The Role of Hygrothermal Modelling for Different Housing Typologies by Estimating Indoor Relative Humidity, Energy Usage and Anticipation of Fuel Poverty

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Highlights:

- There is a huge gap between building energy regulation and its implementation in the construction industry.
- A probabilistic approach is used to design retrofitting solutions for building energetic rehabilitation and relative humidity (RH) management in residential houses from the 1920s and 2010s with the representations in three different areas.
- The work analyses the effect of fuel poverty and anticipating global climate change on a healthier indoor environment.
- The indoor temperature is demonstrated to be efficient in the range between 16^{o}C - 20^{o}C, highlighting the need to review regulation.

Abstract

The nature of deem-to-satisfy standards in building energy performance results in a lack of insight over their consequences. As a result, there is a huge gap between regulation and implementation in the construction industry. The procedure proposed in this article aims to implement the probabilistic approach method to design retrofitting solutions for building energetic rehabilitation and relative humidity management. This is completed by considering the uncertainty associated with a building's physical parameters, savings estimation, weather forecast, occupants' behaviour and building ventilation. A computational hygrothermal modelling approach is utilised to emphasise the differences in the indoor conditions for two typologies of residential houses common in the United Kingdom, located in three cities with different weather conditions and fuel poverty levels: Liverpool, Aberdeen, and Kent. The first model corresponds to houses built to standards from the 1920s', with solid external walls, and the second house

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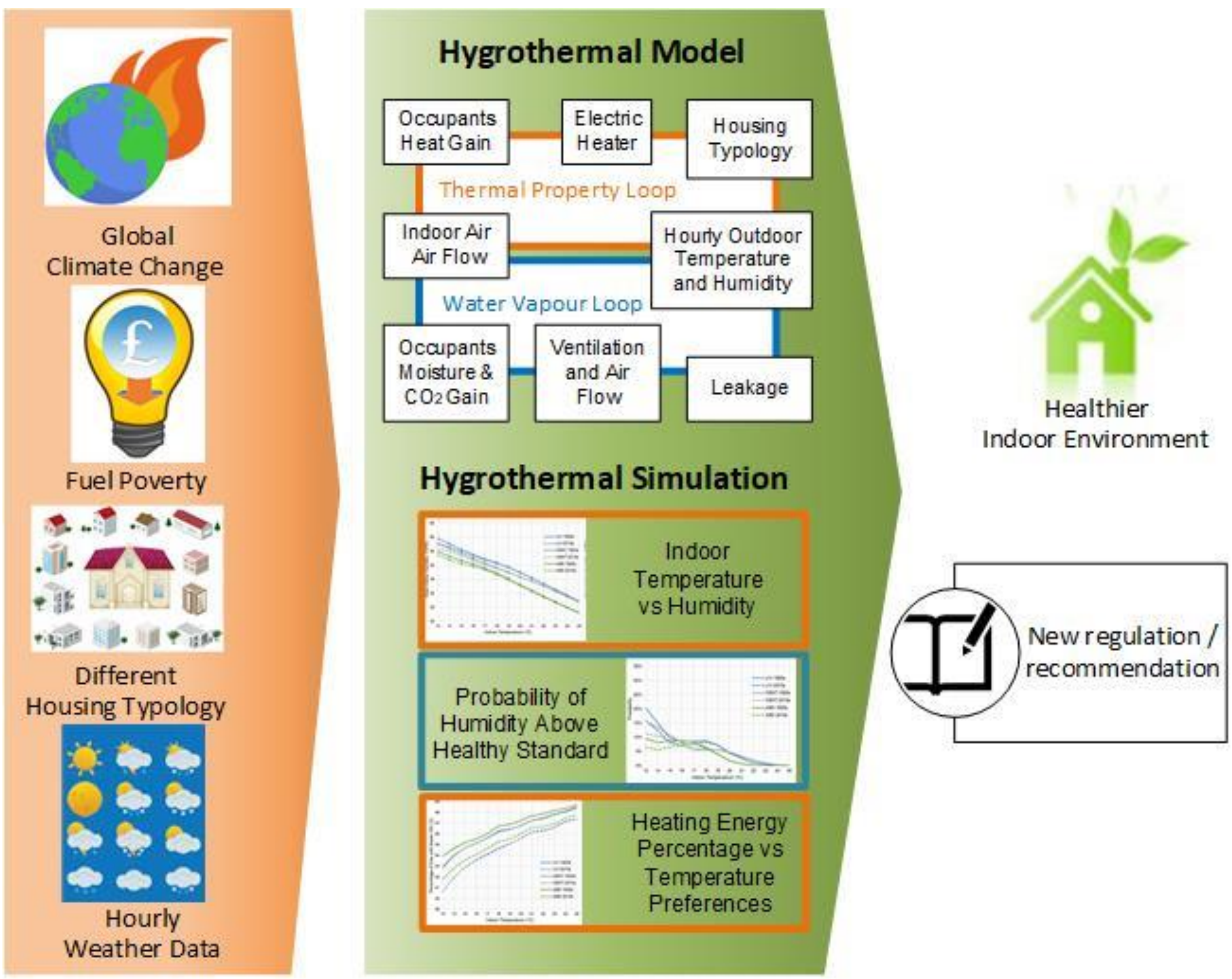
model uses the 2010s' construction solution, where the double-glazed windows and the wall insulation materials are implemented. The indoor temperature is demonstrated to be efficient in the range between 16ºC - 20ºC. Lowering the current temperature set point to about 16ºC will give healthier indoor conditions regardless of dwelling, highlighting the need to review the regulation. The simulation shows that 2% heating energy can be conserved for indoor thermal comfort and extensive environmental benefits. On particular assumption of energy use per household, this work will annually contribute to the carbon footprint reduction of approximately 635.8 - 847 thousand tonnes.

Keywords: occupant comfort, hygrothermal modelling, fuel poverty, indoor air quality, relative humidity

Graphical Abstract:



1. Introduction

In developed and industrialised countries, approximately 80-90% of human behaviour is spent indoors where the air quality can be significantly worse than outside [1, 2]. Despite this, there are only limited standards available for IAQ in housing, where the only exceptions are for places of work[3, 4]. Starting the process of analysing and understanding how occupants' comfort and health is affected by IAQ the quality of the building structure, finish, furnishings, and the degree of crowding of such environments and the various human activities must be considered. Therefore it is crucial for the development and implementation of a strategy to protect and promote the health and safety of those inside dwellings on both a national and international level (such as European prevention plans and United Nations programs on the Sustainability Development Agenda [4] and World Health Organisation (WHO) predictions [4]).

Although there has been a decrease during the pandemic, CO_2 emissions have previously grown by 1.7% to reach 33.1 Gt in 2018 and become the highest growth in emissions since 2013 [5]. Although Global Climate Change (GCC) can decrease heating needs by 2%, the need for air conditioning during summer will increase because of increased humidity[6, 7]. As a function of time, the GCC impact will become increasingly worse and globally will require approximately 3% excess energy [8]. Consequentially, the UK will introduce a Future Homes Standard, mandating the end of fossil-fuel heating systems in all new houses from 2025 [9]. Coupled with this, in the current building stock, many existing dwelling cannot provide enough protection against either heat and/or cold weather fluctuations [10], reducing both IAQ and thermal comfort for dwellings. Thermal comfort has become researchers' focus prior 1920 to date due to the importance in the health aspects, energy usage, wellbeing, air quality factors (such as CO_2 levels) and productivity [11, 12] [13]. The analysis focus on human physiology which brought by Fanger's research, human behaviour and psychology raise by adaptive thermal comfort approach. There is also findings that people can have less body fat by regulating the indoor temperature with frequent cold exposures [14]. The exposure to cold acclimation can improve the subjective responses to cold [15]

To gauge the requirements for parameters to improve thermal comfort and indoor hygrothermal conditions there must be an investigation into the age, the number of properties, energy efficiency (and therefore fuel demand). Consequentially it also must be understood as to how this can be measured and predicted to optimise the retrofit of the current building stock. One of the key success factors in the implementation of regulations is by completing appropriate, relevant, and thorough simulations and modelling, giving a better view, and understanding of the problem and its potential solution. This paper provided the hygrothermal simulation which utilised building typologies from both typical residential properties utilising 1920s and 2010s building codes to model mean indoor relative humidity as a consequential effect of locational weather conditions with the simulation conducted for different thermal setting. This work used MATLAB as a HAM simulator and SIMSCAPE to simplify and accelerate the simulation process where the previous model implements the MATLAB, and the differential equations system was calculated using COMSOL. This paper has a potential influence on nearly 13 million homes in the United Kingdom (UK) and potentially other areas that have the similar conditions. The locations analysed are Kent, Liverpool and Aberdeen and due to their varied climates, to maintain thermal comfort, this model was also able to predict the percentage of time with the heater turned on which represent the energy used for heating.

