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Application of dynamic thermal engineering principles to improve the efficiency of resource use in UK pork production chains

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Abstract. *This paper investigates the potential for incorporation of human commercial building design modelling into the pig production industry. During the last decades pig building design has relied heavily on building manufacturers compared to human commercial buildings that regulate standards to improve the sustainability of the building. Thus, the aim of this paper was to gain a greater understanding of the design requirements for sustainable forms of pig housing, which could potentially improve the welfare of the pig and promote greater resource use efficiency. Part of an existing mechanically ventilated UK pig production building, which represents three adjacent fully-slatted units each capable of holding approximately 292 pigs and measuring approximately 18m x 14m, was used as a basis to create a dynamic thermal model of the building. The model takes into account the possibility of future rises in environmental temperature and the effect of this climate change on building performance and pig growth, feed efficiency and welfare. The results of the model showed that as the finishing pigs increased in size they have the potential to be subject to increasingly poor indoor air quality, during the winter months. The model also shows that improving the thermal properties of the building not only helps with reducing the amount of time that the pigs could potentially spend at extreme low temperatures, by approximately 1115 hours (46 days), but can also help with reducing the number of hours the pigs spend above 26ºC during the summer months, by approximately 8 hours.*

Keywords. *pig building, ventilation, thermal conductivity, sustainable, modelling.*

1.0 Introduction.

Pork is the most consumed meat in the world, with animal feed accounting for 62% of the cost of pig production (BPEX, 2010). For UK producers, feed costs reached a record high in 2013, amounting to £1.06/kg carcass produced, although this decreased by 19% to £0.85 p/kg in 2014 (AHDB, 2014). To be efficient, producers must provide an environment which allows pigs to exhibit their genetic potential to convert feed into muscle growth. Animals need to be kept comfortably within their thermo-neutral zone, thus avoiding energy waste in maintaining body temperature (Close, 1987), and in highly hygienic conditions, thereby avoiding inefficient protein utilisation from immune system activation (Williams *et al.*, 1997).

Direct energy usage in agriculture is relatively small, representing approximately 1% of the UK's energy use (DECC, 2009). However, much of the energy used in pig production is not represented in energy statistics since it is inherent in the food consumed by the pigs. It has been estimated that feed inefficiency can be as much as 30% of feed intake as a result of suboptimal building design (Close, 1978), as illustrated by Lopez *et al.* (1991a) who reported that pigs kept at cold temperatures were 43% less efficient than those kept at an optional temperature. These potentially inappropriate living conditions for the pigs can lead to increased production costs through reduced feed efficiency and increased veterinary charges. Production costs can escalate across the different stages of growth, since pigs require very different environments for adult sows during pregnancy and lactation, and for their progeny through suckling, weaning, and finishing for meat production.

During the last decades, pig building design has relied heavily on the experience of building manufacturers rather than regulated standards. This contrasts with the design of commercial buildings for humans, where substantial advances have been made in improving standards in terms of ventilation, heating and cooling systems for sustainable buildings (e.g. HMSO, 2010)

1.1 Limitations of current UK pig building design

For buildings in the UK, on the few occasions when the external temperature is higher than the internal setpoint temperature (i.e. the intended internal temperature of a space as specified on the control system), approximately 3% of the year, no amount of internal air changes will be able to reduce the internal temperature to the intended setpoint. Thus the thermal conditions inside the building will always be too hot, showing a degree of lift above the prevailing external temperature. At the other end of the scale, in the winter months when temperatures in the UK fall below 0˚C and ventilation rates are reduced to the minimum fan speed limit, this can result in the building being prone to conditions which are too cold and of an inappropriate indoor air quality (IAQ). Both these scenarios will have a detrimental effect on feed efficiency and the well-being of the pig and affect the energy efficiency of the overall pig production programme.

In these circumstances two options are available to reduce the internal extreme high and low temperatures in a mechanically ventilated building. One option is to introduce mechanical air conditioning to control the internal setpoint, which potentially would have a detrimental effect on the overall energy consumption and sustainability of pig production. The second option would be to introduce a passive design into the building structure to reduce heat loss in winter and external heat gains in summer. This can be achieved by increasing the thermal insulation and thermal mass of the building. The introduction of more thermal mass into the building fabric could potentially benefit the internal environment in the summer as it will slow the penetration of direct solar energy gain through the surfaces and potentially help stabilize and reduce the internal extreme high temperatures. This slowing down of solar gain through the building, as a 'time lag', can help with internal temperature control simply by storing the solar energy in the thermal mass of the building fabric, rather than releasing the solar energy into the internal space straight away. The energy stored can then be released into the external environment when the external temperature decreases later in the day, therefore restricting any unwanted solar heat gains into the internal space. Introducing a high amount of thermal insulation will also reduce the amount of internal heat gains that escape from the internal space to the external environment in the cooler winter months; this will potentially keep the internal temperature higher, which could also help in providing more fresh air into the space during winter, thereby reducing levels of ammonia and CO_2 produced by the pigs.

If these passive designs are to be explored, the key factor is infiltration. The building has to be relatively air tight or the passive design fails, due to the external environment simply by-passing the passive infrastructure by leaking into the internal environment. While the thickness of the insulation also needs to be considered in terms of capital cost of the building, as there will be a point where the cost of the insulation will exceed any potential energy savings (Axaopoulos *et al.*, 2014).

Thus, the aim of this paper was to incorporate human commercial building design modelling into the pig production industry in order to gain a greater understanding of the design requirements for sustainable forms of pig housing so as to improve the welfare of the pig and promote greater resource use efficiency.

2.0 Materials and Methods

Figure 1 and Figure 2 represent a section of a finishing pig building at an existing pig production site in Staffordshire (UK), a dynamic thermal model of which was created using DesignBuilder software (V4.2.0.054, EnergyPlus 8.1, DesignBuilder Software Ltd, Stroud, UK). The scaffolding lines around the finishing building in Figure 1 represent the annual path of the sun for that specific location. The dynamic model takes into account thermal radiation, conduction and convection between all the building elements in conjunction with internal and external environment conditions, as well as occupancy density, air flow and solar gains into the building. The model also takes into account the possibility of future rises in environmental temperature and the effect of this climate change on building performance and pig growth, feed efficiency and welfare in the years 2030, 2050 and 2080. These future weather files, which are location-specific and are available for 2030, 2050 & 2080, were used as the basis for the research of Du, Underwood & Edge (2012) into future air-conditioning loads for commercial buildings.

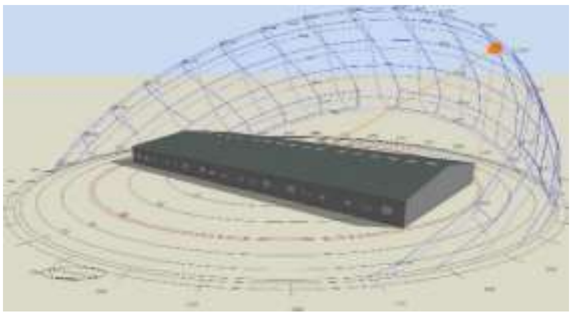

Figure 1. Dynamic thermal model created in DesignBuilder to represent three adjacent units within a finishing pig building (each unit is capable of housing approximately 292 finishing pigs).

