 14 vs. 3 MJ/pig.

When wall insulation is improved, the margin on feed cost is improved by 70 and 23 c€/pig under the SW01 and FR01 climates, respectively. This result is explained mainly by the decrease in feed cost and to a lesser extent by differences in carcass value. Differences in carcass leanness between $Wall_{Op\,2}$ and $Wall_{Op\,3}$ are significant but depend on the climate (interaction: $P < 0.001$). Under the FR01 climate, the improved carcass leanness may be related to the higher amount of energy available for growth, especially for muscle deposition, at the beginning of the fattening period with $Wall_{Op\,3}$. Under the SW01 climate, a similar effect would be expected but the intensity of cold exposure questions the way carcass leanness is calculated presently in the model. A linear relationship based on the concentrations in protein and lipid in the empty body weight at slaughter is used (InraPorc®, v1.7.1.0). But this equation does not account for the effect of the change in the partition of lipid gain between peripheric and internal fat tissues when T_{in} is out of the thermoneutral zone. According to Rinaldo and Le Dividich (1991) and Čobanović et al. (2020), more fat is deposited in backfat than in belly under cold stress. Then, for a given lipid deposition rate, a reduced exposure to cold would result in a thinner backfat. When this criterion is used to assess the carcass leanness at slaughter and when the carcass payment grid is strongly driven by carcass leanness (like in France), the carcass value would be also higher with an increased wall insulation. In practice, the impacts of wall insulation under extremely cold T_{out} are also probably underestimated as health problem induced by cold exposure and consequence of cold air flow and poor air quality associated with minimal ventilation rates are not considered presently in the ThermiPig model.

The last dimension of pig performance concerns the environmental impact of pig production, assessed locally by the amount of N output per pig and globally through the energy consumption. Nitrogen retention is similar with both options of wall insulation, whilst N intake is reduced with $Wall_{Op\,3}$ compared to $Wall_{Op\,2}$. Subsequently, N output is reduced when wall insulation is improved ($P < 0.001$). The higher decrease in DFI under SW01 climate induces a more important decrease in N output, but also a more important decrease in total energy consumption. In practice, in order to compare the different options, a grade-color scale could ease the comparison (for example for a given criteria, from the worse result in red to the best one in green) and identify at a glance the option that gives the most interesting combination of criteria.

Table 2. Comparison of performance obtained with different heat transfer coefficients (HTC) of walls under SW01 or FR01 climate[1].

Climate	FR01		SW01			Statistics[2]		
HTC	Op 2	Op 3	Op 2	Op 3	RSD[2]	C	W	CxW
Growth performance[3]								
Final body weight (kg)	118.4	118.3	117.9	118.0	0.3	***		t
Feed intake (g/d)	2387^{a}	2380^{b}	2418^{c}	2407^{d}	5	***	***	*
Average daily gain (g)	860^{a}	859^{a}	846^{b}	852^{c}	2	***	***	***
Feed conversion ratio	2796^{a}	2791^{b}	2880^{c}	2847^{d}	7	***	***	***
Carcass leanness	59.86^{a}	59.94^{b}	59.96^{b}	59.90^{c}	0.07	*		***
N balance (g)[4]								
Intake	5577^{a}	5564^{b}	5719^{c}	5659^{d}	24	***	***	***
Retained	2168^{a}	2168^{a}	2158^{b}	2159^{b}	10	***		
Output	3409^{a}	3396^{b}	3561^{c}	3500^{d}	18	***	***	***
Economic result (€)[4]								
Feed cost	53.60^{a}	53.50^{a}	54.94^{b}	54.43^{c}	0.37	***	***	**
Margin on feed cost	92.63^{a}	92.86^{b}	90.82^{c}	91.52^{d}	0.31	***	***	***
Electricity	0.966^{a}	0.969^{b}	0.956^{c}	0.958^{c}	0.004	***	***	***
Energy (MJ)[4]								
Indirect (from feed)	1425^{a}	1422^{b}	1462^{b}	1448^{c}	10	***	***	**
Direct (electricity)	142.8^{a}	143.2^{b}	141.5^{c}	141.6^{c}	0.3	***	***	***
Total consumption	1567^{a}	1565^{a}	1603^{b}	1589^{c}	10	***	***	**

