An innovative concept building design incorporating passive technology to improve resource efficiency and welfare of finishing pigs

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Abstract. In conventionally-designed buildings for finishing pigs, extreme weather conditions can impact negatively on feed utilisation and animal welfare. The SPaTHE (Solar, Passive, Thermal, Heat Exchange) concept is an innovative, resource-efficient engineered building designed to provide an internal environment where finishing pigs can thrive. Passive design elements include solar shading and capture combined with integrated earth tubes to facilitate heat exchange with incoming fresh air to reduce extreme summer and winter internal temperatures. The SPaTHE specification was dynamically modelled and compared to an existing conventional finisher building operating in the UK. The same dimensions (18 m × 14 m) and build specification were used for each building, which was designed to hold 292 pigs from 20 to 100 kg liveweight. Results showed that pigs in the optimum configuration of conventional building form spent 661 fewer h y⁻¹ in conditions < 19°C, and 102 fewer h y⁻¹ in conditions > 28°C than with a standard building. Whereas with the SPaTHE design, during 2222 h y⁻¹ the pigs were kept at optimum conditions between 19°C to 22°C. The model also

24 estimated that the SPaTHE design would reduce peak summer internal operative temperature
 25 by 3.4°C when the external temperature was 28°C, and increase the peak winter internal
 26 operative temperature by 1.2°C when the external air temperature is -5.4°C. Hence the concept
 27 design potentially provides an environment which more closely matches the needs of finishing
 28 pigs and thus may contribute to more sustainable food production systems.

29

30 **Keywords.** *pig building, ventilation, sustainable, passive, design, dynamic modelling.*

Nomenclature

ac h^{-1}	Infiltration of air
DT	Dynamic Thermal model
kg	Liveweight of pigs
$\text{kJ m}^{-2} \text{K}^{-1}$	Thermal Mass
kW h y^{-1}	Annual electrical energy consumption
LHP	Latent Heat Produced by the pig
l s^{-1}	Volume flow rate
lx	Illuminance levels
$\text{m}^3 \text{h}^{-1}$	Volume flow rate
m s^{-1}	Air velocity
NOAA	National Oceanic and Atmospheric Administration
q_e	Sensible heat gain of sensible heat to latent heat
q_f	Sensible heat gain through the floor
q_h	Sensible heat gain from heating systems
q_m	Sensible heat gains from ‘mechanical’ sources
q_s	Sensible heat gains from animals
q_{so}	Sensible heat gain from solar radiation
q_{vi}	Sensible heat gain from supply ventilation air
q_{vo}	Sensible heat gain contained in the extract ventilation air
q_w	Sensible heat gain through the building fabric (excl. floor)
SPaTHE	Solar, Passive, Thermal and Heat exchange concept building design
SHP	Sensible Heat Produced by the pig
THP	Total Heat Produced by the pig
TRY	Test Reference Year weather files
$\text{W m}^{-2} \text{K}^{-1}$	U-Value

1 Introduction

Compared to many other livestock reared for meat production, pigs have a relatively low level of insulation in their coats which makes them more sensitive to changes in the housed internal environment. When pigs are exposed to colder conditions, their level of thermoregulatory heat production increases, energy retention from consumed nutrients is depressed and, as a result, feed efficiency is reduced (Lopez *et al.*, 1991). For housed pigs, the environmental temperature range that means they neither need to divert nutrients to keep warm nor reduce feed intake to keep cool is known as the thermoneutral zone (Mount, 1975). When housed in these conditions throughout the finishing production programme, pigs will return a higher feed efficiency and show improved well-being. However, when housed in typical current UK buildings during a typical UK year, maintaining this thermoneutral zone can be challenging (Jackson *et al.*, 2017). This is particularly so if the temperature control in the finishing room relies solely on varying the incoming fresh air via fan ventilation, rather than heating and cooling the air supply, or cooling via a high-pressure misting system. In UK pig finishing buildings, heating and cooling systems for the incoming air are usually not used, due to their associated increased installation, energy and maintenance costs. Cold weather can therefore have a detrimental effect not only on pig productivity, because nutrients are diverted from growth to heat production, but also on the internal air quality, this is because the predominant ventilation control factor is the minimum temperature set point until a fixed minimum ventilation rate is reached (Jackson *et al.*, 2017). Potential faults to ventilation fans, and the possibility for farm staff to alter this minimum fresh air rate if, for example they feel the internal temperature is too cool during extreme cold spells, can exacerbate this problem. The need to maintain a higher minimum ventilation rate can result in farms installing supplementary heating for smaller pigs during cooler external conditions.

Similarly, very warm weather can also have a detrimental effect on pigs. When the internal

environmental temperature increases, pigs will attempt to lie separate from each other and try to place as much body surface area as possible onto a cool or wet surface to help dissipate heat, which can result in wallowing in manure. If the temperature increases further, they will begin to reduce their feed intake in order to decrease their metabolic heat production. This heat stress-induced reduction in feed intake has a significant impact on pig productivity (Renaudeau *et al.*, 2011). St-Pierre *et al.* (2003) estimated the effect of heat stress on three aspects of pig production in the USA, namely decreased performance, increased mortality and decreased reproduction, to give rise to annual losses of approximately €250 million, with the finishing pig stage specifically equating to €196 million.

