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2 The Role of Hygrothermal Modelling for Different Housing Typologies by

3 Estimating Indoor Relative Humidity, Energy Usage and Anticipation of Fuel

4 Poverty

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13 **Highlights:**

- 14 • There is a huge gap between building energy regulation and its implementation in the
- 15 construction industry.
- 16 • A probabilistic approach is used to design retrofitting solutions for building energetic
- 17 rehabilitation and relative humidity (RH) management in residential houses from the 1920s and
- 18 2010s with the representations in three different areas.
- 19 • The work analyses the effect of fuel poverty and anticipating global climate change on a
- 20 healthier indoor environment.
- 21 • The indoor temperature is demonstrated to be efficient in the range between 16°C - 20°C,
- 22 highlighting the need to review regulation.
- 23
-

24

25 **Abstract**

26 The nature of deem-to-satisfy standards in building energy performance results in a lack of insight over

27 their consequences. As a result, there is a huge gap between regulation and implementation in the

28 construction industry. The procedure proposed in this article aims to implement the probabilistic

29 approach method to design retrofitting solutions for building energetic rehabilitation and relative

30 humidity management. This is completed by considering the uncertainty associated with a building's

31 physical parameters, savings estimation, weather forecast, occupants' behaviour and building ventilation.

32 A computational hygrothermal modelling approach is utilised to emphasise the differences in the indoor

33 conditions for two typologies of residential houses common in the United Kingdom, located in three cities

34 with different weather conditions and fuel poverty levels: Liverpool, Aberdeen, and Kent. The first model

35 corresponds to houses built to standards from the 1920s', with solid external walls, and the second house

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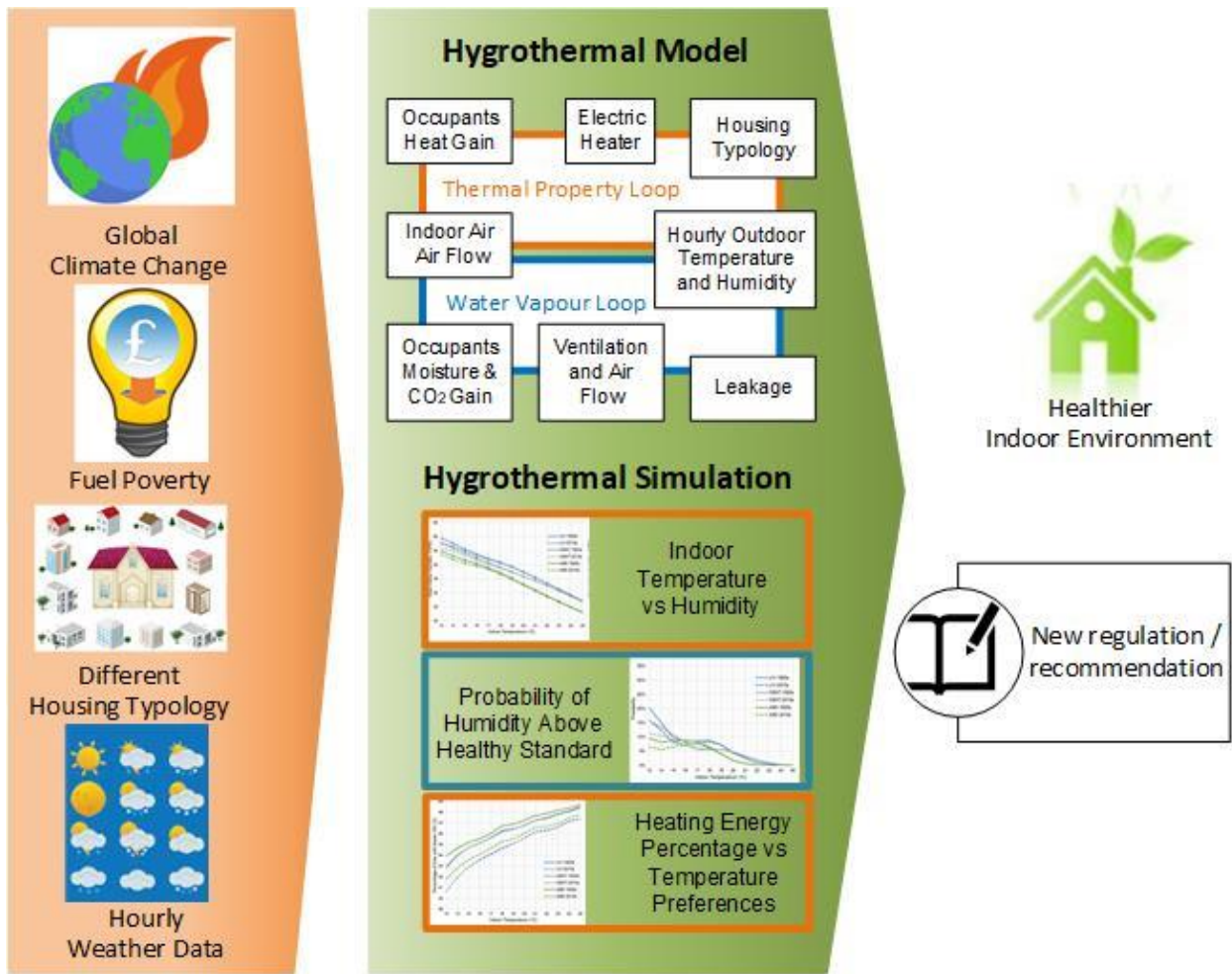
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36 model uses the 2010s' construction solution, where the double-glazed windows and the wall insulation
 37 materials are implemented. The indoor temperature is demonstrated to be efficient in the range between
 38 16°C - 20°C. Lowering the current temperature set point to about 16°C will give healthier indoor
 39 conditions regardless of dwelling, highlighting the need to review the regulation. The simulation shows
 40 that 2% heating energy can be conserved for indoor thermal comfort and extensive environmental
 41 benefits. On particular assumption of energy use per household, this work will annually contribute to the
 42 carbon footprint reduction of approximately 635.8 - 847 thousand tonnes.