[1] *Op 2: concrete paneling (HTC = 0.27 $\mathrm{W.m^{-2}.°C^{-1}}$) vs. Op 3: monolithic brick (HTC = 0.35 $\mathrm{W.m^{-2}.°C^{-1}}$), with similar ventilation rules (Ventil$_{Ref}$) and feeding strategy (TEF-), and no heating power.* [2] *Analysis of variance with the climate (C), wall insulation (W) and interaction CxW as main effects (see P-values in the table: *** $P < 0.01$, ** $P < 0.01$, * $P < 0.05$) and the batch (n = 30) as a random effect, RSD: residual standard deviation. Different superscripts on the same row indicate that means differ with a probability of 5%. The cell of the most interesting result is colored in intense green color, the less interesting one in intense green, and the intermediate values are colored in pastel.* [3] *Performance of pigs alive at the end of the fattening period, feed conversion ratio is expressed in grams of feed intake per kg of body weigh gain.* [4] *Cumulated at the batch scale and divided by 96.*

Impact of the heater capacity. Previous simulations performed with Ventil$_{Ref}$ regulation rules illustrate that wall insulation and heat produced by animals are not high enough to allow for balancing T_{in} under extremely cold outdoor conditions. Other characteristics of the room or management can be questioned in these conditions. The management of the air renewal is crucial to limit the loss of heat and the decrease in T_{in} (Harmon et al., 2012), indeed heat loss can be halved by a minimum ventilation rate regulated with a high accuracy (IFIP, 2013). Supply of extra heat is another effective solution to limit the drop in T_{in}, at least at the beginning of the fattening period or when the number of pigs decreases after the first delivery. Simulations are performed without or with three heating power capacities as illustrated in Figure 4 and Table 3 under the SW01 climate. Figure 4a illustrates that differences in T_{in} are not observed amongst options of heating power all the time, but only when ventilation is at the minimal rate (Figure 4b) as this is the condition required by the system to provide extra heat.

Obviously, the higher the power capacity is, the smaller the drop in T_{in} observed at the beginning of the fattening period (Figure 4a). Although T_{in} is improved only during a limited period, FCR is improved by increased heating power. Up to 37.6 W/pig, it is associated with a significant decrease in DFI and an increase in ADG, corresponding to a reduced energy demand for thermoregulation at the expense of growth. Subsequently, the indirect energy use from the feed, feed cost and N output decrease also (Table 3). Increasing the power capacity above 37.6 W/pig only improves marginally these components of the performance. Without consideration of the impact of cold exposure

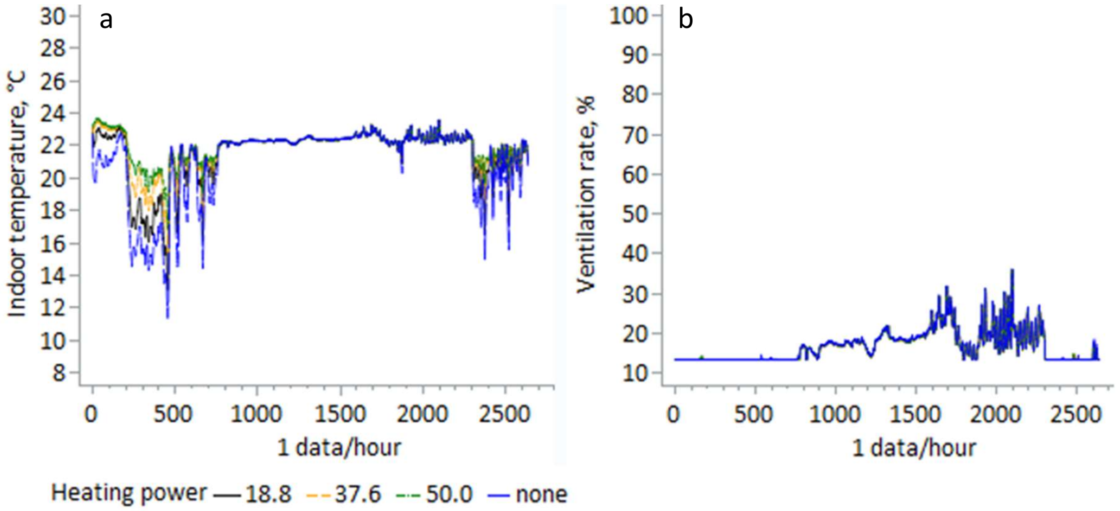

Figure 4. Effect[1] of the heating power capacity (W/pig) on the hourly indoor temperature (a) and ventilation rate (b) all along the fattening period under the SW01 climate[2]

[1] *Ventilation rules: Ventil$_{Ref}$, heating regulation rules: Heater$_{Op\ 1}$, wall insulation: Wall$_{Op\ 3}$, feeding strategy: TEF+.* [2] *See Figure 2.*

Table 3. Comparison of performance[1] obtained with different heater power capacities under the SW01 climate[2].