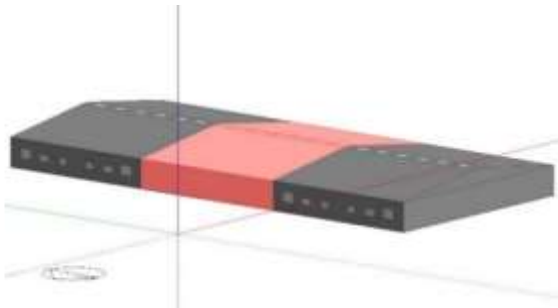

Figure 2. The central unit (shown in red) of the finishing pig building which was selected since it takes into account all other surrounding internal areas.

All results reported and discussed in this paper relate to one central unit of the pig finishing building highlighted in Figure 2. The model represents three part-slatted rooms, capable of holding approximately 292 pigs. Each room is approximately 18m x 14m with a service corridor running outside the rooms along the length of the building. The central unit was chosen to model since it takes account of all other adjoining internal environmental influences. The 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 a respective volume flow rate at 50 Pa of 16800 and 9400 m^3/h per fan. The fans are located in the side wall opposite to the service corridor, operated with a step controller, with air entry through a controlled ridge opening to maintain a 5 m/s inlet jet along the ridge of the ceiling.

Amongst other requirements of the building design such as appropriate feed, floor structure and space requirements, equilibrium of heat is required between the pig and its environment to improve the welfare of the animal and promote greater resource use efficiency. [1]Solar energy gain (q_{so}), heat gain from the pigs (q_s) and heat loss through the building fabrics (q_w & q_f) can be seen in Equation 1.1 and Figure 3. These provide a visual explanation of the energy required to keep the pig at a steady state, which can be explained as building elements that remain unchanged over a period of time so as to, and will produce optimum productivity. Since the equation is balanced, it demonstrates that every aspect of the building mechanisms and external weather conditions will impact on providing an environment for optimum productivity.

$$Gains = Losses \text{ is } \; q_s + q_m + q_h + q_{vi} = q_w + q_f + q_e + q_{vo} \qquad \text{Equation 1.1}$$

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

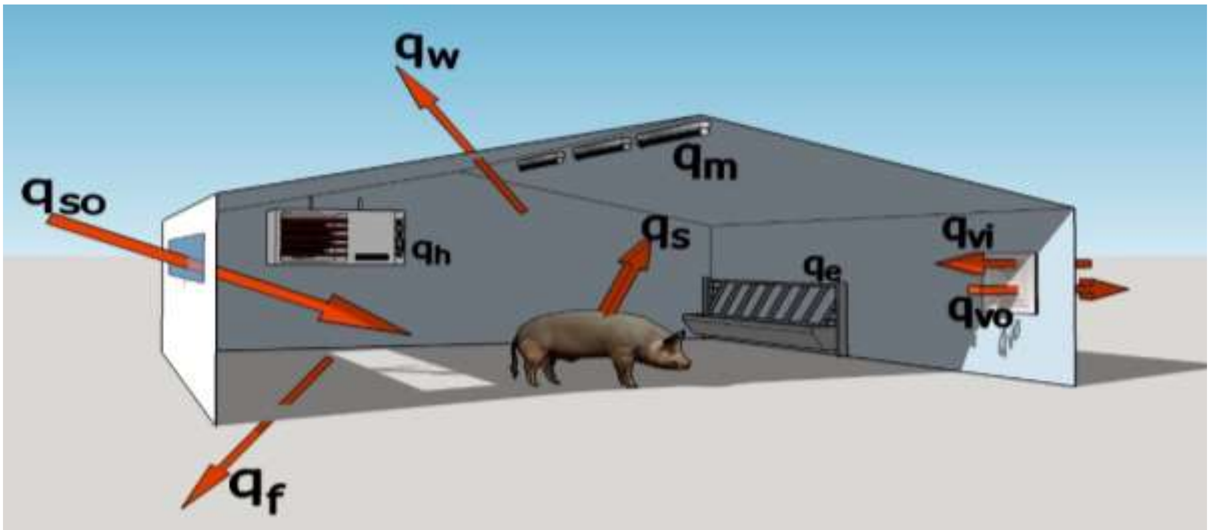

Figure 3. Contributors to a sensible energy balance in an animal housing building; adapted from Albright (1990)

2.1 Estimation of sensible heat production from the pigs (q_s) and sensible heat to latent heat (q_e).

Figure 4 provides estimates of how there is a steady increase in total, sensible and latent heat production (THP, SHP & LHP, respectively) as pigs grow from 20 to 100 kg bodyweight, taking a period of approximately 16 to 18 weeks. The graph shows constant metabolic rates for 292 finishing pigs at 20°C and how they will produce approximately 32kW of sensible heat (q_s) just before slaughter, assuming typical levels of feed intake, compared to only 13kW when they were first introduced into the space (Albright, 1990). Although SHP is connected more closely to body surface area, body surface area is problematic to measure. Therefore heat production proportional to bodyweight can be found by multiplying bodyweight to the power of 0.734 (Albright, 1990).

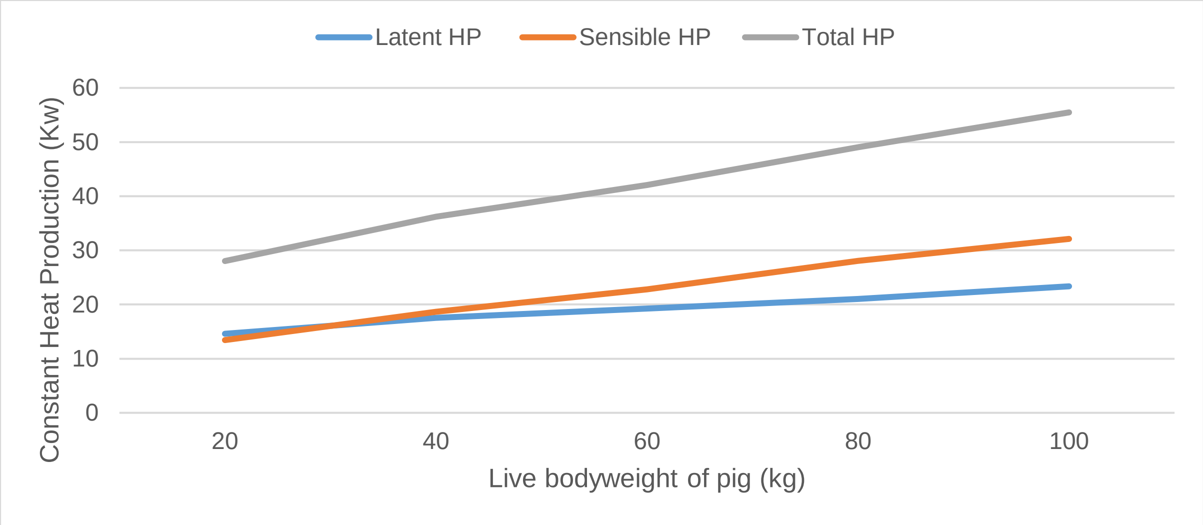

Figure 4. Constant metabolic rates for 292 finishing pigs maintained at a 20ºC internal building temperature, adapted from Albright (1990)

2.2 Estimation of minimum fresh air requirements for indoor finishing pigs

Guidance on indoor air quality with respect to minimum fresh air requirements for finishing pigs varies 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 standard figure to use within the dynamic model. The three sources were, British Standards 5502: BSI (1990), ASABE Swine and equipment handbook MWPS-8 (1983), and English *et al.* (1988). From the latter reference, two values were obtained: the 'minimum' fresh air requirement, which pig producers found difficult to achieve in practice, and so a second value was created, namely the 'acceptable' requirement for fresh air. The figures taken from (MWPS-8, 1983) are based on the cold weather scenario. Table 1 shows how these average fresh air requirements were extrapolated into a measure of litres of fresh air per second per pig for direct input into the model.