Due to the possibility of these large losses at extreme temperatures, pig housing design sometimes includes the capacity to supply extra cooling when required during the year via water misting (Santonja *et al.*, 2017). This type of cooling system works on two principles of heat transfer, namely evaporation and convection. Evaporation uses the surrounding heat to transform water droplets into vapour, hence reducing the surrounding air temperature, whilst convection created by the velocity of extract air passing over the pigs aids the removal of heat and vapour before the pigs actually get wet. However cooling systems can potentially fail, particularly nozzles can block, resulting in the vapour not being produced correctly. As a result, water may reach the floor area with the negative consequences of not sufficiently cooling the internal air temperature and potentially providing an unsafe slippery floor (Baxter and Mitchell, 1977; Christion and Farmer, 1983). Therefore, alternative approaches to building design for finishing pigs are required, while maintaining current construction utility and maintenance costs.

In building design, the term ‘passive’ is used when studying how the natural conditions can be exploited to enhance the sourcing of heat and light from the sun and cooling and ventilation from the wind. The terms ‘sustainable’ or ‘renewable’ are associated with ‘energy efficient’

solutions to reduce energy costs within a building, but such solutions often require a form of energy to run the associated technology, such as controls and pumps, that enable the device(s) to reduce overall energy consumption. For this reason, engineers argue that passive design techniques should always be explored before sustainable solutions are incorporated, as an adaptation that increases running costs and/or carbon emissions is counterproductive (Hacker *et al.*, 2009). Jackson *et al.* (2017) concluded that, even with improvements to thermal mass and/or insulation for conventional finisher buildings, an innovative design approach may still be required to address overheating in summer as temperatures in the future increase through climate change. NASA and the National Oceanic and Atmospheric Administration (NOAA) indicate the Earth's 2016 surface temperatures were the warmest since modern record-keeping began in 1880, while globally-averaged temperatures in 2016 were 1.78 °F (0.99 °C) warmer than the mid-20th century mean (Potter, 2017).

Within agricultural engineering, there are a number of potential sustainable technologies, but rarely are passive design options investigated which might improve the energy performance of buildings and, at the same time, reduce energy inputs and increase feed efficiency and pig welfare. Therefore, the purpose of this paper was to investigate the potential for designing a building that incorporates passive design techniques to provide an optimised thermoneutral internal environment for pigs, when compared to on-site annual temperature data available for an existing conventionally-designed building. The objective of this innovative design process is to reduce the time that pigs spend within too cool and too warm temperature bands, and concomitantly increase the amount of time spent in optimum conditions. The design was sequentially improved until the changes became negligible and/or the design became inefficient or potentially too costly to build. Increasing the time that pigs spend in the optimum temperature band would potentially improve both welfare and feed efficiency of finishing pigs throughout the year, whilst minimising energy and maintenance costs.

2 Materials and methods

2.1 Modelling software

An existing dynamic thermal (DT) model, previously developed by Jackson *et al.* (2017) to investigate the effects of changing the design elements of a conventional building design with a fully-slatted floor, whilst also showing the potential effects of climate change on the pig's environment, was used and updated to the latest version of the software (DesignBuilder V.5.0.3.007, EnergyPlus 8.1; DesignBuilder Software Limited, Stroud, UK). Thus, as the base comparison, the model directly replicates one room of an existing fully-slatted building located on a pig production site at Stafford, UK. Each room is approximately 18 m × 14 m, capable of holding approximately 292 finishing pigs, with a service corridor running outside the rooms along the length of the building which comprises eight rooms in total, allowing for successive batches of pigs which is typical of commercial production. Each room is ventilated by four in-wall panel extract fans (Multifan, Vostermans Ventilation BV, Venlo, Netherlands), comprising two fans of diameter 915 mm and two fans of diameter 574 mm, with respective volume flow rates at 50 Pa of 16800 and 9400 m³ h⁻¹ per fan. The fans are located in the sidewall opposite the service corridor, operated with a step controller, with air entry through a controlled ridge opening to maintain a 5 m s⁻¹ inlet jet along the ridge of the ceiling.

An innovative DT modelling approach was taken to design an equivalent building to house the same number of pigs in each room (292 finisher pigs, from 20 to 100 kg), occupying an area of 250 m². The SPaTHE (Solar, Passive, Thermal, Heat Exchange) concept building is an innovative, engineered building developed to provide an internal environment where finishing pigs can thrive. The building is designed in such a way as to promote ground heat exchange with incoming fresh air, whilst also capturing solar rays in winter to take advantage of free heating, and reducing the solar heat gains penetrating the space in summer. The assumption was that this innovative concept design would be constructed in the same location, with the

same inputs and building specifications as the existing finishing pig building. The efficacy of each of a sequence of design alterations was evaluated against the conventional building over a 12-month period, using the dynamic model to simulate the housing of four successive batches of growing-finishing pigs from entry to the space at 20 kg to subsequent dispatch for slaughter at 100 kg. The aim was to estimate the operative temperatures within the space and compare these data against those for the existing building and each previous design alteration. Thus, throughout this paper, internal environmental temperatures reported are expressed as ‘operative temperatures’, defined as the mean of internal air and radiant temperatures for the calculated space. Operative temperature is used since integration of the radiant aspect can provide a more accurate parameter to evaluate the ‘feeling of comfort’ than simply air temperature alone.