Heater power, W/pig	0	18.8	37.6	50.0	RSD[1]	HP[2]
Growth performance						
Final body weight (kg)	118.0^a	118.1^{ab}	118.2^b	118.4^c	0.3	***
Feed intake (g/d)	2405^a	2400^b	2398^b	2400^b	4	***
Average daily gain (g)	852^a	855^b	857^c	859^d	2	***
Feed conversion ratio	2844^a	2827^b	2818^c	2815^c	7	***
Carcass leanness	60.01^a	59.94^b	59.88^c	59.83^d	0.07	***
N balance (g)						
Intake	6102^a	6073^{bd}	6057^c	6063^d	21	***
Retained	2163	2164	2165	2168	6	t
Output	3938^a	3909^b	3892^c	3895^c	18	***
Economic result (€)						
Feed cost	58.64^a	58.32^b	58.16^b	58.15^b	0.35	***
Margin on feed cost	87.42^a	87.74^b	87.84^{bc}	87.91^c	0.31	***
Electricity	0.958^a	2.129^b	2.882^c	3.200^d	0.068	***
Energy consumed (MJ)						
Indirect (from feed)	953^a	948^b	945^{bc}	945^c	6	***
Direct (electricity)	142^a	315^b	426^c	473^d	10	***
Total	1095^a	1262^b	1371^c	1417^d	8	***

[1] *See Table 2.* [2] *Wall insulation: Wall$_{Op\ 3}$, ventilation rule: Ventil$_{Ref}$, feeding sequence: TEF+.* [3] *Analysis of variance with the heating power (HP, see P-value in the table) as main effect and the batch (n = 30) as a random effect.*

on health and welfare of the pigs and the farmer, improved growth performance, economic return and environmental impact do not compensate for the extra cost of electricity presently. But, as mentioned before, the carcass value is probably underestimated when cold exposure is reduced, due to the way carcass leanness is assessed. Combined with a reduced feed cost, the margin of feed cost is expected to be higher than estimated presently and it may compensate or not for the extra cost of electricity, depending on the market price of meat and electricity.

Impact of the ventilation rules Effects of the regulation rules are investigated in a room insulated with monolithic brick (Wall$_{op3}$), without any additional equipment but ventilation under FR01 and FR06 climates and with different heater capacities under SW01 climate.

<u>When simulations are performed under the FR06 climate</u> (result not presented), the DFI is increased (+20 to 80 g/d) when the final T setpoint is reduced from 22 to 15 or 17°C. Pigs are also heavier on average at delivery (+0.3 to +0.9 kg on average), but without an increase in final BW variability. Simultaneously a slight increase in FCR is observed as well as a limited decrease in carcass leanness. Both results contribute to decrease the margin on feed cost compared to the result obtained with Ventil$_{Ref}$. However, it remains better (around + 2 €/pig) than in winter. The impacts of hot exposure on physical activity (activity, postural changes…) and behavior of pigs beside appetite are not considered presently in the model. The farmer may decide to overcome the limited differences mentioned above based on his knowledge and expertise and to promote one of these options.

Table 4. Comparison of performance[1] obtained with different ventilation rules under the FR01 climate[2].