2. Driving Factors

2.1. *Current problems related to residential dwellings in the UK*

The age range of residential dwelling typologies within the UK is vast, where only 17% of homes were built in the last 30 years (demonstrated within Figure 1 [16]). With variation in age comes a variation in building standards, techniques, and materials from those that are used today to improve energy efficiency and as a result will have different heating requirements. For example, within pre-1919 dwellings, energy costs are over 70% higher than their post-1990 equivalents [17]. Considering Figure 1, over 20% of English residential dwellings are within this category (pre-1919 dwellings), which consequentially produce around double the carbon emissions. Figure 1 also has a secondary y-axis which represents the number of houses that can be assigned to these dwelling ages.

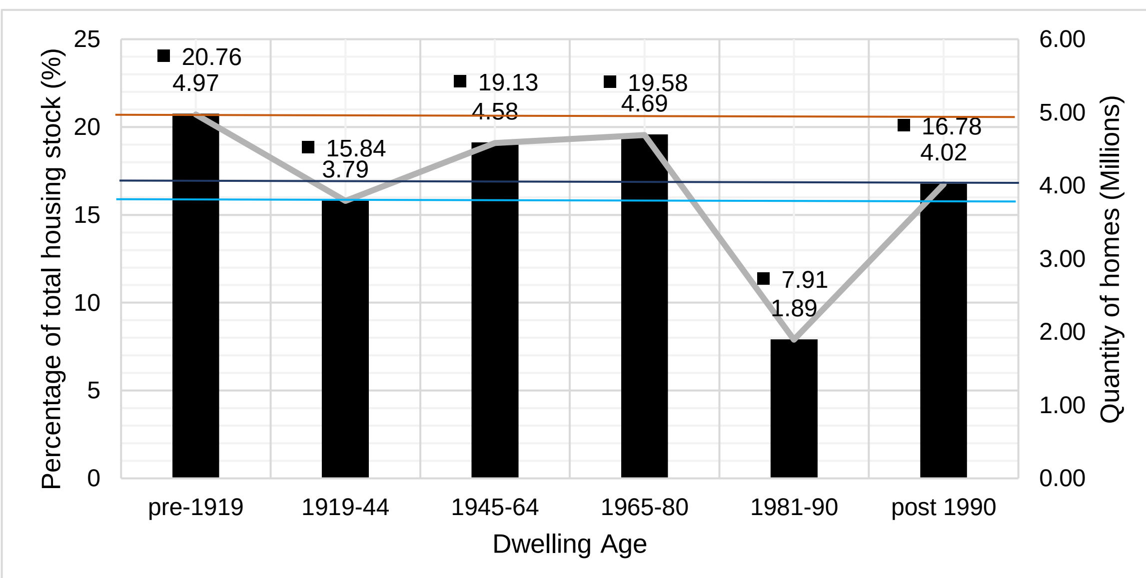


Figure 1. Dwelling age of properties of English homes[16].

The dwellings which are built using solid masonry bricks without air gaps (solid uninsulated walls) are referred to as ‘1920s’ homes and were constructed from both pre-1919 and 1919-44 in Figure 1., this equates to approximately 36.6% of the total dwellings or about 8.76 million homes. The dwellings which are built using the latest well-insulated walls mentioned in Figure 1 as the post-1990 are about 4.02 million or about 16.8% of the total dwellings. This study will focus on these two main groups which are about 12.78 million houses or cover about 53.4% of the total dwelling in the UK.

2.2. Fuel Poverty in the UK and Global Climate Change

Using heating and hot water contributes to approximately 25% of total energy consumption for UK homes. As previously mentioned, there is also a requirement for more energy required to heat these older homes which has a subsequently higher fuel cost. The inability to afford adequate heating energy in a home is defined as fuel poverty [18]. Particularly in pre-1919 homes, the likelihood of fuel poverty is double the national average, where all countries within the UK experience fuel poverty as demonstrated in Figure 2.

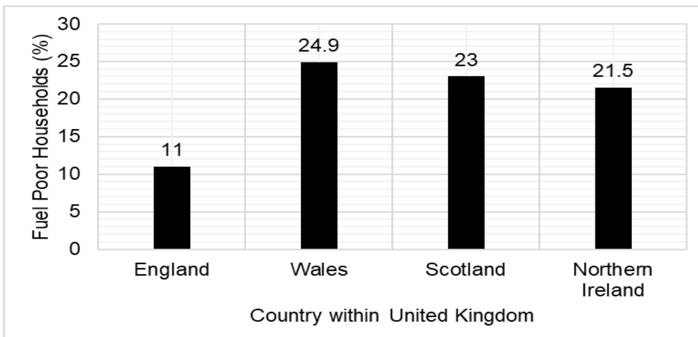


Figure 2. Percentage of fuel poor households within the UK [19, Welsh 20, Scottish 21, Northern Ireland Housing 22]

Understanding how specific regions are affected by fuel poverty is imperative for developing a deeper knowledge and demonstration of locational requirements. Specifically, Figure 3, demonstrates two geographically opposite cities, Liverpool (North West) and Kent (South East) which have been highlighted in purple and orange (respectively). In Liverpool, it is demonstrated to be one of only 14 local authorities in the whole of England to be at the most end of fuel poverty between 14.1-20.9% of homes experiencing it. By contrast, Kent has between 8.1-10% of homes in fuel poverty being one of 106 local authorities.

By comparison, in Scotland, the national average for fuel poverty households from 2016-18 was 25% [23]; this is represented within Figure 4. Aberdeen is highlighted by an orange arrow. The results demonstrated within Figure 4 are that within Aberdeen, fuel poverty is approximately slightly below the national average at 23% of all households being in fuel poverty.

Further to this, Figure 5 demonstrates a clear correlation to fuel poverty homes and the building envelope typology. Solid and un-insulated homes have the largest proportion of homes that fall into the fuel poverty classification at approximately 16% of all homes. Figure 5 shows that if residents live in solid uninsulated homes the average fuel poverty gap is the largest. The fuel poverty gap represents the value or quantity of money required to move the household out of fuel poverty; for solid, uninsulated homes this is over £400 per year.

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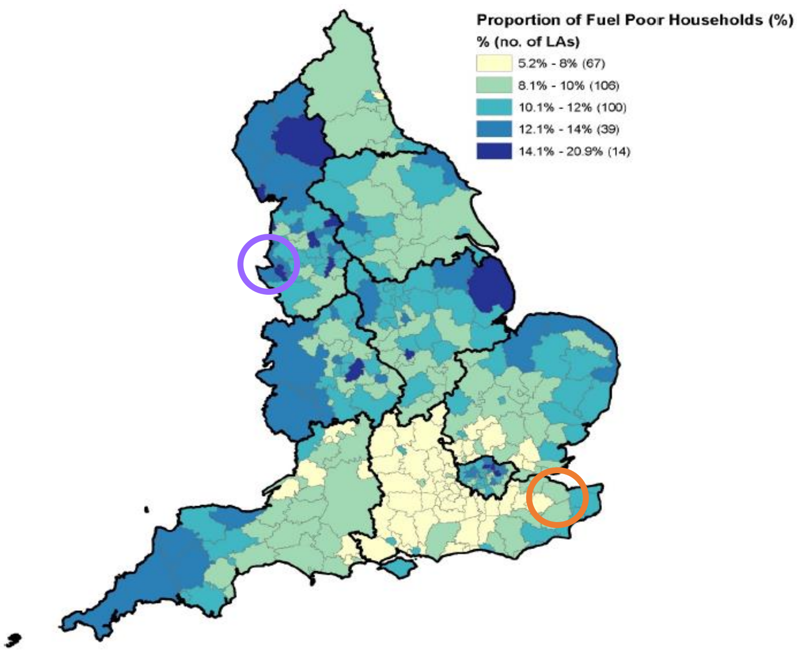


Figure 3. Sub-regional map of fuel poverty (by the proportion of local authority) within England[24].