2.2 Model inputs

The DT model simulates all the required inputs of appropriate internal heat gains, pig metabolic heat output, fresh air requirements and thermal properties of the building (as detailed in Jackson et al., 2017), as it runs through the site-specific annual weather file (University of Exeter, 2008). Operation of the model to simulate each of these inputs is described in detail in each of the following sub-sections. Equilibrium of heat transfer is required between the pig and its environment to improve the welfare of the animal and promote greater resource use efficiency. Equation 1 describes the components of heat balance within the model, including solar energy gain (q_{so}), heat gain from the pigs (q_s), heat loss through the building fabrics (q_w & q_f) and heat loss/gains from building systems (q_{vi} , q_{vo} , q_e , q_m & q_h). Since Eq. (1) is balanced, it demonstrates that every aspect of the building mechanisms and external weather conditions will impact on providing an environment for optimum productivity.

$$\text{Gains} = \text{Losses} \text{ is } q_s + q_m + q_h + q_{vi} = q_w + q_f + q_e + q_{vo} \quad (1)$$

q_s - Sensible heat gains from animals

q_{so} - Sensible heat gain from solar radiation.

q_{vi} - Sensible heat gain from supply ventilation air.

q_f - Sensible heat gain through the floor.

q_m - Sensible heat gains from ‘mechanical’ sources.

q_h - Sensible heat gain from heating systems.

q_w - Sensible heat gain through the building fabric (excl. floor)

q_e - Sensible heat gain of sensible heat to latent heat.

q_{vo} - Sensible heat gain contained in the extract ventilation air.

2.2.1 Estimation of amount of sensible heat produced by the pigs (q_s) and sensible heat to latent heat (q_e)

Figure 1 demonstrates how there is a steady increase in the amount of estimated total, sensible and latent heat produced (THP, SHP & LHP, respectively) by the pigs as they grow from 20 to 100 kg bodyweight, taking a period of approximately 12 weeks. The graph shows constant metabolic rates for 292 finishing pigs at 20°C and how they will produce approximately 32 kW of sensible heat (q_s) just before slaughter, assuming typical levels of feed intake, compared to only 13 kW of sensible heat when they were first introduced into the space. Although SHP is connected more closely to body surface area, it is problematic to measure, therefore heat production as a function of bodyweight is used in this study by raising bodyweight to the power of 0.734 (Albright, 1990).

Fig. 1. Estimated constant heat production (HP) for 292 finishing pigs maintained at a 20°C internal building temperature, adapted from Albright (1990)

2.2.2 Estimation of minimum fresh air requirements for indoor finishing pigs

Recommendations for indoor air quality with respect to minimum fresh air requirements for finishing pigs vary considerably, especially as the pig grows closer to market weight. For this reason, values from three of the leading and historical sources were averaged to create a mean value of litres of fresh air per second per pig to use within the dynamic model, as shown in Table 1. From English *et al.* (1988), two values were obtained: the ‘minimum’ fresh air requirement which, according to the authors, pig producers found difficult to achieve in practice, and so a second value was created, namely the ‘acceptable’ requirement for fresh air. Values taken from the ASABE Swine Housing and Equipment Handbook (MWPS-8, 1983) are based on the cold weather scenario.

Table 1. Estimates of fresh air requirements for finishing pigs weighing between 20 and 100 kg bodyweight

Source	Weight of pig (kg)	Volume of fresh air ($\text{m}^3 \text{h}^{-1}$)	Volume of fresh air (l s^{-1})	Average value used in the model (l s^{-1})
BS5502, (BSI, 1990)	20	5	1.39	1.50
English et al (1988) - Minimum rate	20	7.5	2.08	
English et al (1988) - Acceptable rate	20	4	1.11	
ASABE, MWPS-8 (1983)	13.60 to 34		1.42	
BS5502, (BSI, 1990)	40	8	2.22	2.51
English et al (1988) - Minimum rate	40	15	4.17	
English et al (1988) - Acceptable rate	40	8	2.22	
ASABE, MWPS-8 (1983)	34 to 68		1.42	
BS5502, (BSI, 1990)	60	10.5	2.92	3.95
English et al (1988) - Minimum rate	60	22.5	6.25	
English et al (1988) - Acceptable rate	60	12	3.33	
ASABE, MWPS-8 (1983)	68 to 100		3.30	
BS5502, (BSI, 1990)	80	11.5	3.19	

English et al (1988) - Minimum rate	80	30	8.33	4.82
English et al (1988) - Acceptable rate	80	16	4.44	
ASABE, MWPS-8(1983)	68 to 100		3.30	
BS5502, (BSI, 1990)	100	11.5	3.19	
English et al (1988) - Minimum rate	100	37.5	10.42	5.97
English et al (1988) - Acceptable rate	100	20	5.56	
ASABE, MWPS-8(1983)	100+		4.72	

2.2.3 Selection of Test Reference Year (TRY) weather data

In the UK, DT modelling for human buildings generally uses reference weather year files to comply with current building regulation-approved documents; for example Part L2B, “Conservation of fuel and power in existing buildings other than dwellings” (HMSO, 2013). These weather files are in the form of Test Reference Year (TRY) data, used for energy analysis. Hence Kershaw *et al.* (2010) concluded that TRY is generally the most suitable estimate of average weather data for any building in a given location.

The DesignBuilder software contains pre-installed controlled TRY weather data for different locations around the world. The nearest available TRY weather data location to the existing pig production unit in Staffordshire is the Birmingham weather station, which is approximately 45 miles away.

2.2.4 Existing design properties of the model

Table 2 shows the thermal properties of the existing building design, as taken from the manufacturer’s installation data provided to the client.

Table 2. Thermal properties of the existing building of conventional design with a fully-slatted floor.