Table 1. Current and historical estimates of fresh air requirements (l/s) for finishing pigs weighing between 20 and 100 kg bodyweight

Source	Weight of pig (kg)	Volume of fresh air (m^3/h)	Volume of fresh air (l/s)	Average value used in the model (l/s)
BS5502, (BSI, 1990)	20	5	1.39	
English et al (1988) - Minimum rate	20	7.5	2.08	**1.50**
English et al (1988) - Acceptable rate	20	4	1.11	
ASABE, MWPS-8(1982)	13.60 to 34		1.42	
BS5502, (BSI, 1990)	40	8	2.22	
English et al (1988) - Minimum rate	40	15	4.17	**2.51**
English et al (1988) - Acceptable rate	40	8	2.22	
ASABE, MWPS-8(1982)	34 to 68		1.42	
BS5502, (BSI, 1990)	60	10.5	2.92	
English et al (1988) - Minimum rate	60	22.5	6.25	**3.95**
English et al (1988) - Acceptable rate	60	12	3.33	
ASABE, MWPS-8(1982)	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(1982)	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(1982)	100+		4.72	

2.3 Selection of Test Reference Year (TRY) weather data

Human UK building dynamic modelling 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, and Design Summer Year (DSY) data which are generally used for assessing potential overheating within the space. Kershaw *et al.* (2010) compared 15 different building types from light weight studio flats to heavy-weight offices, including buoyancy driven ventilated offices and fully air conditioned offices. Analysis of the results showed that using DSY constantly under estimated the extent of overheating inside the building, which could potentially lead to higher than expected levels of overheating within the building and reduced thermal comfort for occupants. 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 test reference year (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. Future predicted weather data of 2030, 2050 and 2080 are available for the Birmingham location via the project 'PROMETHEUS', which was an Engineering and Physical Sciences Research Council (EPSRC) funded project involving a collaboration between Exeter University, the Met Office, the Royal Institute of British Architects (RIBA), the Chartered Institution of Building Services Engineers (CIBSE) and the Building Research Establishment (University of Exeter, 2008). One of the aims of PROMETHEUS was to freely provide future reference year weather data for use in dynamic models which could categorise the problems new buildings will face as a result of climate change and so assist the building industry adjust to the challenges of environmental change. In the current project, the future weather files used within the model were based around a medium-low Pattern Scaling Factor (PSF). Figure 5 shows the twelve future weather patterns available, which is the basis of the work of Hacker *et al.* (2009) on the use of climate change data for building simulation modelling. Low, medium-low, medium-high and high represent an estimate of the scale of increase in external temperature for the specific location compared to the TRY. The year 2080 medium-high has the scaling factor of 1.0, which is the reference timescale and emissions scenario, meaning any other scenarios on the timescale can be predicted from this reference.

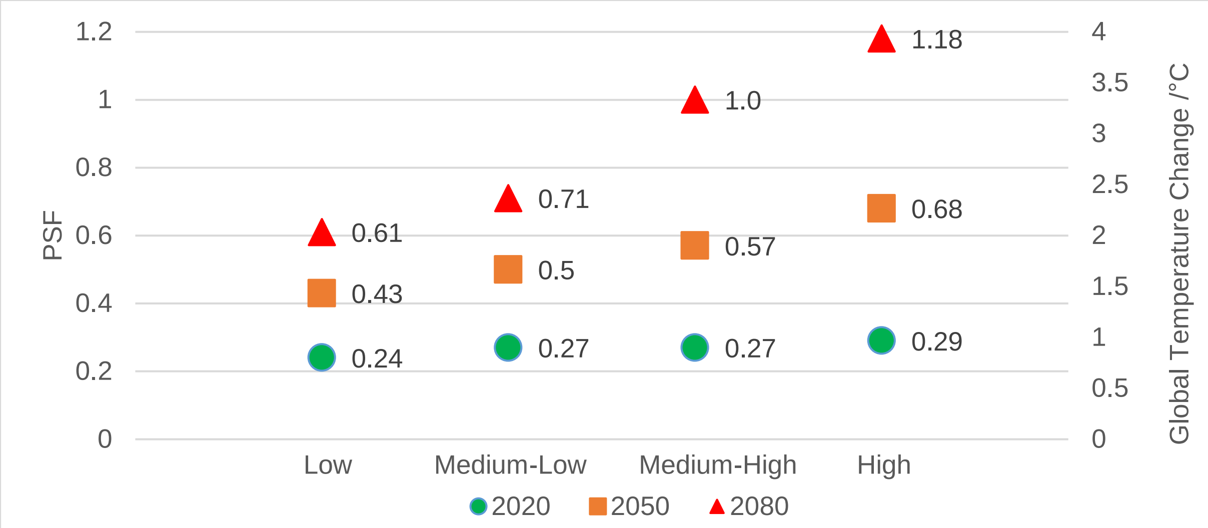

Figure 5. Pattern Scaling Factor (PSF) for predicted weather data for predicted future weather files in 2020, 2050 & 2080, adapted from Hacker *et al.* (2009)

2.4 Existing and improved passive design properties of the model

Consideration was given as to how the design of the existing building could be improved. Thus Table 2 shows the thermal properties of the existing building and an improved design. Properties of the existing building were taken from the manufacturer's installation data. The improved design not only has enhanced wall and roof U-values, but the thermal mass has also been increased to represent an external brick layer and internal concrete block layer, and the infiltration rate has been lowered to reduce the amount of air leakage in the building so that the internal environment can be better separated from external influences.

Table 2. Thermal properties of the existing building and one of an improved design.

	Thermal Mass (KJ/m^2-K)		U-Value (W/m^2-K)		Infiltration (ac/h)	
	Existing	**Improved**	**Existing**	**Improved**	**Existing**	**Improved**
External Walls	5.6	134.8	0.49	0.35		
Roof			0.52	0.21		
Windows			1.96	1.96		
Infiltration					0.7	0.3

2.5 Operation of the model, data measurement and validation

The model output is an estimate of the amount of time that pigs spend at different temperatures during the course of one year. The results are shown for two situations where the environment is modelled to be 'below' and 'above' the internal setpoint temperature tolerance of 19°C to 21°C. This provides a more detailed analysis of the actual number of hours the pigs are potentially spending outside their optimum temperature range. The results that show the 'below setpoint tolerance' have been based on the minimum fresh air requirements of 1.5, 2.51, 3.95, 4.82 and 5.97 l/s for 20, 40, 60, 80 and 100 kg pigs respectively as shown in Table 1. The 'above setpoint tolerance' results are based on the maximum amount of fresh air that the existing fans can provide for the space, which was calculated directly from the fan static pressure characteristics at 50 Pa, which resulted in a maximum volume flow rate for the four fans of 52,300 m3/h, equivalent to 14,528 l/s and 49.7 l/s per pig for the 292 pigs in the 18 m x 14 m room. When calculating the above setpoint tolerance hours, this maximum fresh air rate needs to be used for all pigs, irrespective of bodyweight, since in practice most building control systems have no adjustments for estimating pig liveweight. Instead, the system would simply require maximum fresh air when the temperature was at a critical level above the setpoint.