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

44 **Graphical Abstract:**



45

46 **1. Introduction**

47 In developed and industrialised countries, approximately 80-90% of human behaviour is spent indoors
 48 where the air quality can be significantly worse than outside [1, 2]. Despite this, there are only limited
 49 standards available for IAQ in housing, where the only exceptions are for places of work[3, 4]. Starting the
 50 process of analysing and understanding how occupants' comfort and health is affected by IAQ the quality

51 of the building structure, finish, furnishings, and the degree of crowding of such environments and the
52 various human activities must be considered. Therefore it is crucial for the development and
53 implementation of a strategy to protect and promote the health and safety of those inside dwellings on
54 both a national and international level (such as European prevention plans and United Nations programs
55 on the Sustainability Development Agenda [4] and World Health Organisation (WHO) predictions [4]).

56 Although there has been a decrease during the pandemic, CO₂ emissions have previously grown by 1.7%
57 to reach 33.1 Gt in 2018 and become the highest growth in emissions since 2013 [5]. Although Global
58 Climate Change (GCC) can decrease heating needs by 2%, the need for air conditioning during summer
59 will increase because of increased humidity[6, 7]. As a function of time, the GCC impact will become
60 increasingly worse and globally will require approximately 3% excess energy [8]. Consequentially, the UK
61 will introduce a Future Homes Standard, mandating the end of fossil-fuel heating systems in all new
62 houses from 2025 [9]. Coupled with this, in the current building stock, many existing dwelling cannot
63 provide enough protection against either heat and/or cold weather fluctuations [10], reducing both IAQ
64 and thermal comfort for dwellings. Thermal comfort has become researchers' focus prior 1920 to date
65 due to the importance in the health aspects, energy usage, wellbeing, air quality factors (such as CO₂
66 levels) and productivity [11, 12] [13]. The analysis focus on human physiology which brought by Fanger's
67 research, human behaviour and psychology raise by adaptive thermal comfort approach. There is also
68 findings that people can have less body fat by regulating the indoor temperature with frequent cold
69 exposures [14]. The exposure to cold acclimation can improve the subjective responses to cold [15]