Ventilation rule[3]	Ref	Op 1	Op 2	Op 3	Op 4	Op 5	Op 6	RSD[1]	V[4]
Growth performance									
Final body weight (kg)	118.3^{a}	118.9^{b}	118.8^{bc}	118.7^{c}	118.7^{c}	118.6^{c}	118.7^{c}	0.3	***
Feed intake (g/d)	2380^{a}	2441^{b}	2430^{c}	2461^{d}	2443^{e}	2529^{f}	2493^{g}	5	***
Average daily gain (g)	859^{a}	869^{b}	867^{c}	866^{d}	866^{d}	861^{e}	863^{f}	2	***
Feed conversion ratio	2791^{a}	2831^{b}	2822^{c}	2865^{d}	2841^{e}	2960^{f}	2912^{g}	7	***
Carcass leanness	59.94^{a}	59.38^{b}	59.41^{bc}	59.43^{c}	59.43^{c}	59.68^{d}	59.55^{e}	0.07	***
N balance (g)									
Intake	5563^{a}	5678^{b}	5650^{c}	5737^{d}	5688^{b}	5917^{e}	5825^{f}	23	***
Retained	2168	2167	2164	2165	2164	2169	2166	9	ns
Output	3400^{a}	3511^{b}	3487^{c}	3572^{d}	3522^{e}	3748^{f}	3659^{g}	18	***
Economic result (€)									
Feed cost	53.51^{a}	54.53^{b}	54.26^{c}	55.14^{d}	54.64^{b}	56.95^{e}	55.94^{f}	0.35	***
Margin on feed cost	92.86^{a}	91.17^{b}	91.39^{c}	90.45^{d}	90.97^{e}	88.92^{f}	89.69^{g}	0.34	***
Electricity	0.969^{a}	0.999^{b}	0.988^{c}	1.001^{d}	0.995^{e}	1.047^{f}	1.021^{g}	0.002	***
Energy consumed (MJ)									
Indirect (from feed)	1422^{a}	1449^{b}	1442^{c}	1465^{d}	1452^{b}	1513^{e}	1486^{f}	9	***
Direct (electricity)	143.2^{a}	147.7^{b}	145.9^{c}	149.2^{d}	147.0^{e}	154.8^{f}	151.0^{g}	0.3	***
Total	1565^{a}	1596^{b}	1588^{c}	1614^{d}	1599^{b}	1668^{e}	1637^{f}	9	***

[1]See Table 2. [2]Wall insulation: Wall$_{Ref}$, heating power: null, feeding sequence: TEF-. [3]See Table 1. [4]Analysis of variance with the ventilation rule (V, see P-value in the table) as main effect and the batch (n = 30) as a random effect.

Impact of pad cooling The pad cooling system is activated when T_{out} increases above 25°C, that occurs frequently under the FR06 climate (Figure 6a). When pad cooling is activated, T_{in} remains almost all the time below 28°C, whereas higher values are observed otherwise (Figure 6b).

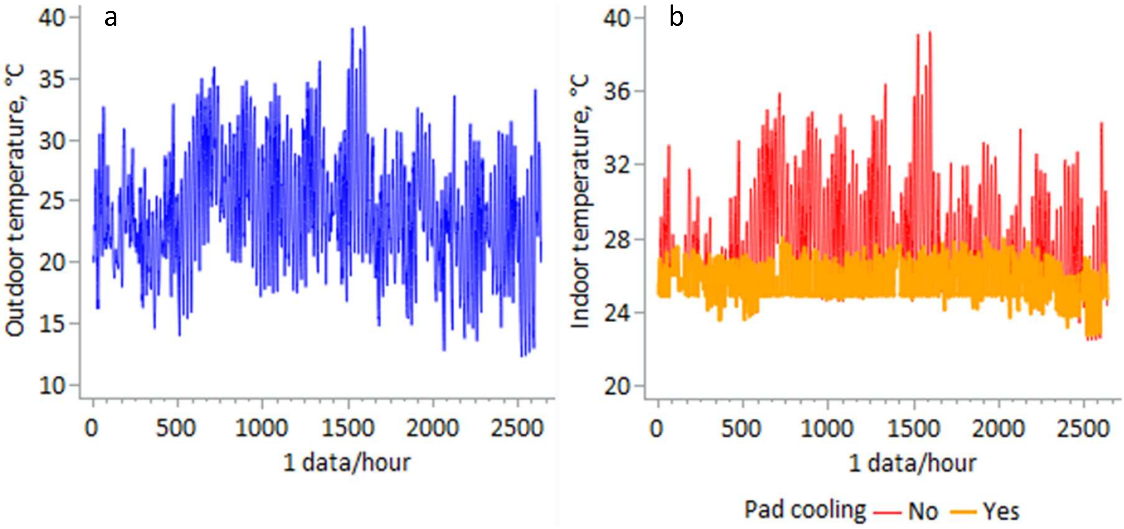

Figure 5. Hourly outdoor temperature under FR06 climate (a) and effect[1] of pad cooling on the hourly indoor temperature (b).

[1]Wall insulation: $Wall_{Ref}$, ventilation rule: $Ventil_{Ref}$, feeding sequence: TEF+.

Table 5. Comparison of performance[1] obtained with two feeding sequences with or without pad cooling under summer climate FR06[2].