The model was run for each climate change scenario with and without changes to the building fabric, in order to estimate the amount of time that pigs could potentially spend at high and low temperatures outside the setpoint tolerance range. All temperatures shown on the graphs are 'operative temperatures', unless otherwise stated. Operative temperature is the temperature linked to thermal comfort of the pig since it is the result of the combined effects of mean radiant temperature and air temperature.

Validation of the model has two components. Firstly, validated software has been 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 and velocity data, gathered from sixteen temperature sensors and four air velocity sensors located in each of two test rooms on the Staffordshire unit. These real data were continuously monitored for a period of twelve months and downloaded for comparison studies. When temperature estimates from the model are compared with actual data collected on-site, the match appears to be a relatively close one as can be seen in Figure 6a & 6b which show data for both a typical day and a relatively warm respectively.

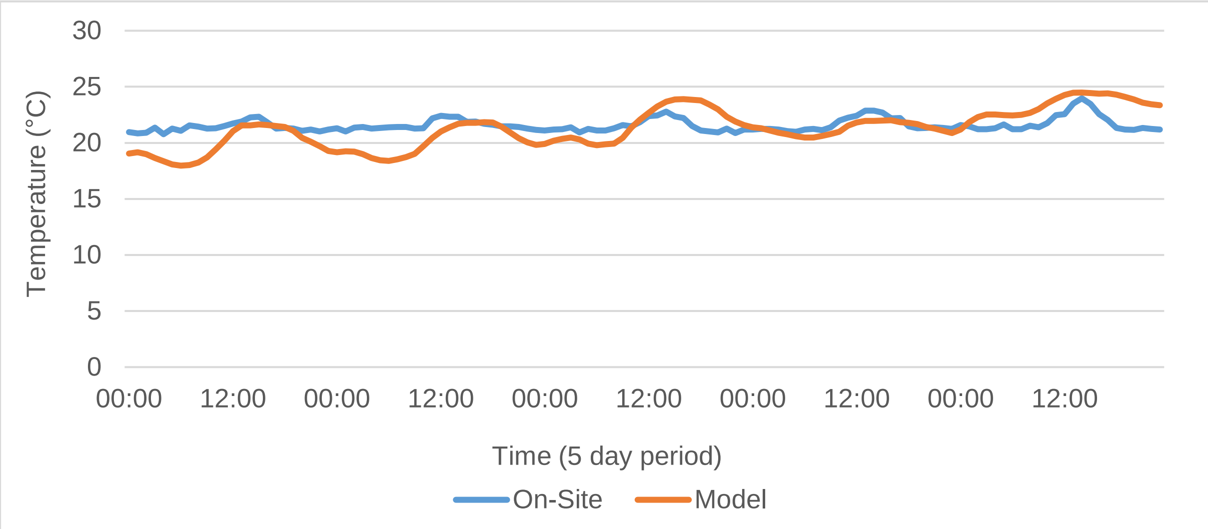

Figure 6a. Comparison of internal temperature recorded from on-site sensors with estimates from the model for a typical day (average of a 5 day period).

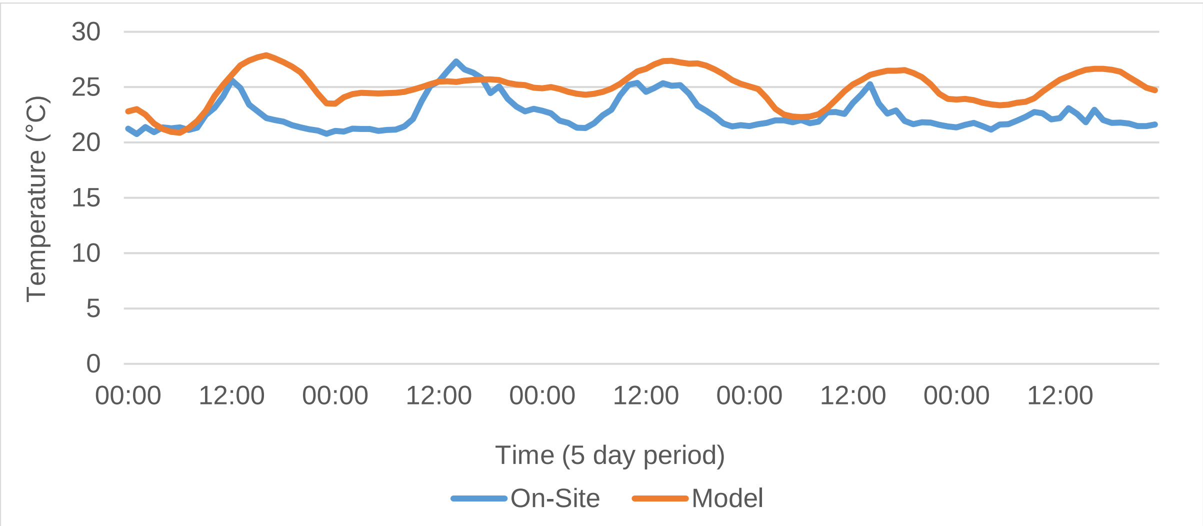

Figure 6b. Comparison of internal temperature recorded from on-site sensors with estimates from the model for a relatively warm day (average of a 5 day period).

3.0 Results

3.1 Indoor Air Quality (IAQ)

Figure 7 indicates that in the existing building as the pigs grow in size, the number of hours they will potentially spend at a temperature below the lower internal setpoint tolerance increases. This result may initially seem counterintuitive, since how can the room become subject to cooler conditions for a longer period of time even as the pigs metabolic heat production increases? The explanation is shown in Table 1; as the pigs grow so there is also an increase in the requirement for a greater amount of fresh air into the space, such that the increasing minimum ventilation rate offsets the increasing metabolic heat production. However, in reality more time at temperatures below the internal setpoint would probably not happen and instead Figure 7 provides evidence that indoor pigs have the potential to be subject to increasingly poor indoor air quality (IAQ) as they grow, rather than being subject to cold temperatures. Since the internal temperature setpoint is the overriding factor for the ventilation system controller, the controller would try and maintain the setpoint of 20ºC. Therefore, the requisite rates of fresh air shown in Table 1 may not be achieved, since the volume of incoming fresh air (l/s) would be reduced in order to maintain the internal temperature setpoint of 20ºC. These reduced rates of incoming fresh air would most likely lead to a rapid deterioration in air quality, since contaminants are potentially not being removed as intended.