Thermal Mass ($\text{kJ m}^{-2} \text{K}^{-1}$)	U-Value ($\text{W m}^{-2} \text{K}^{-1}$)	Infiltration (ac h^{-1})
Existing	Existing	Existing

External Walls	5.6	0.49	
Roof		0.52	
Windows		1.96	
Infiltration			0.7

201

202 Figure 2 shows the heat output (W m^{-2}) for each of the four successive batches of the 292 pigs
 203 transferred into the environment, and how this matches the growth of the pigs over a 12 week
 204 period from a mean liveweight of 20 kg, as they are first placed in the room, to 100 kg
 205 liveweight. There are four periods of cleaning between batches, at the point where pigs are
 206 removed for slaughter and the room is cleaned before the next batch, as happens normally on
 207 a pig farm.

208 The model of the existing building is based on the constant supply of increasing minimum fresh
 209 air requirements for the pigs as they progress through the 12 week finishing period, rather than
 210 controlling the internal environment via an internal temperature setpoint which could
 211 potentially risk the minimum fresh air requirements not being achieved. Jackson *et al.* (2017)
 212 previously estimated that in the existing building the annual time that 40, 60 80 and 100 kg
 213 pigs respectively would be kept below the internal lower setpoint of 19°C was 161, 1154, 1468
 214 and 1848 h.

Fig. 2. Annual heat output transferred into the environment for 292 growing pigs of mean liveweight from 20 to 100 kg in a 12-week period in the existing building of conventional design with a fully-slatted floor, assuming a period of 5 days to clean between batches

Therefore, rather than an increasing linear heat output line being shown in Fig. 2 as the pigs enter at 20 kg to removal at 100 kg, it can be seen that the heat output of the pigs transferred into the environment fluctuates. This fluctuation indicates how the operative temperature of the internal environment and its relative humidity can affect the estimated mean heat output transferred into the environment. It can be seen that the heat output for the two summer batches (April to July, and July to October) is more erratic than for the winter batches, due to higher diurnal external temperature variations in the summer months affecting the internal operative temperature

2.3 Optimisation of the SPaTHE concept building

A series of design options and passive technologies were explored for their potential to influence the internal operative temperature of the finisher unit and thus increase the time that pigs would spend in the designated thermal range.

2.3.1 Optimum orientation

The optimum building orientation of the space to be investigated, along with the adjoining spaces, is an important design consideration and an essential part of reducing heat and cooling loads. In this work, optimum orientation was the parameter that maximised the amount of time that pigs were kept within the building setpoint temperature range. The passive design consideration which can be applied to buildings in the Northern and Southern hemispheres receives twice as much direct sun during winter months on facades facing south and north respectively, while the west and east-facing facades receive four times the amount of solar radiation in summer months (Valladares-Rendón *et al.*, 2017). Since the existing comparator finishing building was orientated south, the concept building design was also orientated south to allow for direct comparison. However Fig. 3 shows the north and south elevations and a plan view of a section of the existing finisher building, from which it can be seen that the existing building has a north façade service corridor running the full length of the finishing units. This form of the concept building was investigated to determine the optimum location and orientation of the service corridor, glazing size and location, and overall shape of the building. All the results discussed in this paper relate to one particular finishing room, the central room of the three adjacent rooms as highlighted in Fig. 3. Although the existing production site has

eight adjacent finishing rooms in a line, the model takes into account only the central room and the two adjacent rooms which could potentially affect the environment of the central room.

Fig. 3. North, south and plan view of a section of the existing finishing building of conventional design with fully-slatted floor comprising 8 identical rooms, with the service corridor on the north elevation; results reported relate to one particular room, as highlighted in pink

2.3.2 Optimum building form

Figure 4 shows the existing building ('a') and seven selected alternative forms ('b to h') of the building which were modelled. The access passageway has been removed from the diagram for clarity of presentation. The changes to the building form, volume, glazing and shading options are listed in Table 3. Each individual change was investigated by modelling for its consequences for the amount of time at which the finishing room functioned at the optimal internal operative temperatures (i.e. ≥ 19 to $< 22^{\circ}\text{C}$), along with ≥ 16 to $< 19^{\circ}\text{C}$ for the later stage finishing pigs and ≥ 22 to $< 25^{\circ}\text{C}$ for the earlier stage finishing pigs, two bands of overheating (≥ 25 to $> 28^{\circ}\text{C}$ and ≥ 28 to $< 33^{\circ}\text{C}$) and two bands of a cooler environment (≥ 9 to $< 13^{\circ}\text{C}$ and

263 ≥ 13 to $< 16^{\circ}\text{C}$).

264

265 Fig. 4. Existing building form (a) and alternative forms (b to h) which were modelled. Details of each form are given in Table 3. All
266 building forms are orientated south to the left-hand side of the figures.

267

268 The hours pigs spent at each of these seven operative temperature bands for each revised
269 building form ('b to h') were compared to the equivalent operative temperature bands for the
270 existing building form ('a') to explore if there were any differences and, if so, in which
271 temperature band the differences had occurred. This operative temperature information then
272 led to the next alteration in design, until the changes became negligible and/or the design
273 became inefficient or potentially too costly to build.