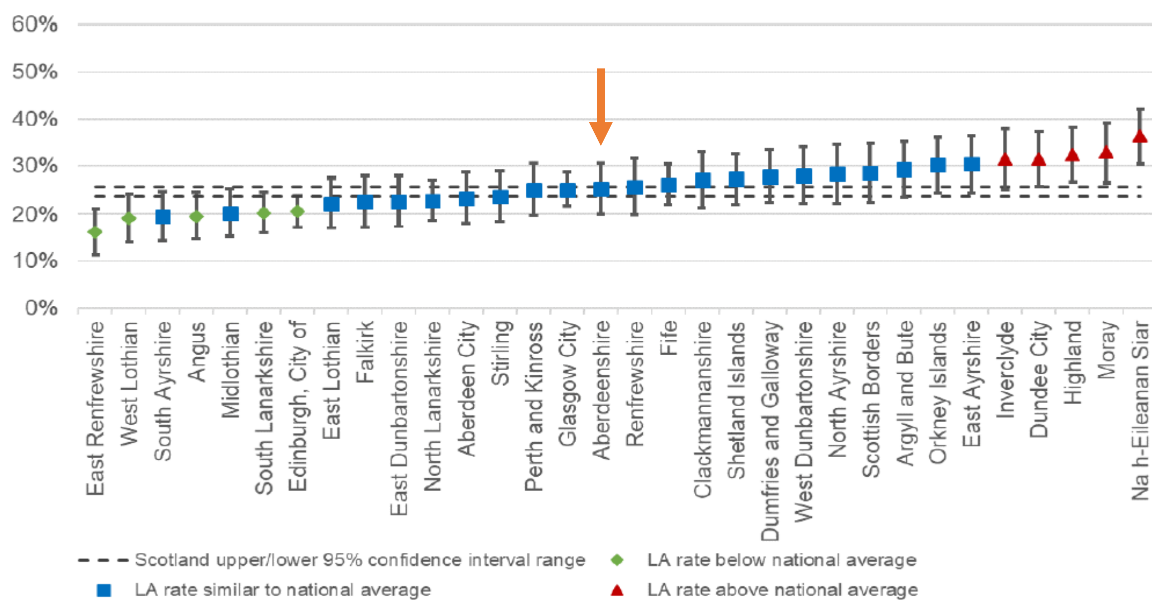


Figure 4. Percentage of fuel poverty homes in Scotland (by the local authority) (where Aberdeen is highlighted by an orange arrow) [23].

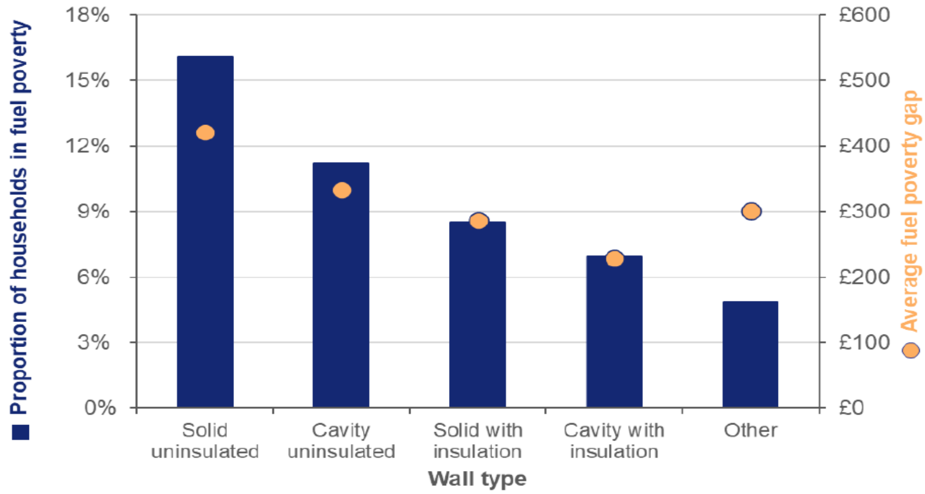


Figure 5. Effect of wall type on the proportion of households in fuel poverty and average fuel poverty gap[19].

2.3. Indoor Air Quality (IAQ)

Considering the thermal comfort of the indoor environment, can severely reduce the energy demand for residential properties. Many different bacterium and health effects thrive in different RH (see Figure 6). The recommended levels within domestic properties as outlined in H.M.Government [25] are the daily average to be less than 85% RH, weekly average to be less than 75% RH and monthly average to be less than 65% RH. These regulations have been modified since the previous 2006 edition of the Building Regulations Part F. It was noted by H.M.Government [25] that these regulations were reformed to comply with research conducted by Altamirano-Medina, et al. [26].

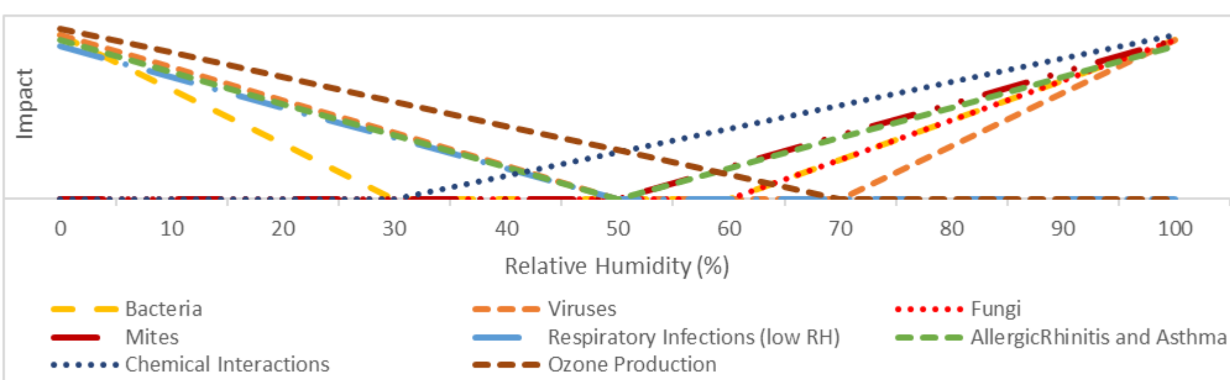


Figure 6. The optimum zone for RH against different types of household nuisances [27].

Maintaining RH level to minimise the problems is one of the key drivers for avoiding sick building syndrome (SBS), attributing to several long-term occupant hazards such as upper respiratory illnesses [28].

Thermal comfort affects all occupants and directly impacts health and productivity [29] which is further exaggerated when succumbing to SBS [30]. SBS was explored by Yu and Crump [31] and Barreca, et al. [32].

2.4. Analysis of other modelling by other researchers

Simulations can model the probabilistic phenomena, for example, random resources availability and weather. Modelling also can introduce some level of abstraction. This allows the problems to be portrayed accurately according to the time and resources available. Some approaches are also available to be used in the modelling of each fundamental aspect [33]. The computational fluid dynamics calculation and modelling are also common to analyse indoor thermal conditions [34]. Other research has also been conducted to consider the thermal comfort factors in dwellings from using mathematical models, laboratory testing, numerical calculations and further computer-based simulations to develop the desired performance of building materials [35]. Another mathematical model and the validation is presented in Lelievre, et al. [36] and Richter, et al. [37].

Multiple simulation steps were also being done for increasing the accuracy of the model. In this work, Heat, Air and Moisture (HAM) models are being elaborated in three steps: semi-infinite wall approach, adiabatic building envelope, and building envelope with heat and moisture internal gains. This basic model then followed with the complex model with adiabatic building envelope with heat and moisture internal gains integrated with validated building energy simulation (BES)[38]. Besides using WUFI Plus, 3D hygrothermal modelling also uses other software such as COMSOL Multiphysics [39] [40]. Some of the simulation software models such as TRNSYS and TAS do not consider relative humidity. The hygrothermal simulation software such as WUFI Plus can consider the humidity and additional loads such as occupancy [41] using Nottingham's weather files. The thermal comfort parameter for relative humidity uses the ASHRAE thermal comfort envelope which has the upper comfort limit of 70%RH using WUFI Plus. The calibration and validation process using the climatic chamber compared with the software model has been completed in Antretter, et al. [42]. The validation using the actual measurement in the real building, compared with the simulation result, has been explored in Coelho, et al. [43] and Francesca, et al. [38]. Coelho, et al. [43] addresses the importance of using detailed outdoor weather file and the soil temperature. The real data from the weather station, even if it is not located directly on the premises, will help obtain a more precise result. Using the weather files obtained from WUFI and EnergyPlus database resulted in lower precision. The importance of using multiple geographical locations for simulation is also mentioned in work for simulating the moisture [44].

Further to the previous research mentioned, Ji, et al. [45] uses a model to compare a 1920s' house with the real house built inside the thermal chamber. The house model is developed in Integrated Environment Solutions Virtual Environment (IESVE) and implemented with blocked chimney due to health and safety considerations. This model uses Manchester weather data for simulation. This work shows that the construction details will improve the model accuracy. The model is then further extended by Ji, et al. [46] to show the effects of a retrofit to a building. From this study, heating demands can be reduced by 27% in a retrofitted house, but the space heating demands can vary significantly depending on how the building is heated (as per the occupants' preference). This result addresses the importance of assessing the thermal settings concerning the indoor condition inside the house. Ventilation, including infiltration and leakages, also have a substantial impact on space heating energy demands.