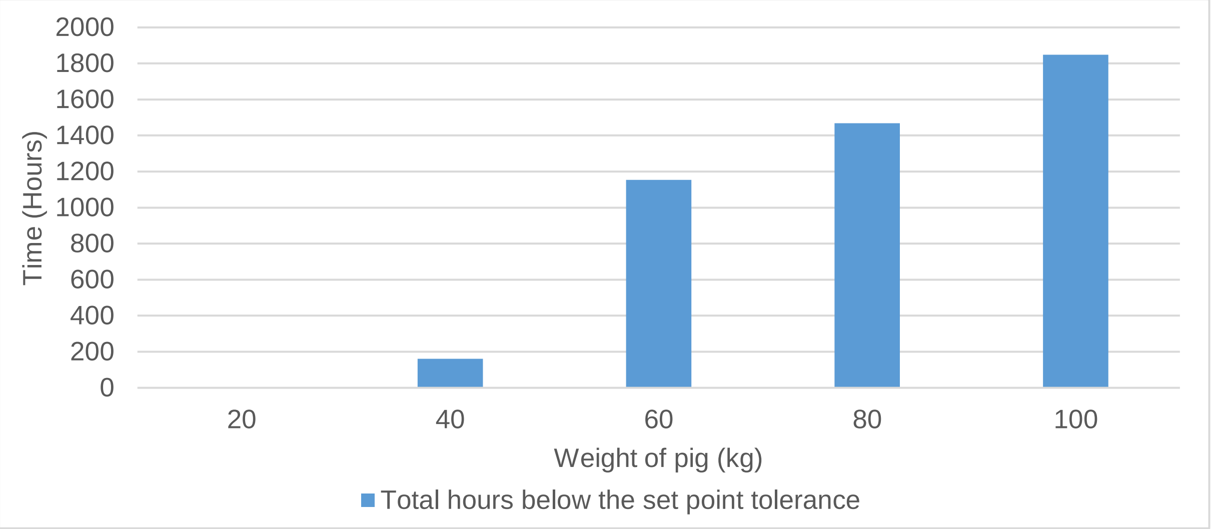

Figure 7. Estimated annual amount of hours that pigs will be kept below the internal lower setpoint tolerance temperature of 19°C in the existing unit, assuming average fresh air requirements.

Figure 8 provides a breakdown of the hours shown in Figure 7, for the temperatures below the lower setpoint tolerance temperature, showing that as the pigs gain weight the issue of extreme low temperatures is exacerbated due to the increased requirement for more fresh air. In reality, these data indicate that, unless the increased minimum ventilation rate over-rides the set temperature in the control system, as the pigs grow they are spending more time in an environment with poor indoor air quality. Figure 8 shows that in seeking to achieve the correct fresh air requirements for 60 to 100 kg pigs this would potentially bring the internal environment down to approximately 15ºC in winter. Once again, in reality the temperature controls of the room would try and maintain 20ºC, which would unavoidably provide a poor indoor air quality for the larger pigs through reduced supply of fresh air.

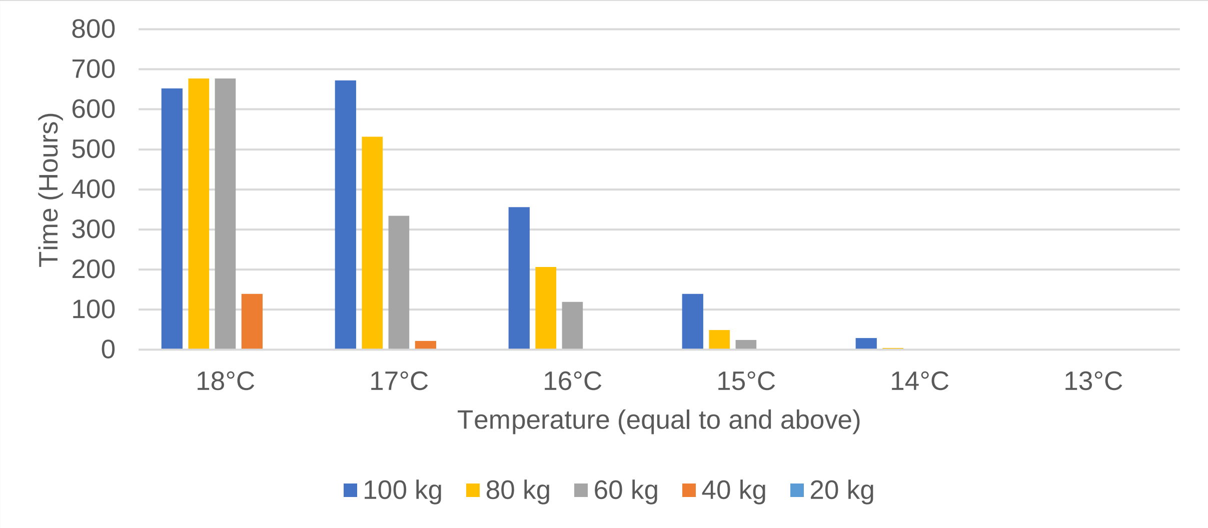

Figure 8. Breakdown of the annual estimated amount of hours 292 pigs of weights between 20 and 100kg spend below the lower setpoint tolerance temperature of 19ºC, assuming average fresh air requirements.

3.2 Maximum fresh air capacity

Assuming maximum fresh air capacity, Figure provides evidence that indoor pigs in the existing unit have the potential to be subject to increasingly high operative temperatures as they grow. This is due to a combination of internal heat gains and external environmental influences, namely solar heat gains and infiltration quickly penetrating though the building fabric.

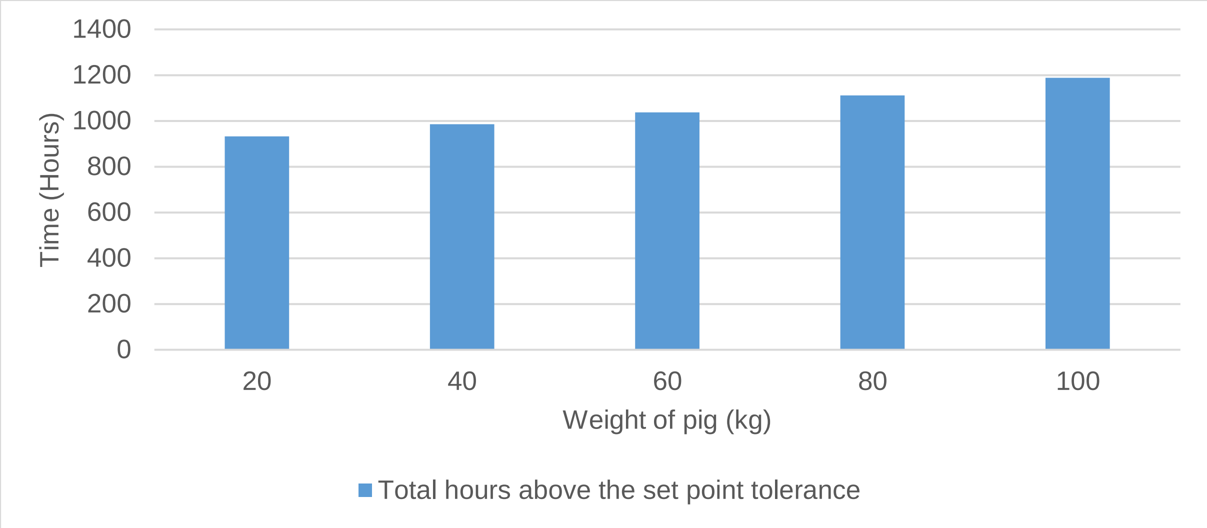

Figure 9. Estimated annual amount of hours that pigs will be kept above the higher internal setpoint tolerance temperature of 21°C, assuming maximum fresh air capacity of 49 l/s/pig.

Figure provides a breakdown of these increased internal temperatures shown in Figure 9. It can be seen that with increasing body size and metabolic heat production there is a steady increase in the amount of time that pigs will spend above the internal setpoint tolerance. This effect of liveweight starts to level out at around 25ºC, indicating that the pigs' metabolic heat production is no longer having a major effect on the environment, as the leading factor in determining the operative temperature is now the external environment.