274 Table 3 Room volume and description of alternative forms of concept building design modelled to optimise the building form
275 assuming a common floor area of 250 m²

Building form	Room volume (m ³)	Optimising alterations
a	992	N/A – Existing building
b	950	Flat roof and additional 1000 mm in height
c	925	New shape, to reduce the area of south facing roof
d	692	New shape to reduce the area of south facing roof

e	887	Alteration to roof shape, by decreasing north pitch
f	887	Alteration to north window, by increasing area of glazing
g	933	Overhang introduced to south glazing
h	950	Overhang integrated into roof shape and service void introduced
SPaTHE		Introduction of earth tube heat exchanger

276

277 **2.3.3 Earth tube model**

278 Underground air ducts, commonly known as earth tubes, can provide free heating and cooling
279 to a ventilated space via heat exchange from the surrounding ground in winter and summer
280 respectively (Deglin *et al.*, 1999). However, the effectiveness of earth tubes is dependent on
281 factors such as pipe diameter, length, depth and rate of air flow. A pipe which is longer, has a
282 smaller diameter and with a low air velocity will result in a greater earth tube performance (Lee
283 and Strand, 2008). It was assumed that a 3.5 m maximum deep pit would be a realistic depth
284 at which to install a pipe, rather than incurring greater installation costs to bury the pipe at an
285 even greater depth to gain a better return of heat exchange from the surrounding earth. For this
286 reason, the earth tube in the model was specified with a depth of 3.5 m and length of 100 m,
287 while the default specifications from DesignBuilder were retained for a plastic corrugated pipe
288 of wall thickness 0.02 m, thermal conductivity $200 \text{ W m}^{-1} \text{ K}^{-1}$ and a diameter of 1 m. Soil
289 specification was ‘heavy and damp’ and average soil temperature was set at 12°C . The model
290 does not consider the energy requirements of a fan to draw air through the earth tube, but purely
291 takes minimum fresh air requirements of the pigs to dictate the air flow. The effect of
292 incorporation of the earth tube on time spent in each of the seven operative temperature bands
293 was modelled for building form option ‘h’ to produce the final option, namely the ‘SPaTHE’
294 design.

2.3.4 Daylight

Daylight is not the same as sunlight. Direct sunlight through glazing can have a large effect on thermal comfort within an internal environment, depending on façade orientation, amount of glazing and height. However, in steady state daylight design, façade orientation has no effect on the amount of daylight entering the internal environment; instead steady state daylight design is purely affected by amount of glazing, height and shading (BSI, 2008), combined with a cleaning factor of the glazing, which in this case was set at 0.8. Thus, a 20% reduction in light transmittance through the glazing was applied due to the glazing potentially becoming dirty during the twelve-week growing period for each batch of pigs. Any change made in optimum building form (section 2.3.2) that alters the amount of glazing will change the internal environment and the daylight entering the space. This variation in daylight entering the space has a direct influence on the annual energy consumption for lighting. Daylight design was therefore also investigated within the DesignBuilder software model to illustrate any potential energy consumption savings (assuming a typical UK energy cost of 0.14€ per unit), while adhering to best available techniques for intensive rearing of pigs (Santonja *et al.*, 2017). Each room was modelled with 16 identical 34 W linear LED luminaires providing 4300 Lumens per luminaire, with 16 hours of light per day. Daylight dimming was introduced to both the existing building and the SPaTHE design for direct comparison over a full production year, to provide, whenever possible, a maintained lighting level of 100 lx on the floor of the finishing room.

2.4 Validation of the model

Validation of the model has two components. Firstly, validated software was used. The EnergyPlus component of the DesignBuilder model is funded by the U.S. Department of Energy (DOE), which requires that three types of tests, namely analytical, comparative and executable, are carried out with each new release to stay within international regulations.

Secondly, the model built using the software and input data used was validated by comparing internal room temperature estimates from the model with on-site temperature data, gathered from sixteen temperature sensors located in each of two test rooms in the existing building in Staffordshire. These real data were continuously monitored for a period of twelve months and downloaded for subsequent analysis. When temperature estimates from the model were compared with collected on-site, the match appears to be a relatively close one as can be seen in Figs. 5a & 5b which show data for both a typical day and a relatively warm day respectively.

Fig. 5a. Comparison of internal temperature recorded from on-site sensors in an existing building of conventional design in the UK with equivalent estimates from the model for moderate days over a 5-day period

Fig. 5b. Comparison of internal temperature recorded from on-site sensors in an existing building of conventional design in the UK

with equivalent estimates from the model for relatively warm days over a 5-day period

3 Results

3.1 Effect of optimised building form on operative temperature

Whilst 33 alternative building forms in total were considered, in some cases the building form resulted in either a marginal impact on the temperature bands or, in some cases, even resulted in a deterioration in building performance from the previous building form. Hence Fig. 6 shows the results for just seven selected building forms that were part of the iterative design process to optimise the environment. With the exception of options 'b' and 'c', the optimised building designs generally improved the internal environment for the pigs. In contrast to the other designs, pigs housed in options 'b' and 'c' spent fewer hours within the optimal temperature range (of ≥ 19 to $< 22^{\circ}\text{C}$), and spent more time above 25°C than for the existing building. Options 'd' and 'e' resulted in a reduced number of hours spent in the peak overheating range (≥ 28 to $< 33^{\circ}\text{C}$) of -26 and -57 hours respectively. However, these two options also led to reductions in the time spent at the optimum temperature range (≥ 19 to $< 22^{\circ}\text{C}$) of 243 and 62 h compared to the existing building. The remaining building options 'f, g and h' resulted in increasing time spent within in the optimal temperature range (≥ 19 to $< 22^{\circ}\text{C}$) of 69, 106 and 105 h, respectively, with a reduced number of hours spent in the peak overheating range (≥ 28 to $< 33^{\circ}\text{C}$) of 136, 189 and 183 h respectively, compared to the existing building. The results for option 'h' indicate that the pigs would potentially spend 661 fewer h y^{-1} below 19°C , thus too cold, and 102 fewer h y^{-1} above 28°C in conditions that are too hot.