3. Methodology

3.1. Modelling Approach and input characteristics

This work utilises computer-based simulations to simulate the effect of outdoor temperature and humidity on the internal temperature and humidity in the presence of occupants within different dwelling typologies. This value was then used to predict the indoor condition in the houses with two different construction typologies: the first model is the houses built in the 1920s' where the wall and floor insulation was not common. The second house model is using 2010s' construction solution where the double-glassed windows and the wall insulation materials are implemented.

3.1.1 Construction Typology

As demonstrated within Figure 1, approximately 16% of all homes were built within the 1920s where the construction was non insulated solid brick (as per Figure 7a). Within this paper, when '1920s' home is mentioned, it does not just refer to this period it also refers to any dwelling built to the same building standard of a solid masonry wall. While the 2010s' construction is the representation of the 'newer' and updated construction methodology (see Figure 7b). Similar to that of the 1920s typology, for this paper any building with the same construction is included in this description. These construction typologies are based upon 'to scale' British Research Establishment (BRE) exemplar houses built on-site at the Liverpool

John Moores University (LJMU) Byrom Street (as pictured in Figure A1 in the Appendix) and are used to do hygrothermal experimental tests and simulations.

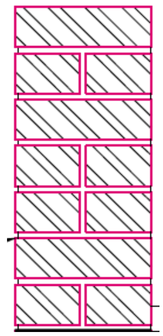


Figure 7a. 1920s Solid masonry wall.

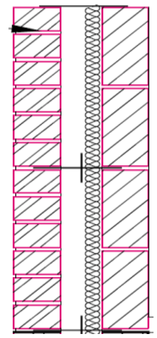


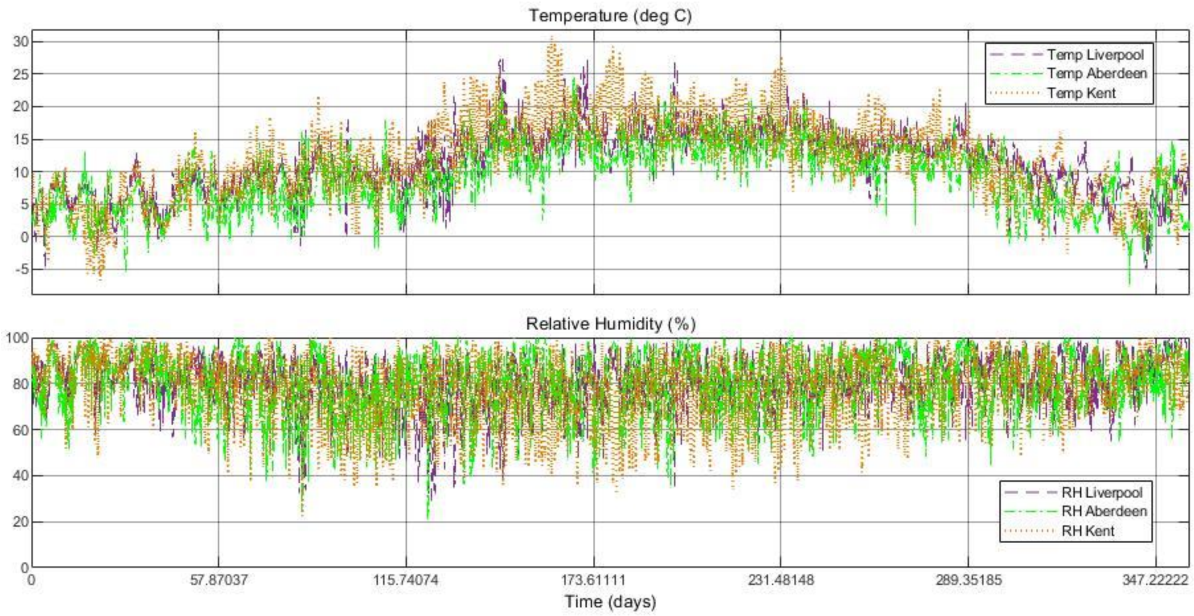
Figure 7b. The 2010s Outer facing brick, 50mm clear cavity, 40mm insulation board, medium density inner.

3.1.2. Location environmental conditions

Using a computer simulation allows the indoor conditions to be simulated for different parts of the UK, based upon their differing weather conditions. The locations of the simulated dwellings are in Liverpool (representing North West England), Kent (representing South East England) and Aberdeen (to represent North East Scotland). Besides the difference in the characteristics of fuel poverty, Aberdeen was selected to represent the coldest place in the UK, Kent as the hottest and Liverpool as the location in the middle.

The data used for this simulation uses Centre for Environmental Data Analysis (CEDA) hourly weather data for 2017[47] and is demonstrated for Liverpool, Aberdeen and Kent in Figure 8. If needed, the model will also allow us to predict the indoor condition using the future weather forecast (for example in 2030)[48] as future weather data for the UK can also be obtained in CEDA datasets [34, 49]

Figure 8 demonstrate that out of the three locations there is a greater temperature range in Kent compared to Aberdeen and Liverpool. Aberdeen had the coldest temperature reading among the three locations, but Kent had the lowest mean temperature (7.54°C) in 2017 compared with Aberdeen (8.56°C) and Liverpool (8.25°C). The mean temperature of all cities was still below 9 °C. When considering RH Aberdeen had the lowest mean RH (80.57%RH), but all area still had the mean relative humidity above 80% (Kent 82.99% RH and Liverpool 82.26%RH).



Location	Temperature				Humidity			
	Max	Min	Mean	Std. Dev	Max	Min	Mean	Std. Dev
Liverpool	27.8 °C	- 4.9 °C	8.247 °C	4.904	100%	29.00%	82.26%	11.15
Aberdeen	24.4 °C	- 7.7 °C	8.559 °C	4.908	100%	21.00%	80.57%	13.03
Kent	30.8 °C	- 6.8 °C	7.535 °C	6.013	100%	22.50%	82.99%	14.15

Figure 8. The chart of hourly annual temperature (upper chart) and relative humidity (lower chart) for Liverpool, Aberdeen and Kent in 2017.

3.2. Model Input Parameters

The model uses the approach of a single room, (similar to PASSYS test cells [50]) with two and four occupants constantly present inside the room. This model is deployed using MATLAB-Simulink-Simscape software. Consisting of two related parts simulated simultaneously, the model contains both a thermal model and a moisture model, where the input parameters can be found within Table 1. Some parameters related to the materials are simplified to match with the simulation approach.

3.3. Model Detailing and Assumptions

SIMSCAPE is a feature of SIMULINK in MATLAB where the simulation of the physical model can be completed simultaneously to represent identical physical conditions. This hygrothermal modelling was implemented with two loops of physical properties. The first loop is for the water vapour property and the second is the loop for thermal property – demonstrated in Figure 9.

Table 1. Model Parameters.

<table>
<tr><td colspan="5">General</td></tr>
<tr><td colspan="2">Input Parameter</td><td colspan="3">Value</td></tr>
<tr><td colspan="2">Number of Occupants</td><td colspan="3">2 and 4</td></tr>
<tr><td colspan="2">Sensible heat per occupant, (W)</td><td colspan="3">100</td></tr>
<tr><td colspan="2">Ventilation area, (m^2)</td><td colspan="3">0.01</td></tr>
<tr><td colspan="2">Flow (m/s)</td><td colspan="3">0.05 and 0.025</td></tr>
<tr><td colspan="5">Room Dimensions</td></tr>
<tr><td colspan="2">Input Parameter</td><td colspan="3">Value</td></tr>
<tr><td colspan="2">Room Volume (m^3)</td><td colspan="3">31.84 (4.35 x 3.05 x 2.4)</td></tr>
<tr><td colspan="2">Window Area (m^2)</td><td colspan="3">2.8314</td></tr>
<tr><td colspan="2">Door Area (m^2)</td><td colspan="3">3.4</td></tr>
<tr><td colspan="5">Housing Typology Characteristics</td></tr>
<tr><td>Typology Description</td><td>Specific Heat Capacity (J/(kg K)</td><td>Thermal Conductivity (W/mK)</td><td>Wall Thickness (m)</td><td>Density (kg/m^3)</td></tr>
<tr><td>1920s house solid brick wall</td><td>800</td><td>0.98</td><td>0.215</td><td>1920</td></tr>
<tr><td>2010s house internal blockwork concrete block</td><td>1000</td><td>0.51</td><td>0.1</td><td>1400</td></tr>
<tr><td>2010s house insulation</td><td>1500</td><td>0.022</td><td>0.09</td><td>30</td></tr>
<tr><td>2010s house outer facing brick</td><td>800</td><td>0.98</td><td>0.1025</td><td>1920</td></tr>
</table>

Even when the model is divided into two loops, the simulation of the water vapour loop and the thermal property loop is completed simultaneously. This means that their parameters are integrated and strongly correlated between each loop. The approach of splitting the model into two loops has the benefit of the modularity aspects; the parameters defined in each loop can be properly identified and modelled in different modules. Each loop can be isolated and executed to identify the effect of altering the simulation parameters independently on each separated loops and in an integrated environment simulation. The intersection of the loop is in the constant volume chamber component. This block model the moist air behaviour inside a constant room volume. The mass and energy storage parameters are modelled with the possibility of changing the simulated input parameters. Pressure and temperature will change based on the thermal capacity and pressure of the moist air inside the chamber. The liquid water condenses out of the moist air volume when it reaches saturation, but the rate is not logged in this simulation stage.