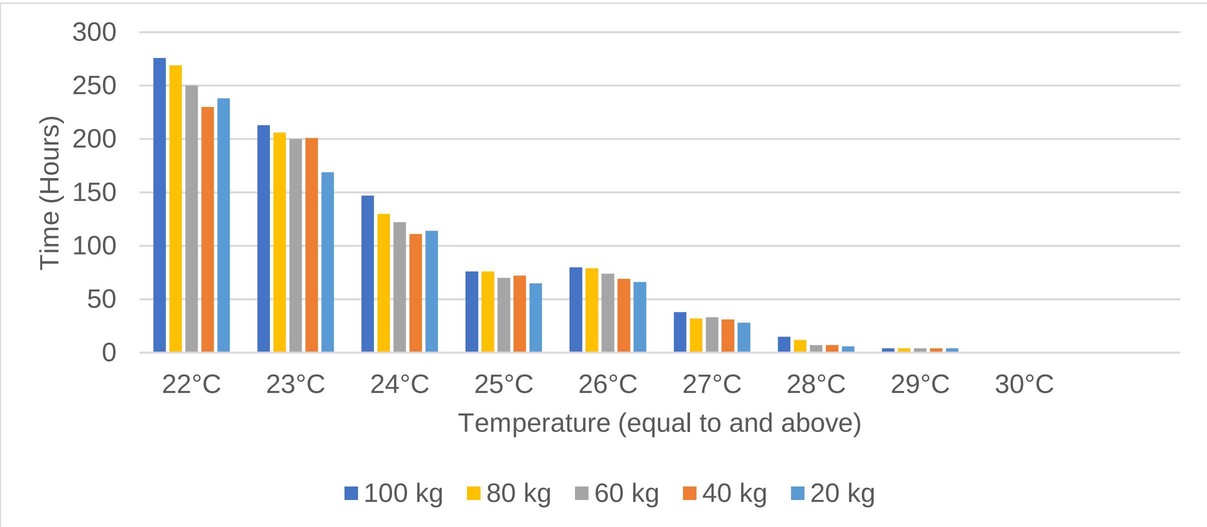

Figure 10. Breakdown of the estimated annual amount of hours 292 pigs of weights between 20 and 100kg spend above the higher internal setpoint tolerance temperature of 21°C, assuming maximum fresh air rates of 49 l/s/pig.

3.3 Comparison of thermal environments in existing and improved design buildings

Figure 11 and Figure 12 provide a comparison of the existing building and one of an improved design for 60 kg pigs for minimum or maximum rates of fresh air respectively. Figure 11 shows that the greater the thermal mass of the building fabric, the warmer the pigs will be during the cooler months with a decrease of 1115 hours (46.5 days) in the amount of time that pigs will spend below the internal setpoint tolerance temperature.

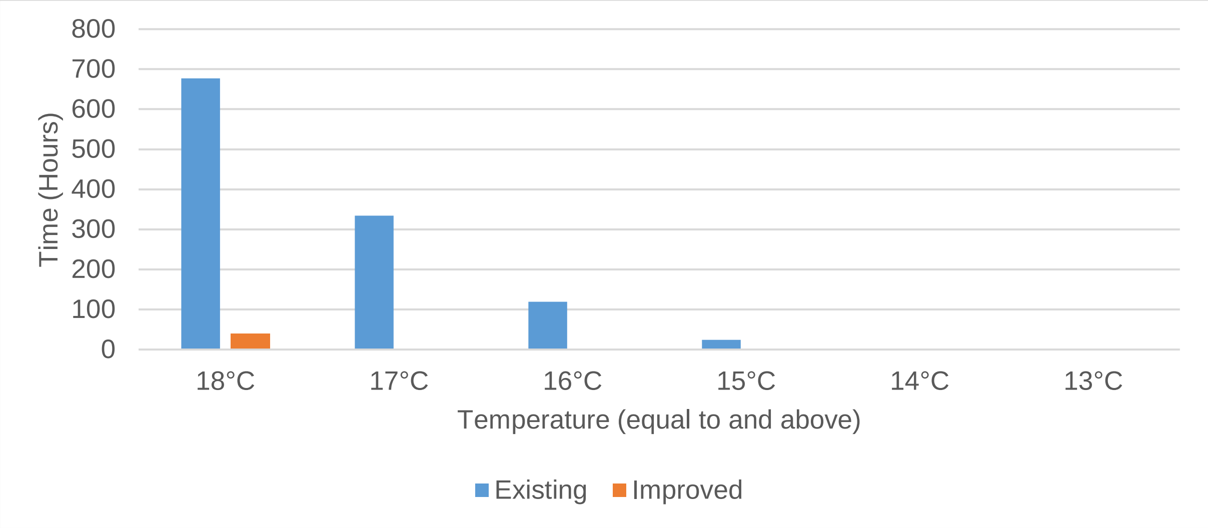

Figure 11. Estimated of amount of hours that 292 pigs of 60 kg bodyweight spend below the lower internal setpoint tolerance temperature of 19°C, assuming a minimum fresh air rate of 3.95 l/s/pig for an existing or improved design of building.

In contrast, the data in Figure 12 show that improving the building design has a detrimental effect by increasing the number of hours the pigs will spend above the internal setpoint tolerance temperature of 21°C when the maximum ventilation rate is used, with an annual increase of 137 hours (5.7 days) compared to the existing building. However, results show that the number of hours within the setpoint tolerance range (i.e. between 19 and 21°C) also increase by 46 hours (1.9 days). These counter-intuitive results are due to a reduction in the number of hours spent below the internal setpoint, and a concomitant increase in the number of hours within and above the setpoint tolerance band

Figure 12 also illustrates how the improved building design reduces the extent that pigs are exposed to extreme high internal temperatures. It can be seen that there is a reduction of 8 hours in the time the pigs spend at extreme high temperatures of above 27ºC.

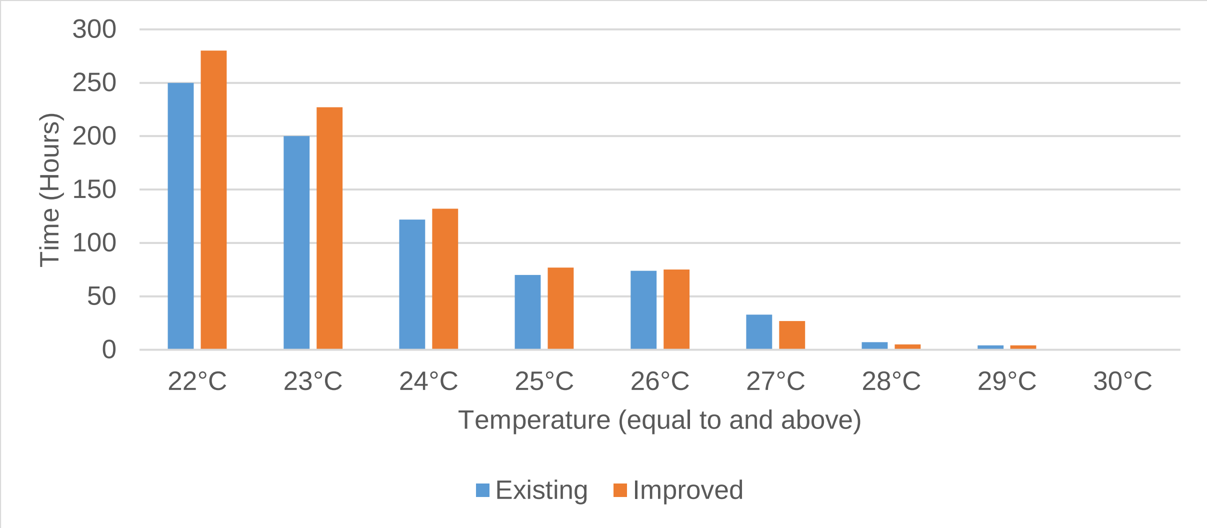

Figure 12. Estimated annual amount of hours that 292 pigs of 60 kg bodyweight spend above the internal setpoint tolerance temperature of 21°C, assuming a maximum fresh air rate of 49 l/s/pig for an existing or improved design of building.