Fig. 6. Estimated annual amount of hours finishing pigs from 20 to 100 kg will spend within the existing building of conventional design and optimized forms (b to h) between the temperature ranges of 9°C to 33°C. For a 12-week period with 5 d cleaning, four times a year

3.2 Effect of including an earth tube on operative temperature

Figure 7 illustrates the impact of including an earth tube as an addition to the optimum building form (i.e. the SPaTHE form) on time spent in different temperature zones compared to the existing building and option 'h' for finishing pigs from 20 to 100 kg over a 12 week period with 5 d between the four batches per annum. Introduction of the earth tube dramatically increased the estimated amount of time the pigs spent within in the optimum temperature range (≥ 19 to $< 22^{\circ}\text{C}$), by 2222 h and 2117 h respectively compared to the existing building and the optimised building form without the earth tube (i.e. option 'h'). Whilst estimation of ventilation energy costs used to operate the SPaTHE concept building are outside the scope of the current study, it was estimated that the overall impact of adding an earth tube compared to the existing conventional ventilation design is minimal. Although ventilation requirements may increase to

draw air through the earth tube, the fact that internal conditions are expected to be closer to those required by the pigs means that the fans will potentially run at a lower level during the year.

Fig. 7. Estimated annual amount of hours finishing pigs from 20 to 100 kg will spend within the existing building of conventional design, one of improved design (form 'h') and the SPaTHE design with an underground earth tube at a temperature range of between 9°C to 33°C (results are for a 12-week period assuming 5 d cleaning, downtime four times a year)

3.3 Effect of SPaTHE design on peak operative temperatures

The results also suggested that, when the external temperature is 28°C, the SPaTHE design leads to a 3.4°C reduction in the peak summer internal operative temperature compared to the existing building. Comparison also indicated an increase of 1.15°C in the minimum winter internal operative temperature when the external air temperature is -5.4°C.

Figure 8 indicates the effect of the estimated 3.4 °C reduction in internal temperature during the peak 28 °C external air temperature on the pigs' heat output transferred into the internal environment. The cooler conditions shown in the SPaTHE model compared to the existing building show an increase of 13 W m⁻² of the pig heat output transferred into the environment. This cooler environment allows the pigs to transfer body heat into the environment during the hottest period, of approximately 3250 W per room.

Fig. 8. Occupancy heat output transferred into the environment, for 292 growing pigs in a 10-day summer period in the existing model and the SPaTHE model

3.4 Effect of SPaTHE design on daylight penetration

Figure 9 shows a dramatic increase in the average daylight illuminance levels for the SPaTHE design, namely 122 lx compared to 6.3 lx for the existing finishing room. In turn, this lead to reduced energy consumption for lighting, as shown in Table 4. The estimated lighting energy consumption for the existing finishing room was 1757 kW h y⁻¹ compared to 610 kW h y⁻¹ for

the SPaTHE design. In the SPaTHE design, daylight contributed to 60.6% of the overall required annual lighting energy consumption compared to just 5.5% for the existing finishing room (assuming a glazing cleaning maintenance factor of 0.8). Although the glazing on the north and south facades are of a similar size, approximately 9 m², it can be seen from **Error! Reference source not found.**⁹ that there is a higher floor illuminance level for the north side of the room than the south, namely 200 lx compared to 100 lx.

Table 4 indicates that a higher contribution towards the lighting energy consumption is provided by the north glazing compared to the south glazing of 531 and 408 kW h y⁻¹

Fig. 9. Representation of light intensity at floor level for the existing building of conventional design with 1 m² of glazing on the north façade and the SPaTHE building with 18 m² of glazing over the south and north façade (measured by illuminance isolines lux levels)

Table 4. Daylight energy evaluation savings for a room in the existing building of conventional design and the SPaTHE finishing concept design

	Portion (%)		Energy consumption/provision (kW h y ⁻¹)		Light on floor area (m ²)	
	Existing	SPaTHE	Existing	SPaTHE	Existing	SPaTHE
North wall glazing	5.46	34.27	101.50	531.28	17.85	94.50
South wall glazing	0	26.33	0	408.22	0	77.00
Artificial light required	94.58	39.40	1757.14	610.95	235.55	81.90
Daylight provided	5.46	60.60	101.50	939.50	17.85	171.50

410

411 Assuming an energy cost of 0.14€ per unit, the increased amount of daylight penetrating the
412 SPaTHE room (60.6% versus 5.5% in the existing room) contributed to an approximate saving
413 in energy cost of €156 per annum on lighting alone. For the existing pig production site with
414 16 finishing rooms all of the same design, this would equate to a saving of around €2487 per
415 annum.

416 **4 Discussion**

417 The aim of this study was to investigate the potential for an innovative passive building design
418 to improve the welfare and feed efficiency of finishing pigs, by increasing the time that pigs
419 spend in the optimum temperature zone whilst minimising the need for supplementary heating
420 and cooling during annual peak low and high external temperatures. Once the optimum
421 building orientation, form and glazing specification had been established, the additional impact
422 of an underground earth tube to condition the incoming fresh air was explored. The intended
423 outcome of this improved design was to increase the number of hours that pigs' spent within
424 the optimal zone of ≥ 19 to $< 22^{\circ}\text{C}$, combined with ≥ 16 to $< 19^{\circ}\text{C}$ for the later stage finishing
425 pigs and ≥ 22 to $< 25^{\circ}\text{C}$ for the earlier stage finishing pigs, and reduce time spent in high and
426 low-temperature zones of ≥ 9 to $< 16^{\circ}\text{C}$ and ≥ 25 to $< 33^{\circ}\text{C}$ respectively.