The moist air node is available for adding or removing moisture within the air. In this model, this feature is utilised to model the occupant's presence. The occupant's presence will give additional moisture because of the effect of human respiration with the different metabolism rate and other activities such as cooking. This component is the intersection between the water vapour loop and the thermal loop.

Besides affecting the water vapour loop in terms of increasing the humidity, the occupant's presence will also raise the temperature of the moist air volume due to the heat dissipated by the human body. Liquid water condenses out of the moist air volume when it reaches saturation. In the thermal loop, the convective and conductive heat transfer between the air, the surrounding wall, roof, floor and the occupants are simulated.

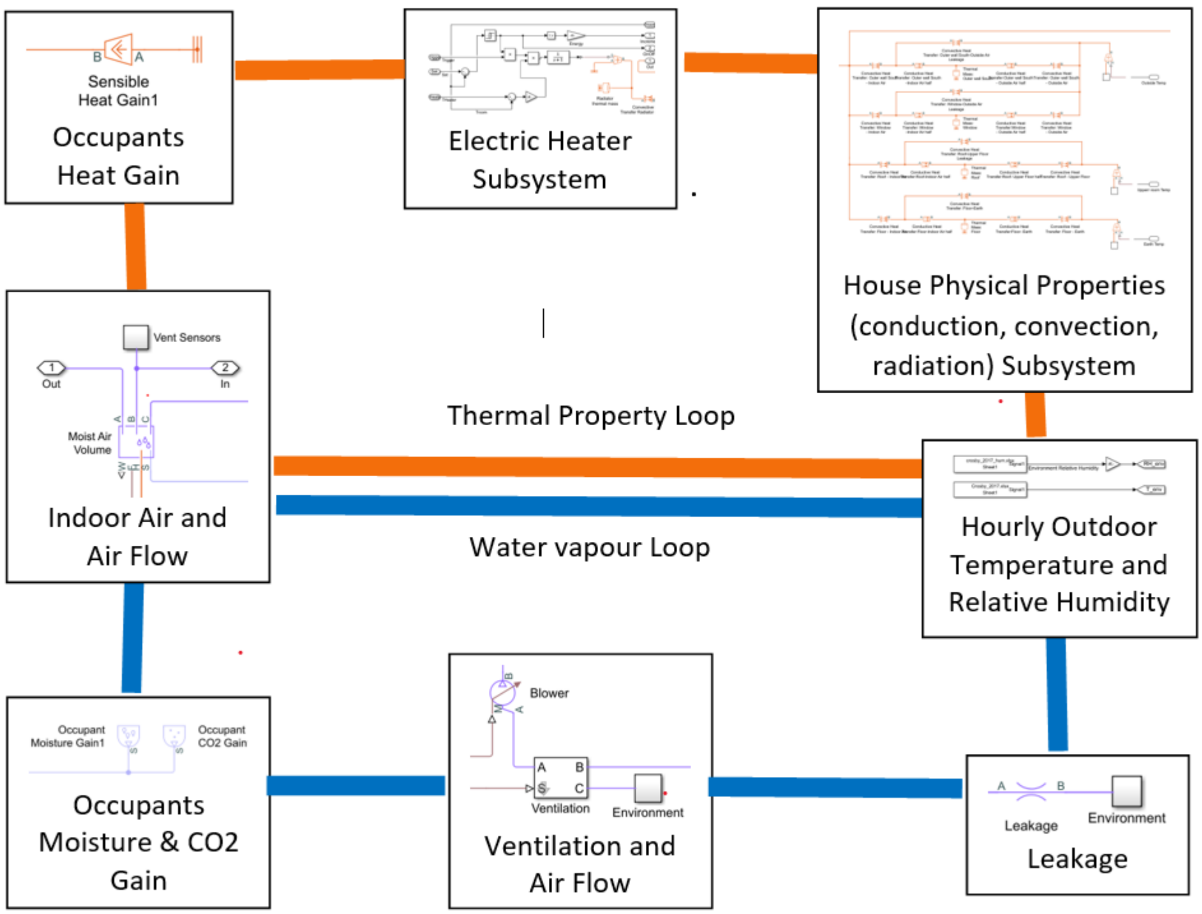


Figure 9. Overview of the Simscape MATLAB Model

The heater model in this simulation is the convective panel electric heater model with the closed-loop control, shown in figure 10. The heater will be turned on if the room temperature falls below the setpoint and turned off if the temperature rises above the temperature set point. Measuring the percentage of heater activation time between different housing typology and location will generate an annual quantification of energy usage for typology and locational comparisons. The heater part is connected to the thermal property loop in the constant volume chamber component hence, a change in heater state will give an impact on the indoor air moisture.

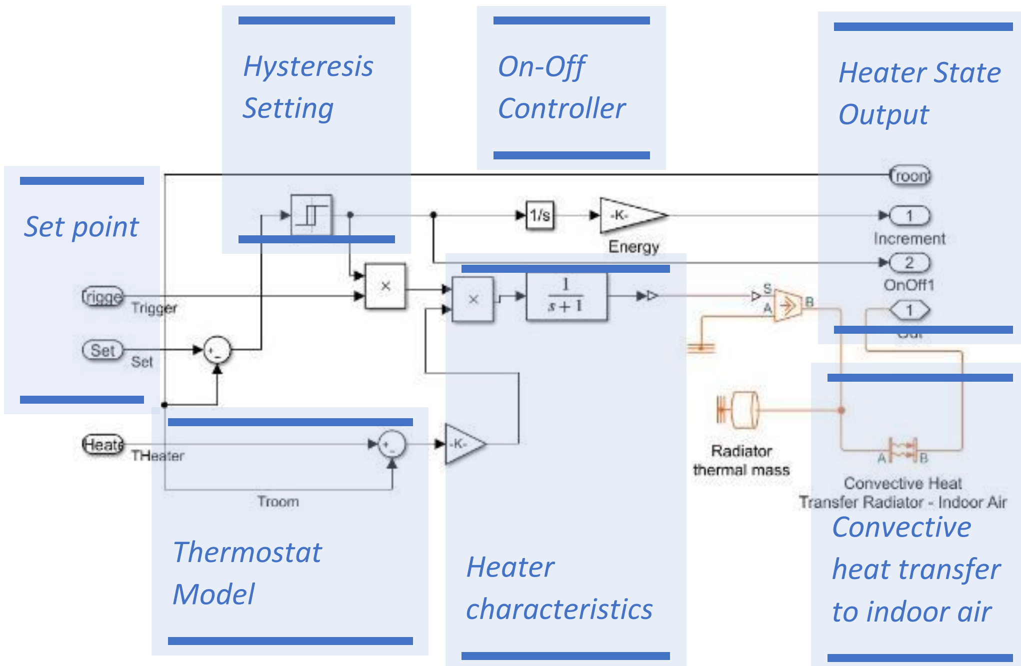


Figure 10. Simplified electric heater model in the Simscape simulation.

This model uses the following assumptions:

- The heater is a model of the convective panel electric heater. The temperature of the panel when switched on is 40 ^{o}C. Dimensionally, the panel heater is 0.9 x 0.4 m^2 with a mass of 46.7 kg and radiator specific heat capacity is 447 %J/(kg K) and the heat transfer coefficient is assumed to be 100 %W/m^{2}K
- Occupants are simulated to be present all the time (24 hours) and having the same activity level. The amount of moisture produced to use the approximation of occupants being at a low activity or resting and as per BS 5925:1991 [51] and the ASHRAE Handbook Fundamentals - 2017 [52] RH is no greater than 70%. Each occupant is assumed to produce a 50 g/h moisture level as per BS 5925:1991 standard (as the value is 40 g/h for resting and 55 g/h for heavy activity) . The model uses this single figure to represent the effect of human respiration with the different metabolism rate and other activities such as cooking.
- The solar heat gain is simplified in this model and not calculated using the weather files as temperature and humidity are.
- There is no air conditioning used in this model, the thermal set point is applied as a threshold for the heater to be activated.