Thermic effect of feed	TEF+	TEF+	TEF-	TEF-	RSD[1]	Statitics[3]		
Pad cooling	No	Yes	No	Yes		Pc	TE	PcxTE
Growth performance								
Final body weight (kg)	114.8^a	116.7^b	115.0^c	116.7^b	0.3	***		
Feed intake (g/d)	2120^a	2260^b	2122^a	2264^c	5	***	***	
Average daily gain (g)	794^a	831^b	797^c	834^d	2	***	***	
Feed conversion ratio	2683^a	2737^b	2679^c	2735^b	7	***	*	
Carcass leanness	62.59^a	61.29^b	62.47^c	61.13^d	0.07	***	***	
N balance (g)								
Intake	5553^a	5790^b	5153^c	5363^d	3	***	***	**
Retained	2157^a	2169^b	2159^a	2165^b	9	***		*
Output	3396^a	3620^b	2993^c	3198^d	2	***	***	**
Economic result (€)								
Feed cost	53.14^a	55.53^b	53.20^a	55.48^b	0.43	***		
Margin on feed cost	91.40^a	90.91^b	91.50^a	90.83^b	0.30	***		
Electricity	1.127^a	1.115^b	1.126^c	1.114^d	0.002	***	***	
Energy consumed (MJ)								
Indirect (from feed)	865^a	903^b	866^a	902^b	7	***		
Direct (electricity)	166.6^a	164.8^b	166.4^c	164.6^d	0.2	***	***	
Total	1031^a	1068^b	1032^a	1067^b	7	***		

[1]See Table 2. [2]Wall insulation: $Wall_{Ref}$, ventilation rule: $Ventil_{Ref}$. [3]Analysis of variance with the pad cooling (Pc), thermic effect (TE) of feed and their interaction (PcxTE) as main effects (see P-values in the table) and the batch (n = 30) as a random effect.

With the TEF+ strategy When conventional diets are used, the reduced exposure to acute heat stress associated to pad cooling activation allows for an improvement of DFI by 140 g/d and of ADG by 37 g/d that results in a heavier final BW (+1.9 kg, Table 5). Beside FCR is increased by 54 g/kg and N output by 224 g/pig, margin on feed cost per pig is 0.5 € lower, and the decrease in direct energy (-2 MJ/pig) does not compensate for the indirect energy consumption (+38 MJ/pig). Based on the present results, the first conclusion would be that pad cooling is not worth it, even when extra consumption of water is not considered. But it may be reconsidered in the future. Le Bellego et al. (2002) and Serviento et al. (2020) observed significant effects of hot temperature on the metabolism, especially on protein synthesis, that would mean that carcass leanness (then carcass value and margin on feed cost) is overestimated when no pad cooling is used.

With the TEF- strategy Under hot conditions, a slight but significant increase in DFI of TEF- diets is observed as expected. As less heat is produced during the metabolic use of these diets, a given cumulated amount of heat produced by the group of pigs can be obtained from a higher amount of feed intake with a limited impact on the thermal balance at the room scale. Increased DFI is associated to an increased ADG, and FCR is also improved without pad cooling (Table 5). The most important effect is observed on N intake, as low TEF diets present usually a lower crude protein content than conventional (TEF+) diets for the same concentration in essential amino acids. Subsequently, the lower N intake, associated with a significant decrease in FCR or not, contributes to an important decrease in N output (-403 and -422 g/pig, without and with pad cooling, respectively).

CONCLUSION Nowadays, dealing with climate change and the efficient use of resources when designing or renewing pig barns is necessary, but it is difficult with regards to the numerous characteristics that must be considered, either solely or in combination. The modelling approach gives cheap and unlimited possibilities to compare in a very reactive way different options with regard to their specific impacts on the multicriteria performance of the pigs. Based on *in silico* results (not on absolute values), it is possible to compare different options and to consider the positive and negative variation before making a decision, depending on the weight given to each component of the performance (feed efficiency, economic result, environmental impact, energy consumption…) by the farmer or the technical designer. The investigation carried out with the ThermiPig model in the present paper demonstrate its ability to describe the multicriteria performance of pigs associated with different characteristics of the room or management. The outputs of the bioclimatic growth model are expected to be further improved in the future. Ongoing developments focus on the thermodynamic representation of slurry and its contribution to the thermal balance and air quality at room scale. Additionally, the impact of housing conditions on metabolism and composition of body weight gain but also on animal welfare, health and resilience will be considered. With this kind of promising tool, it becomes easy to test different systems of pig production and to select the most optimal one depending on the climate.

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