427 **4.1 Effects of optimum building form**

428 Figure 6 shows how the adoption of a flat roof building form (option 'b' shown in Fig. 4),
429 increased the amount of direct solar gains throughout the year compared to the existing
430 conventional building form. The design will be a warming of the space throughout the year,
431 with an increase in time spent overheating in summer and a reduction in time spent within
432 cooler temperatures in the winter months. Building form 'c' amplifies this increase in internal
433 temperature, probably due to the further increase in roof surface area and another southern

façade located in the middle of the roof. Introducing the pitch back to the south-faced roof, along with a slightly lower pitch and/or a flat roof on the north façade (options ‘d, e & f’ respectively in Figure 4), which enables partial shading to the north-facing roof, increased the time spent in the optimal temperatures band i.e. 19°C to 22°C, and reduced overheating in the summer but yet increased time spent in the cooler temperature bands during the winter periods. By introducing an overhang onto the south façade glazing and a buffer zone to the north facing roof (options ‘g & h’), the extent of overheating was reduced, hours spent at the cooler temperatures were reduced whilst time spent in the optimal temperature bands was increased.

In a previous paper, Jackson *et al.* (2017) illustrated how greater thermal mass and insulation of a pig building could improve the quality of its internal environment for the finishing pigs, especially around the high and low extreme temperature bands. Jackson *et al.* (2017) calculated that introduction of greater insulation to the existing pig building model reduced the amount of time pigs spent below 19°C by 1115 h y⁻¹, while the optimised building form ‘h’ in the current paper reduced this by 661 h y⁻¹. However, the optimised building form ‘h’ performed better by increasing the number of hours spent in the optimal zone by 105 h y⁻¹ and reducing the hours spent overheating by 183 h y⁻¹, compared to the insulated and thermally improved version of Jackson *et al.* (2017).

Inclusion of an earth tube to design ‘h’ to produce the SPaTHE design (Fig. 7) resulted in a major improvement in conditions for the pigs compared to both the Jackson *et al.* (2017) model and the optimised building form model, with time spent in the optimum operative temperature range (≥ 19 to $< 22^\circ\text{C}$) increasing by approximately 3 months (2222 and 2117 h, respectively). The respective decrease of 3.4°C and increase of 1.15°C for summer and winter peak internal temperatures in the SPaTHE concept design suggests this would be a substantial benefit to the pigs throughout the peak summer external temperatures, which can compromise their welfare and can have a profound effect on feed conversion rates (St-Pierre *et al.*, 2003; Renaudeau *et*

al., 2011; Gabler and Pearce, 2015). The impact of including the underground air duct is also in agreement with Lee and Strand (2008), who indicated that earth tubes have a greater capacity for providing cooling rather than heating an internal space.

4.2 Metabolic heat output in the concept design

Figure 8 shows the effect of the optimised building and the introduction of an earth tube on the pigs' heat output transferred into the internal environment throughout the four batches during the year. It can be seen that the fluctuation of the pigs' heat output (W m^{-2}) transferred into the internal environment is a direct effect of the changes in internal environmental temperature. The diurnal variation was reduced in the SPaTHE design, with the heat output of the pigs transferred in winter and summer months decreasing and increasing respectively compared to the existing building. This reduction in diurnal variation of pigs' heat output transferred into the environment is a direct result of an increased amount of time that the SPaTHE internal operative temperature remains within, or closer to, the optimal zone compared to the existing building. This separation of the extreme external conditions and the diurnal external temperature variation from the internal environment provides closer control of the internal operative temperature by the ventilation system and will be future-proofed and less affected by climate change (Rotter and Geijn, 1999). A direct result of the summer external environment having a reduced impact on the operative internal temperature allows for an increased heat output transferred into the environment. This higher temperature difference (ΔT) between the operative temperature and the pig's internal body temperature in the summer periods will encourage the pigs to consume more food throughout the warmer external periods. Likewise, the reduction, albeit modest, in ΔT in winter months compared to the existing building will likely lead to improved feed conversion rates (Nienaber *et al.*, 1989). This improvement in the ΔT between the internal environment and the pigs' body temperature can also typically be viewed in the lying patterns of pigs, where the pigs can be observed spending less time huddling

for warmth in cold weather or separating and wallowing to cool their core temperature during high internal operative temperatures (Nasirahmadi *et al.*, 2015). Figures 8 and 10 show that the SPaTHE design allows for the pigs to potentially transfer a greater amount of body heat into the environment in the summer periods than the existing conventionally-designed building, rather than having to rely on finding cooler areas of the pen in which to lie i.e. against stainless steel items such as feeders and under dripping water nipples or even in dunging areas.

Fig. 10. Annual occupancy heat output, for finishing pigs of weights from 20 to 100 kg in a 12-week period in the existing conventionally-designed building and the SPaTHE model, assuming a period of 5 days between batches

4.3 Daylight penetration in the concept design

It is likely that poor daylight penetration could occur due to the incorrect location and size of glazing, increasing the extent of overheating within a space is foreseeable. However, as shown throughout this modelling process, glazing design can be used to improve the number of hours that a given space will be within a required temperature range. Daylight penetration also has

the potential to provide a better environment for the pigs to sleep, eat and dung. The results illustrated in section 3.4 show that the south side of the pen space is darker than the north, therefore the pigs will have a tendency to sleep in this area rather than dunging in it (Hacker *et al.*, 1973) Taylor *et al.* (2006) demonstrated that finishing pigs had no preference between illuminance levels of <4, 4, 40 and 400 lx while actively eating and drinking, but did show a preference for dunging in the more brightly lit areas of the pens.