- Roof and floor constructions parameters are simplified in this model for the 1920s' and 2010s' house typology and considered to have the same impact in the indoor temperature.
- The condensation rate is not logged in this model and the risk of condensation is not assessed.
- The ventilation state is also being varied - ventilation with the rate of air velocity 0.025 m/s and 0.05 m/s. In this rate of ventilation, the CO_2 level is below 1000 ppm for 2 and 4 occupants. This model uses the CO_2 gain per occupant value of 0.01 g/s and the CO_2 level in the fresh air is using the assumption of 0.04 % as stated in BS 5925:1991 [51].

3.4. Model Validation

The simulation uses three cities within the UK: Kent, Aberdeen and Liverpool, to represent conditions all over the UK. The measurement data taken from ASHRAE Global Thermal Comfort Database II [53] for Liverpool and all available UK data were used to validate the model. The data from Liverpool were selected to represent one area of the UK with average weather conditions with 197 measurements data available in the database. All areas across the UK were selected from the database with the data entry of 14,187 measurements from Midland, London, Hampshire, Oxford, St. Helens, Chester and Liverpool. These measurements were taken in naturally ventilated buildings such as offices and classrooms. The data set years are 1994, 1995, 1996, 1998, 1999, 2011 and 2012, with the data span throughout the years.

The measurements data in ASHRAE Global Thermal Comfort Database II are used to compare air velocity values in m/s and the RH in percentage (%). For the Liverpool region, the measurement data shows that the average temperature is 21.18 ^{o}C with a standard deviation of 1.60 and the RH value of 44.55 % with a standard deviation of 5.92. The average value of indoor air velocity is 0.06 m/s with a standard deviation of 0.05. Our simulation shows that for the Liverpool area with an average temperature of 21 ^{o}C and the indoor air velocity of 0.05 m/s, the RH is 44.52%. This result comparison can be seen in Table 2.

Table 2. Model Validation.

	Simulation Result			ASHRAE Global Thermal Database II						
Area	Tempera-ture (^{o}C)	Relative Humidity (%)	Indoor Air Velocity (m/s)	Tempera-ture (^{o}C)	Std Dev	Relative Humidity (%)	Std Dev	Indoor Air Velocity (m/s)	Std Dev	Number of Samples
Liverpool	21	44.52	0.05	21.18	1.60	44.55	5.92	0.06	0.05	197
United Kingdom	22	40.63	0.05	22.67	1.93	41.87	13.14	0.07	0.06	14187
	23	38.70	0.05							

The global UK areas show that the mean of the RH is 41.87%, with a standard deviation of 13.14. This value is measured at the mean temperature of 22.67 ^{o}C with a standard deviation of 1.93. The mean air velocity value is 0.07 m/s with a standard deviation of 0.06. Our simulation shows that for the average temperature between 22 ^{o}C and 23 ^{o}C with the indoor air velocity of 0.05 m/s, the RH is between 38.7% and 40.63%. The average RH value deviation is less than 2%, so it justifies our simulation result.

4. Results and Discussion

Simulations were completed to compare the performance of the housing location and construction typologies with 2 and 4 people inside a room over 24 hours as demonstrated in Figure 11. The ventilation rate is 0.05 m/s for Figure 11 a and c. For Figure 11 b and d the ventilation rate is 0.025 m/s. In terms of CO_2 levels, a ventilation rate of 0.05 for 2 occupants inside the room will reach about 650 - 700 ppm; whereas for 4 occupants inside the room, CO_2 levels will reach about 900 to 950 ppm. Both of which are still considered within the healthy region. By comparison, when the ventilation rate is halved to 0.025, the CO_2 level will rise to 900 - 950 ppm for 2 occupants and with 4 occupants these levels rise to an unhealthy level of 1400 - 1450 ppm. Besides simulating the CO_2 values, this work will also focus on relative humidity levels and if they can be considered healthy. What is demonstrated is that the annual mean indoor humidity is among the value range with no negative health effects, based on the simulation as outlined in H.M.Government [25] except the case of 4 occupants with a ventilation rate of 0.025.

There is only a slight difference in the humidity between 1920s' dwellings and 2010s' with the ventilation flow 0.05 (shown in Figure 11 a). This is observed particularly for both building typologies in Aberdeen after approximately 15^{o}C whereafter there is no difference in mean indoor RH. The trend for all three locations is almost linear, proportionally with the temperature change. However, for Liverpool and Kent at approximately 15^{o}C, the RH for 2010s homes remains negligibly larger than that of its 1920s counterpart. This difference is sustained until 21.5^{o}C for Liverpool and 23^{o}C for Kent homes. In terms of location, Liverpool and Kent based homes have a similar RH with a difference in RH of 1% from 13-21^{o}C where above this temperature (21-25^{o}C) RH appears to be the same. However, initially in Aberdeen RH is only 2% lower than Kent but at approximately 16 ^{o}C this difference increases to 3.5% RH and is sustained until the end of the simulation at 25^{o}C.

Similar to the case of 2 occupants (in Figure 11a), the values of annual mean indoor humidity in Figure 11 c are among the healthy values based on the simulation. What Figures 11 a-d demonstrate is that due to the increase in people within the room, the starting RH values are approximately 3% high than those in Figure 11 a. What can be demonstrated within Figure 11 c is that there is a gap (of approximately 1%) in

RH between 1920s' dwellings and 2010s' in the temperature from 13-18°C. After this temperature, both housing typologies seems to have the same mean indoor RH and the only difference is the location of the dwelling, where the trends are almost linear, proportionally with the temperature change. With less ventilation flow, the mean humidity value difference between 1920s' dwellings and 2010s' are distinguishable, especially with lower temperature settings. The efforts to reduce comfort temperature settings to conserve energy will be supported by the modern house typology which has lower relative humidity compared with the old typology.