3.4 Effects of future weather patterns

Results of incorporating predicted future weather files for the Staffordshire location into the model for 60kg pigs are shown in Figure 13 and Figure 14. As already shown in Figure 11 and Figure 12, the improved building design can reduce the number of hours the pigs potentially spend at extreme temperatures. Figure 13 shows that the occurrence of extreme low temperatures will decrease and become less of a problem to control the internal temperature as the Earth's external temperature increases with time. In contrast, Figure 14 demonstrates how, in the future, the external temperature will rise, a phenomenon which will make it increasingly challenging to control the internal building temperature due to an increase in the number of hours that the external temperature will be above the internal building temperature setpoint.

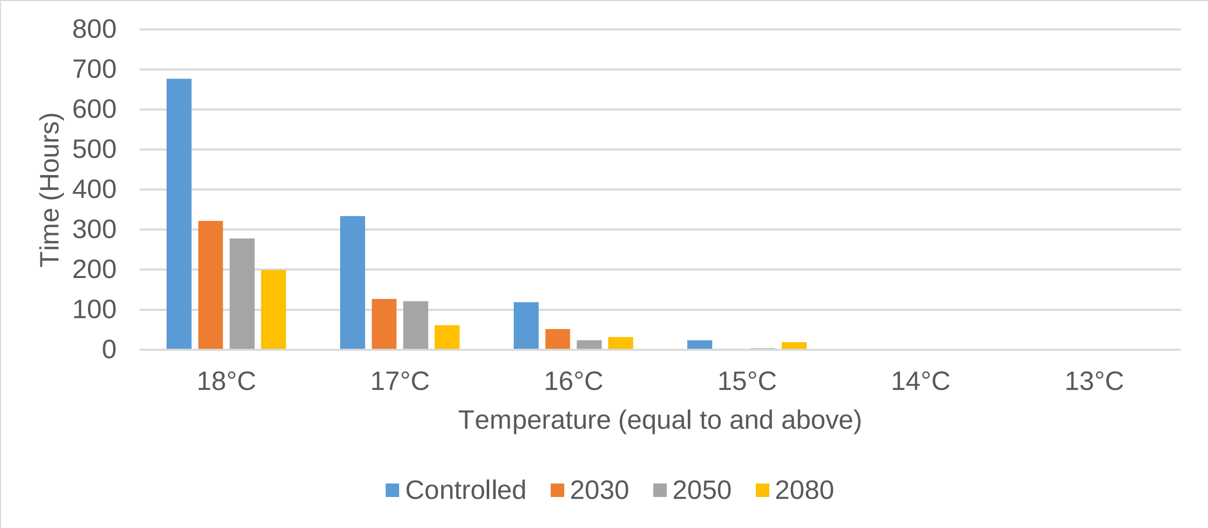

Figure 13. Breakdown of estimated annual number of hours that pigs of 60kg bodyweight will be below the lower internal setpoint tolerance temperature of 19°C assuming a minimum fresh air requirements of 3.95l/s/pig, for test reference year (TRY) controlled and future weather data in the years 2030, 2050 & 2080.

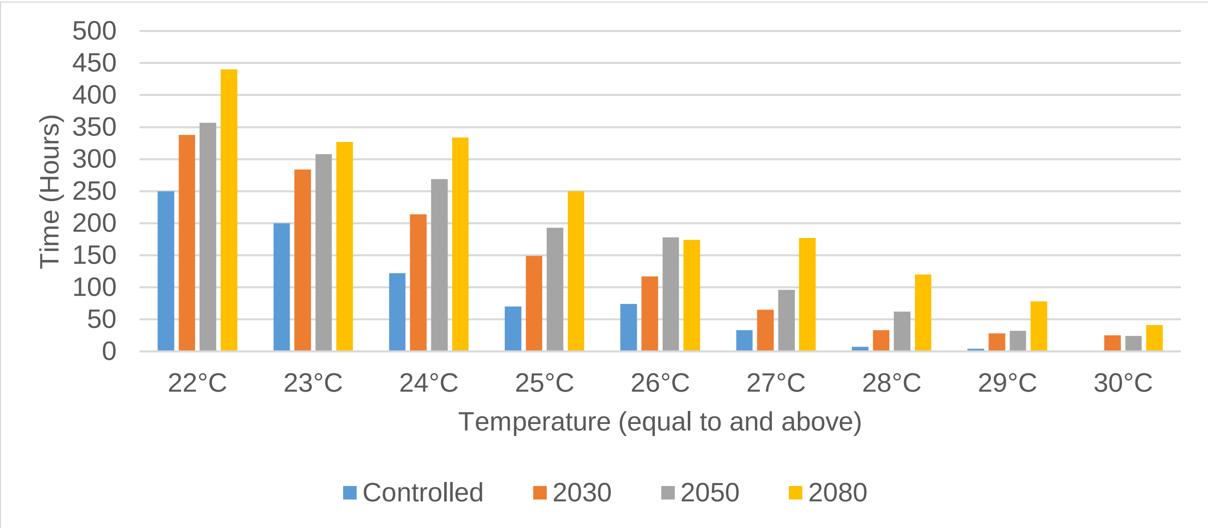

Figure 14. Breakdown of estimated annual number of hours that 292 pigs of 60 kg will be kept above the higher internal setpoint tolerance temperature of 21°C, assuming maximum fresh air requirements of 49 l/s/pig, for test reference year (TRY) controlled and future weather data in the years 2030, 2050 & 2080.

4.0 Discussion

This modelling exercise demonstrated that the type of finishing pig buildings currently in widespread use in the UK at the present time are inadequate in design to meet the range of environmental conditions currently experienced, and that this situation may be exacerbated with future predicted weather changes.

4.1 Internal air quality

The finding that finishing pigs in controlled environment buildings in the UK are prone to overheating in the summer months as shown in Figure 9 is not a new one. Indeed this problem has been known since the introduction of the housed environment for pigs, and it has remained the greatest environmental challenge to indoor pig production. As the pigs grow, their metabolic heat output increases and therefore, at high summer temperatures, it becomes harder to maintain the internal setpoint of the pigs' environment.

The particular existing building on which the model is based, as described in Section 2.4, has a relatively poor insulation U-Value, low thermal mass and high infiltration rate. Therefore, the high external temperatures and solar gains penetrate into the internal environment almost instantaneously. One solution to influence this mechanically ventilated internal environment is to change the building fabric and build quality in terms of infiltration. The improved building design has the potential to time lag the penetration of a high temperature external environment into the internal environment until later in the day, when the external air used to ventilate the building is cooler. This possibility was subsequently explored in the model and the effects clearly seen in Figure and Figure 12 which provide a breakdown of the temperatures in this scenario and confirm that the amount of time the pigs potentially spend at both extreme high and low temperatures is reduced.