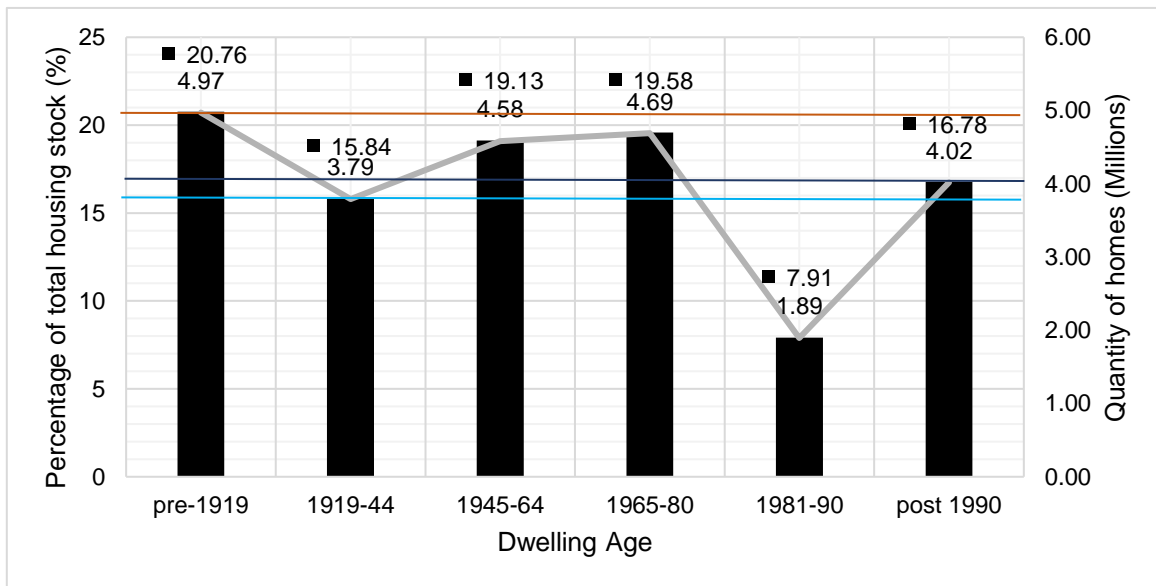
70 To gauge the requirements for parameters to improve thermal comfort and indoor hygrothermal
71 conditions there must be an investigation into the age, the number of properties, energy efficiency (and
72 therefore fuel demand). Consequentially it also must be understood as to how this can be measured and
73 predicted to optimise the retrofit of the current building stock. One of the key success factors in the
74 implementation of regulations is by completing appropriate, relevant, and thorough simulations and
75 modelling, giving a better view, and understanding of the problem and its potential solution. This paper
76 provided the hygrothermal simulation which utilised building typologies from both typical residential
77 properties utilising 1920s and 2010s building codes to model mean indoor relative humidity as a
78 consequential effect of locational weather conditions with the simulation conducted for different thermal
79 setting. This work used MATLAB as a HAM simulator and SIMSCAPE to simplify and accelerate the
80 simulation process where the previous model implements the MATLAB, and the differential equations
81 system was calculated using COMSOL. This paper has a potential influence on nearly 13 million homes in

82 the United Kingdom (UK) and potentially other areas that have the similar conditions. The locations
 83 analysed are Kent, Liverpool and Aberdeen and due to their varied climates, to maintain thermal comfort,
 84 this model was also able to predict the percentage of time with the heater turned on which represent the
 85 energy used for heating.

86 2. Driving Factors

87 2.1. Current problems related to residential dwellings in the UK

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



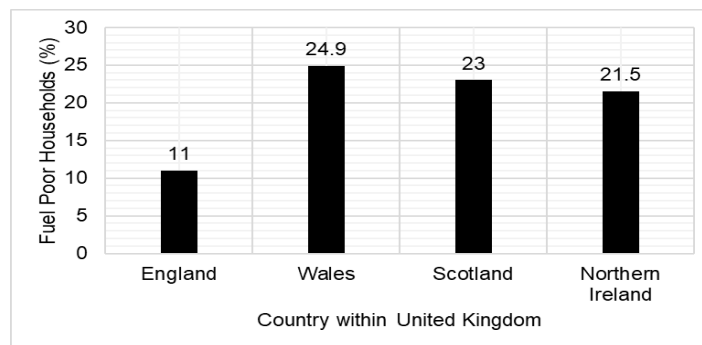
96 **Figure 1.** Dwelling age of properties of English homes[16].

97 The dwellings which are built using solid masonry bricks without air gaps (solid uninsulated walls) are
 98 referred to as '1920s' homes and were constructed from both pre-1919 and 1919-44 in Figure 1., this
 99 equates to approximately 36.6% of the total dwellings or about 8.76 million homes. The dwellings which
 100 are built using the latest well-insulated walls mentioned in Figure 1 as the post-1990 are about 4.02 million

101 or about 16.8% of the total dwellings. This study will focus on these two main groups which are about
102 12.78 million houses or cover about 53.4% of the total dwelling in the UK.