4.4 Potential benefits of the concept design on time management

With the introduction of the service void above the room for finishing pigs, the SPaTHE design has the facility to remove all services, i.e. water, electric cables and feed tubes, from the working area. In this innovative design, lighting is recessed in the ceiling and the pitched roof of the existing room has also been replaced with a flat roof, both of which have the potential to reduce the amount of time required for cleaning between batches of pigs. Currently, the existing 8 finishing rooms work on a 5-day change over between batches, of which an estimated 12 h are set aside for washing each room (thus 768 hours per annum for the whole building). Discussion with pig producers suggests that such changes to the internal surfaces as proposed in the SPaTHE design could reduce the cleaning time by approximately 3 h. This would benefit pig production for the existing site of 8 finishing rooms, with four batch changes per year per room, by reducing labour for washing by 192 h y⁻¹ and in turn lead to a greater use of the building and potentially a reduction in housing cost.

4.5 Potential for further cost savings in the concept design

The main cost savings from the SPaTHE concept design discussed in this paper are based around improved feed efficiency for pig growth, due to the internal environment matching or being closer to the animals' thermoneutral temperature zone for a greater amount of time during the year. However, there are potentially more subtle savings to be included, such as the

estimated reduction in manual labour for cleaning the rooms of 8 d (192 h) per annum, which would also have an associated approximate reduction of 192 h in water use and electricity consumption per annum from running the jet washer(s). Moreover, the energy savings due to daylight dimming, shown in the results for increased glazing and the improved daylight penetration, do not take into account further cost savings that would arise from the expected longer lamp life and reduced labour required to replace failed lamps.

4.6 Further design opportunities

In this study, the building materials used in the SPaTHE building were the same as in the existing building to reduce the potential for increased build costs associated with introducing new materials, while the earth tube was modelled at a similar depth (3.5 m) to typical UK installation for slurry holding tanks. This gives the SPaTHE design a greater chance of being built as a prototype. Once built, this prototype could be used to confirm the model outputs and the potential effect on sustainable intensification, welfare, feed conversion efficiency, cleaning times and energy costs, before the SPaTHE finishing building could be adopted by the pig industry in the UK, and subsequently adapted for other countries.

Daylight penetration on the north façade glazing of the SPaTHE was designed to serve a second purpose, namely to potentially provide a downdraft directly over the slatted dunging area. Providing a specific dunging area that is brighter and cooler is likely to be more attractive to the pigs than the remaining surrounding area, and this could encourage pigs to dung in this specific area, maintaining the hygiene in other parts of the pen, which is important for maintaining pig welfare. A small percentage of the incoming air (5 to 10%) could be extracted from the dunging area directly into an air scrubber before this contaminated air mixes with air from the remaining sleeping and eating areas, and therefore the larger percentage of extracted

air which enters the surrounding external environment. Such an approach would provide an energy-efficient way to remove any potential aerial contaminants from the internal atmosphere, maintaining air quality for the benefit of pig health and for the humans working and living in close proximity to the pig production site.

As previously mentioned, Hacker *et al.* (2009) argued that passive design should always be investigated before sustainable solutions are incorporated. The SPaTHE design therefore represents a substantial incremental improvement in agricultural passive building design, to which further sustainable technologies could in time be added to enhance the building.

Unfortunately, in the current study, there has not been scope to consider a detailed analysis of the investment cost of the SPaTHE design. Whilst the building materials and the floorplan are broadly the same as the existing conventionally-designed building, the degree of novelty/complexity may mean that the SPaTHE concept design may cost more to build. During the design process of the SPaTHE concept, costs were considered as a secondary design criterion, for example the potential for a reduced slatted dunging area will result in lower construction costs for the slurry pit which could offset the installation of the underground earth tube. The southern-orientated roof is designed in such a way as to promote easy integration of solar thermal, photovoltaics and rainwater capture, without the need to interrupt the pig production process. The introduction of the service void allows for mechanical and electrical services to be installed in a clean and accessible environment. Finally, the intention of the SPaTHE concept is for the building to be supplied as a modular design, with each room capable of holding 250 to 300 finishing pigs, so that the number of rooms can adjusted to suit the particular size of farm. The service voids for each room are connected, thereby allowing for the potential for heat recovery systems to be applied to the extract air. This would allow for heat recovered from exhaust warm air from rooms containing large pigs to heat rooms holding smaller pigs. Clearly this requires further research, e.g. to consider possible savings in energy

use and resource efficiency using SPaTHE buildings of different sizes and in different locations around the world.

5 Conclusions

In this study a DT model was used to evaluate a novel passive building concept design for finishing pigs that includes changes in building form and orientation, along with daylight design combined with ground heat exchange. The results indicate that, compared to a conventionally-designed building with a fully slatted-floor, the SPaTHE design has the potential not only to improve resource efficiency and the welfare of pigs housed therein, but also to reduce energy costs associated with pig production. Empirical confirmation of such improvements, however, would require the construction of a prototype SPaTHE building and its operation and monitoring over a number of production cycles. Nevertheless, results suggest that the SPaTHE finishing building passive design should be able to cope adequately with current and projected future changes to the external environment while meeting the thermal environment needs of finishing pigs.

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