However, caution must be exercised when considering the potential low temperature results from the model, since the actual overriding factor within the real pig unit would be the temperature setpoint, with the ventilation rate reducing to its minimum setting in order to try and maintain the 20ºC setpoint. So, rather than the pigs being subject to low temperatures, the actual effect could be poor indoor air quality. The improved building design benefits from an increased internal temperature in the very cold months, which provides an opportunity to increase the fresh air supply during these periods and in turn to provide a better internal air quality for the pigs.

4.2 Coping with climate change

Figure 13 shows that predicted global climate change may help to improve indoor air quality for indoor-housed pigs in the UK, at least in the winter months. As the Earth's temperature increases with time, the ventilation systems can potentially provide a greater amount of fresh air to the pigs in the winter months, and this is likely to improve indoor air quality. However, Figure 14 shows that the greatest challenge to the sustainability of pig production in the future is the overheating of the pigs in the summer months, which will only become accentuated as the Earth's temperature increases with time. Given these predictions, the first thought may be to introduce mechanical cooling into pig production the pig building, but no ventilation system that uses an energy source should be considered until all passive designs have been explored (Thorne, 2006) or the cost of pig production will simply increase and resource efficiency decrease. As the results in Figure 13 and Figure 14 suggest, in the quest for robust housing designs for the future, the first points to explore should be thermal mass, insulation and infiltration. Improving these aspects of the building specification will minimise the influence of the external environment on the internal space of the pigs and, once this has been achieved, the space can then be correctly controlled. If the space is not adequately separated from the external environment, then the pigs would simply be in an environment that matches or quickly time lags the external environment.

Results also suggest that providing ammonia sensors within the space could help to control the ventilation system, in terms of providing the correct levels of fresh air requirements. As the pigs increase in weight, the number of hours the pigs spend below the internal setpoint tolerance temperature was forecast to increase due to the increased fresh air requirement. This fresh air requirement takes into consideration that the larger and heavier pigs produce more manure and therefore generate higher levels of ammonia. Therefore the inclusion of maximum ammonia thresholds into the building control system could help in providing optimum fresh air requirements throughout the finishing period, without having an adverse effect on the internal temperature setpoint.

4.3 Operative temperature and pig performance

Although the current version of the model does not, as yet, provide output data of the effects of thermal environment on pig performance, there is evidence in the literature of the effect of operative environment on pig performance. Pig productivity studies have shown that to maintain a steady state of growth, temperature fluctuations of more than 3ºC around the desired temperature are to be avoided, although ±5ºC around the desired temperature can be acceptable for pigs larger than 70 kg in body weight and fed *ad libitum* (Close, 1987). This is exemplified in the work undertaken by Quiniou *et al.* (2000) who studied the effect of ambient temperature on individual feeding behaviour of six groups of pigs with increasing body weight. Only slight differences were observed in the feeding behaviour across the majority of the temperatures and weights, apart from the heavier pigs maintained at a high (i.e. 29ºC) ambient temperature.

Lopez *et al.* (1991b) investigated the effects a cold diurnal temperature on average daily gain, feed intake and feed efficiency of 48 Duroc, Landrace and Yorkshire finishing pigs of approximately 85 kg liveweight over a 3 week period. Two environmental controlled chambers were used: a thermo-neutral treatment (TN) room set at a constant 20ºC, and a cold-stress (CS) room which was set to cycle from a low of -5ºC between 24:00 and 06:00 to a high of 8ºC between 10:00 and 16:00. The mean hourly rate of increase and decrease of temperature throughout the daily cycle was 2.16ºC and 1.62ºC respectively. Results showed that the pigs housed in the CS chamber grew 27% more slowly than the pigs in the TN chamber, equivalent to 16 g/day less liveweight gain per ºC below 20ºC. Pigs in the CS chamber also consumed more feed than the TN pigs, an extra 12 g/day for each ºC below 20ºC. Overall, CS pigs were 43% less efficient than TN pigs in converting feed into gain during the 3 week study.

Lopez *et al.* (1991a) carried out a second study into the effects of a hot diurnal temperature on average daily gain, feed intake and feed efficiency of 96 Duroc, Landrace and Yorkshire finishing pigs of approximately 90 kg liveweight over a 3 week period. Again, two environmentally controlled chambers were used: the thermo-neutral treatment (TN) room set at a constant 20ºC, while the second hot diurnal treatment room (H) was set to cycle from a low of 22.5ºC between 24:00 and 06:00 to a high of 35ºC between 16:00 and 18:00, with all pigs given *ad libitum* access to feed. Although no differences were found between TN and H pigs in terms of feed efficiency, the H chamber pigs grew 16% slower 16% and consumed 11% less feed than TN pigs. Overall, H chamber pigs gained 18 g/day less and consumed 44 g/day less feed for every 1ºC above 20ºC.

Taking into account these studies of the effects of temperature variations on pig performance, data from the current model suggests that there is potential to improve feed intake and efficiency of conversion into liveweight gain throughout the warmer periods and potentially annually. In contrast, it is difficult to estimate the effects of internal environment on pig performance during the winter months since, as mentioned previously in reality the ventilation control system setpoint would try and maintain the 20ºC by reducing the ventilation rate at the expense of indoor air quality, which might subsequently compromise respiratory health of both animals and workers (Banhazi, 2013; Donham, 2013; Gustafsson *et al.*, 2013).

6.0 Conclusions

Results of the dynamic thermal model developed in this study show that the environment inside a finishing pig building could increasingly result in prolonged periods of poor air quality as the pigs get older. This suboptimal internal environment could have affect the welfare and feed efficiency of the animals, along with subsequent detrimental effects on profitability of the enterprise and the health and welfare of both pigs and farm personnel. Improving the design of the simulated building resulted in a decrease in the amount of time that pigs will spend below the lower internal setpoint tolerance temperature, by 1115 hours (46 days). In the same way, there was also a reduction in the amount of time pigs will spend at extreme high temperatures of above 27°C, albeit a more modest reduction of 8 hours per room. Incorporation of predicted future weather data for the years 2030, 2050 & 2080 indicates that, as external environment temperature increases, indoor air quality may improve since there could be less exposure to low environmental temperatures leading to minimum ventilation rates. However, these results also illustrate that a different approach may be required to the ventilation system to cool the space to the internal temperature setpoint as the external temperature increases through global warming. If not controlled correctly, rising environmental temperatures could also have a negative influence on internal environment of the pig building and in turn affect pig welfare, feed efficiency and cost of production.

Thus, the model developed in this paper can provide a greater understanding of the design requirements for sustainable forms of pig housing for the future, which could potentially improve the welfare of the pig, farm personnel and promote improved resource use. While the model also has the potential to provide quick and detailed analysis of different ventilation scenarios in terms of airborne contaminants as Topisirovic and Radivojevic (2005) observed notable differences between single and dual ventilation systems for the same space of an experimental finishing room.

With changes to the location parameters, the model is capable of producing results that could provide guidance on the amendments required to international building standards, necessary to provide pig building manufacturers with the tools to deliver high quality environments which are capable of coping with future environmental changes whilst optimising maintaining pig performance and welfare. The model also provides the pig production industry with knowledge of how existing buildings, built to current standards, will be performing in the future and what changes if any can be made to protect the industry from ever increasing costs.

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