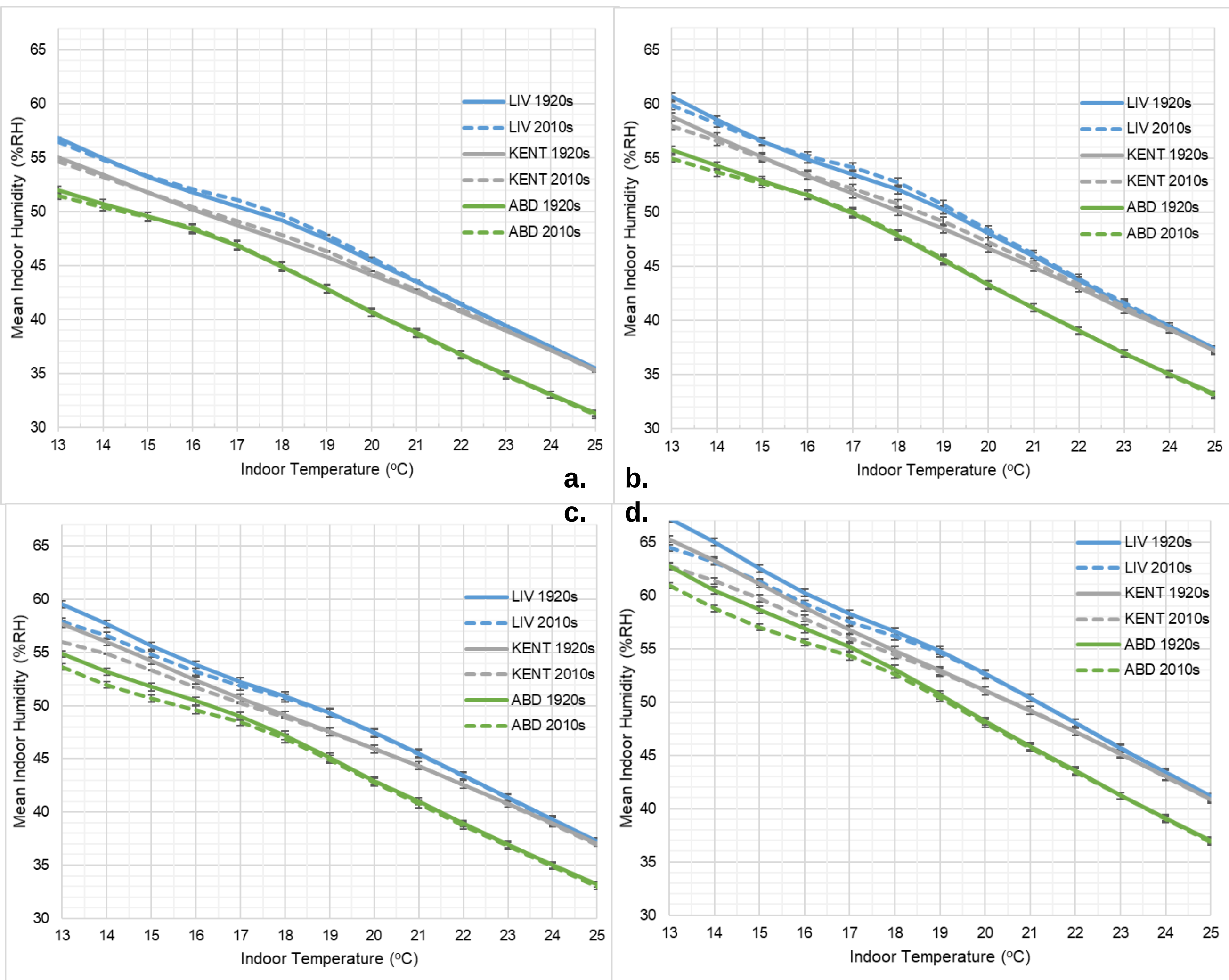


Figure 11. Comparison of mean indoor relative humidity (% RH) for the 1920s and 2010s housing typologies in Liverpool, Aberdeen and Kent over the entire year of 2017 with **a.)** 2 occupants and flow 0.05m/s, **b.)** 2 occupants and flow 0.025, **c.)** 4 occupants and flow 0.05m/s and **d.)** 4 occupants and flow 0.025.

Figure 12 a, b and c demonstrate the probability of the relative humidity exceeded 70%, all the results show the value below 25%. Only in Figure 12 d, for a dwelling with 4 occupants and ventilation flow 0.025 has the relative humidity exceeded 70% value above 25%. Besides CO_2 level, the value of the RH makes IAQ conditions unhealthy. The graph displayed in Figure 12 a - d are not linear because of the humidity change due to the heater effect. The use of a heater will decrease the indoor relative humidity. The 2010s' dwelling tends to have higher humidity compared to the 1920s' dwelling. This happens due to the difference in the heater state. In 1920s' dwelling, the desired temperature has to be achieved with the heater activated, while in the 2010s' dwelling, the temperature still can be reached with no heater as 2010s' dwelling has better insulation to maintain the indoor temperature.

The correlation between the probability of the relative humidity exceeded 70% in Figure 12 a and the percentage of the heater activated is shown in Figure 13 a is negatively correlated. In 1920s' dwellings, for Liverpool, Kent, and Aberdeen, the values are -0.9579, -0.9830, and -0.9345. For the 2010s' dwellings, for Liverpool, Kent, and Aberdeen, the values are -0.9372, -0.9711, and -0.8817. This result shows that the decrease in the use of the heater will increase the probability of the relative humidity exceeded 70%, particularly the dwellings in Kent have the biggest inverse correlation values.

To minimize the probability of the indoor RH not exceeding 70%, the location will not give significant value if the temperature inside the dwelling is maintained at least 16^{o}C. In this value of temperature set point, the number of people inside the room will affect more compared to the house location. Recommending this temperature set point to become the recommended standard temperature setting for comfort will consider giving a more uniform impact to the comfort.

Figures 12 c and 12 d shows that the 2010s' dwelling typology beginning to show the superior result compared to the 1920s'. The probability of the RH exceeds 70% can be lowered down while still conserve the energy for indoor heating. The correlation values between the probability of the relative humidity exceeded 70% in Figure 12 c and the percentage of the heater activated is shown in Figure 13 c is similar with the 2 occupants. In 1920s' dwellings, for Liverpool, Kent, and Aberdeen, the values are -0.9694, -0.9903, and -0.9405. For the 2010s' dwellings, for Liverpool, Kent, and Aberdeen, the values are -0.9624, -0.9754, and -0.8564. The two groups have negative correlation values with the dwellings in Kent have the biggest inverse values.

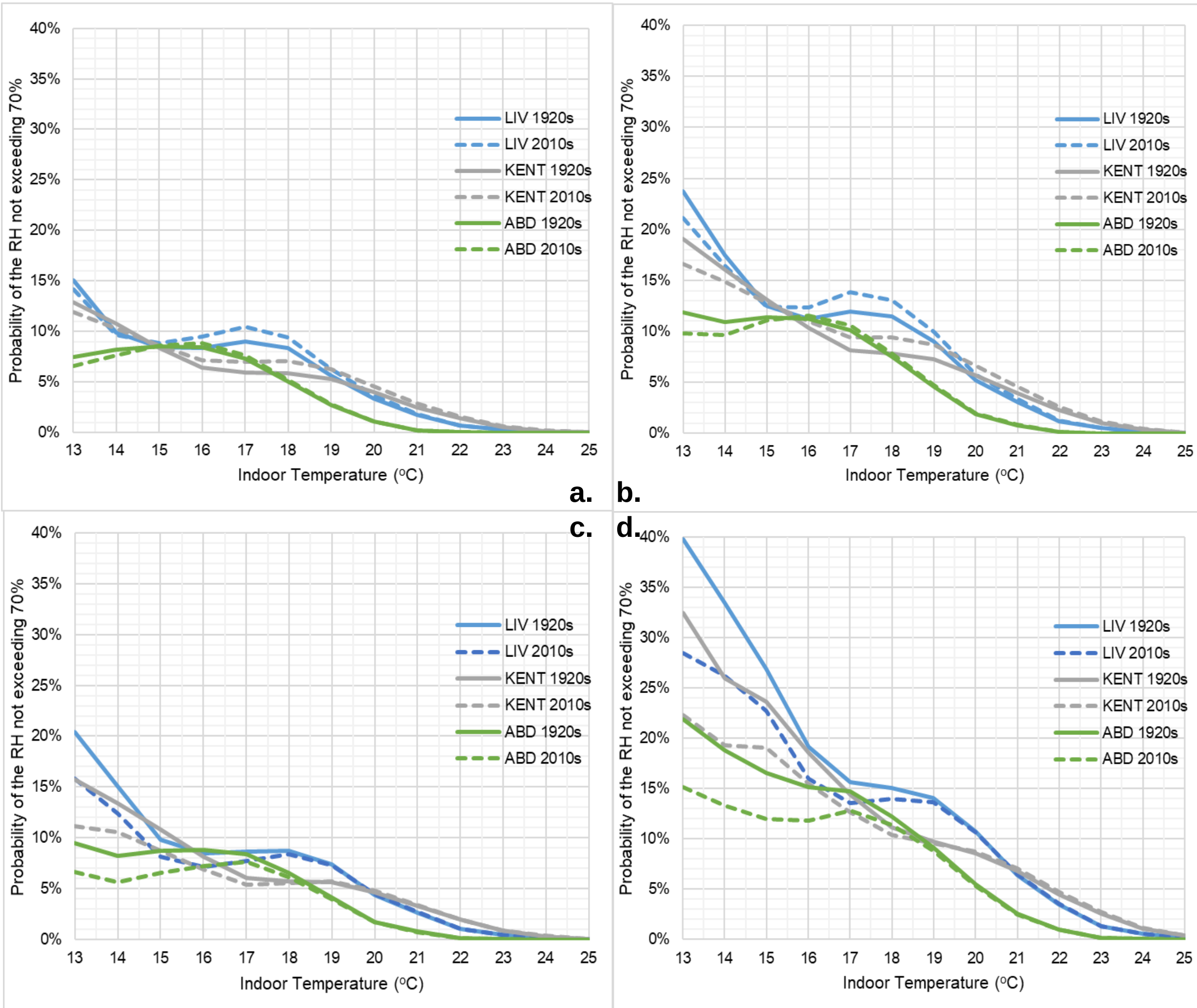


Figure 12. Comparison for the probability of indoor RH becoming >70% RH 1920s and 2010s housing typologies in Liverpool, Aberdeen, and Kent over the entire year of 2017 with **a.**) 2 occupants and flow 0.05m/s, **b.**) 2 occupants and flow 0.025, **c.**) 4 occupants and flow 0.05m/s and **d.)** 4 occupants and flow 0.025.

When the outdoor temperature reduces and there is a requirement of a heater for this 'optimum' indoor temperature to be reached. In terms of RH, the correlation between the probability of the relative humidity exceeded 70% in Figure 12 a and the percentage of the heater in the 'on' state shown in Figure 13 a is negatively correlated. This result shows that the decrease in the use of the heater will increase the probability of the relative humidity exceeded 70%, particularly the dwellings in Kent have the most significant inverse correlation values. Therefore, the lower the annual temperature in the area will benefit more from reducing the minimum indoor temperature setpoint to 16^{o}C. This judgement is based on the annual temperature of Liverpool in 2017, which is 8.247 ^{o}C warmer than the annual temperature of Kent, which is 7.535 ^{o}C. Aberdeen has the lowest inverse correlation among the other two cities due to its annual temperature value, which is the warmest compared to Kent and Liverpool. The annual temperature of Aberdeen in 2017 was 8.559 ^{o}C, as shown in figure 8.

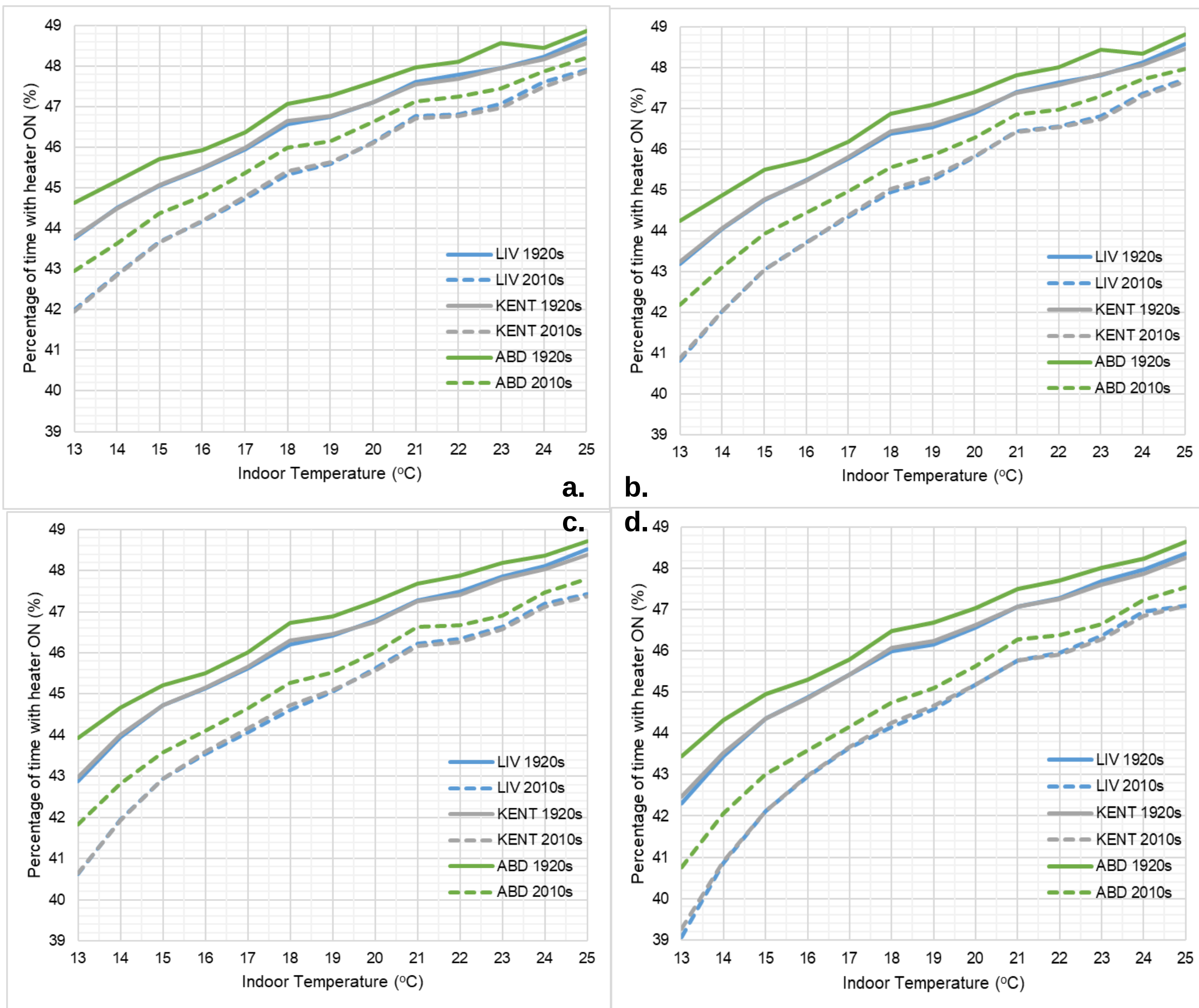


Figure 13. Comparison for the percentage of time with the heater on in 2017 for the 1920s and 2010s housing typologies in Liverpool, Aberdeen and Kent with **a.)** 2 occupants and flow 0.05m/s, **b.)** 2 occupants and flow 0.025, **c.)** 4 occupants and flow 0.05m/s and **d.)** 4 occupants and flow 0.025.

This trend shows that to minimize the probability of the indoor relative humidity not exceeding 70%, the location will not give significant value if the temperature inside the dwelling is maintained at least 16^{o}C in the house with 4 occupants. The house typology will have a significant impact on thermal comfort when the temperature set point is below 16^{o}C. When the temperature set point is above 20^{o}C, the dwelling typology becomes no longer important to the comfort but only give the impact in the energy usage. The indoor temperature is demonstrated to be efficient in the range between 16^{o}C - 20^{o}C. Therefore, recommending 16^{o}C temperature set point to become the minimum set point for comfort standard temperature would be desirable.

Outlined in Figure 13 a, the energy used for the heating in the dwelling is represented by the percentage of the heater activated. The more percentage value, the more energy spent to reach the desired indoor temperature. The heating energy usage represented by the heater on state percentage over the year can be compared between different set point and different housing typology. To reach the indoor temperature set point of 13 °C, the Liverpool 1920s' house heater must be turned on for about 44% throughout the year, while the Liverpool 2010s' house heater will be on for about 42%. The result will be proportional to about a 1% difference in the 25°C set point. To reach the comfort temperature of 16 °C for example, the heater in the Liverpool 1920s' house will be turned on 45.5% in a year, but it only needs 44% in a year for the 2010s' house in Liverpool to reach the minimum temperature of 16°C. With the same temperature setting in the Aberdeen 1920s' house typology, it needs higher on time which is 46% due to the lower outdoor temperature. However, lowering the temperature from 18 °C to 16 °C for example will decrease more than 1% of the heating energy.

Like the dwelling with 2 occupants, Figures 13 c and d show the heater state for 4 occupants, The heater activated time is decreased with the use of better insulation material in the 2010s' dwelling. The two additional occupants' presence will decrease the heater on time to more than 1% in the 2010s' dwelling with 13°C setpoints shown in Figures 13 c and d but less than 1% in the 1920s' house. The value decrease also will be less significant in the higher temperature set point.

Based on the simulation result where 2% of heating energy can be conserved by the 2010s, dwelling typology and with the assumption of 16,500 kWh - 22,000 kWh on annual heating energy consumption per household per year, the energy-saving per house per year will be in the range of 330 - 440 kWh. If it's multiplied by the number of '1920s' homes which are approximately 36.6% of the total dwellings (approximately 8.76 million homes), the total energy conservation across the UK will reach about 2.89 - 3.85 billion kWh. The carbon reduction per year can reach approximately 635.8 - 847 thousand tonnes with 220 gCO2eq/kWh.

5. Conclusion

Simulations and modelling can give a better view of the parameters required to improve thermal comfort and indoor hygrothermal conditions. This work examined dwelling typology from the 1920s and 2010s, in addition to locational environmental conditions from Kent, Liverpool and Aberdeen, whilst varying occupancy (2 and 4 people) to represent the UK dwellings.

This paper successfully modelled the use of a heater by considering the outside temperature and the requirement of its "power on" to maintain high indoor thermal comfort. From modelling the quantity of time and temperature the heater would be required to function for, the effects on RH and energy demand of each dwelling can be studied.

The simulation result shows that the 2010s' dwelling has an advantage of decreasing energy for heating. Furthermore, the number of occupants within the dwelling does not significantly reduce the energy required for heating 1920s' dwellings but can reduce energy requirements for heating 2010s' properties, especially in lower setpoint temperature. The indoor temperature is demonstrated to be efficient in the range between $16^{o}C$ - $20^{o}C$.

Regarding indoor RH, lowering the current temperature set point to about $16^{o}C$ will give healthier indoor conditions regardless of the dwelling location. Because of the uniformity of all home locations to this temperature, it could be proposed and recommended that this be a potential standard indoor temperature setting for optimum thermal comfort.

When considering the quantity of 1920s homes within the UK, reducing the set point temperature to $16^{o}C$ will annually contribute to the carbon footprint reduction of approximately 635.8 - 847 thousand tonnes, what this paper has therefore highlighted the true impact of lowering an indoor setpoint temperature for indoor thermal comfort and its extensive environmental benefits.

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