103 2.2. Fuel Poverty in the UK and Global Climate Change

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



109

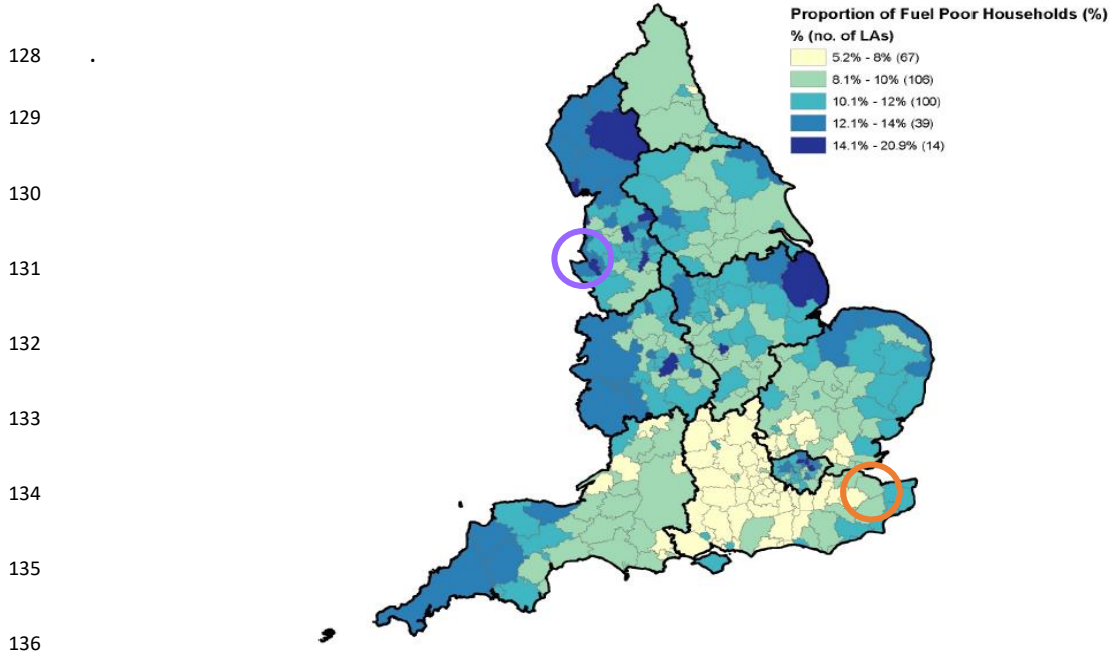
110 **Figure 2.** Percentage of fuel poor households within the UK [19, Welsh 20, Scottish 21, Northern Ireland
111 Housing 22]

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

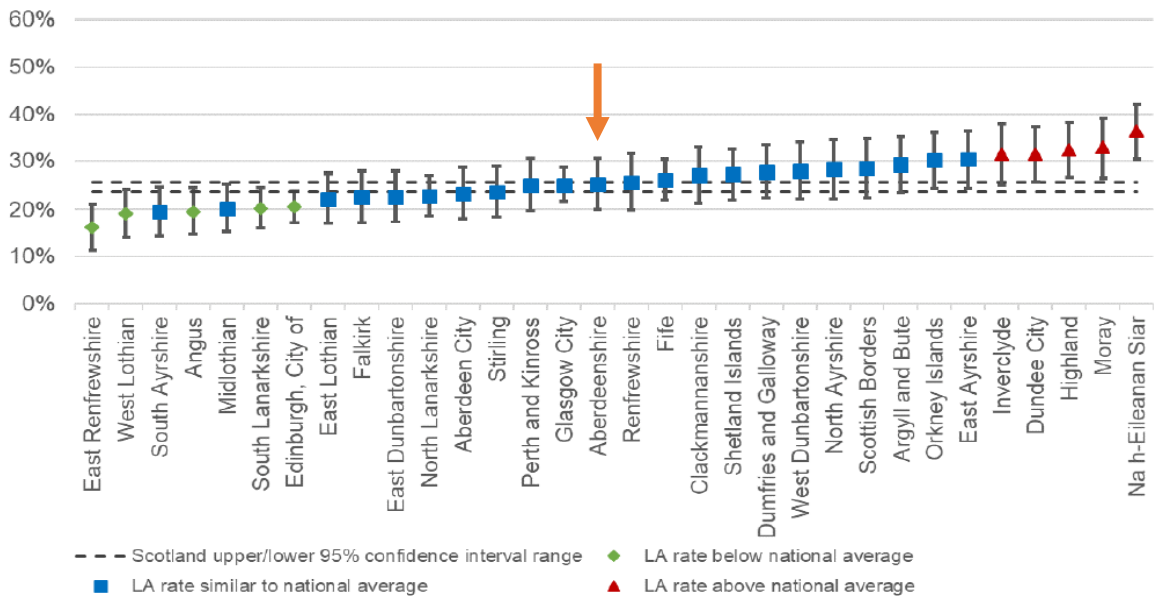
118 By comparison, in Scotland, the national average for fuel poverty households from 2016-18 was 25% [23];
119 this is represented within Figure 4. Aberdeen is highlighted by an orange arrow. The results demonstrated
120 within Figure 4 are that within Aberdeen, fuel poverty is approximately slightly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

122 Further to this, Figure 5 demonstrates a clear correlation to fuel poverty homes and the building envelope
123 typology. Solid and un-insulated homes have the largest proportion of homes that fall into the fuel poverty

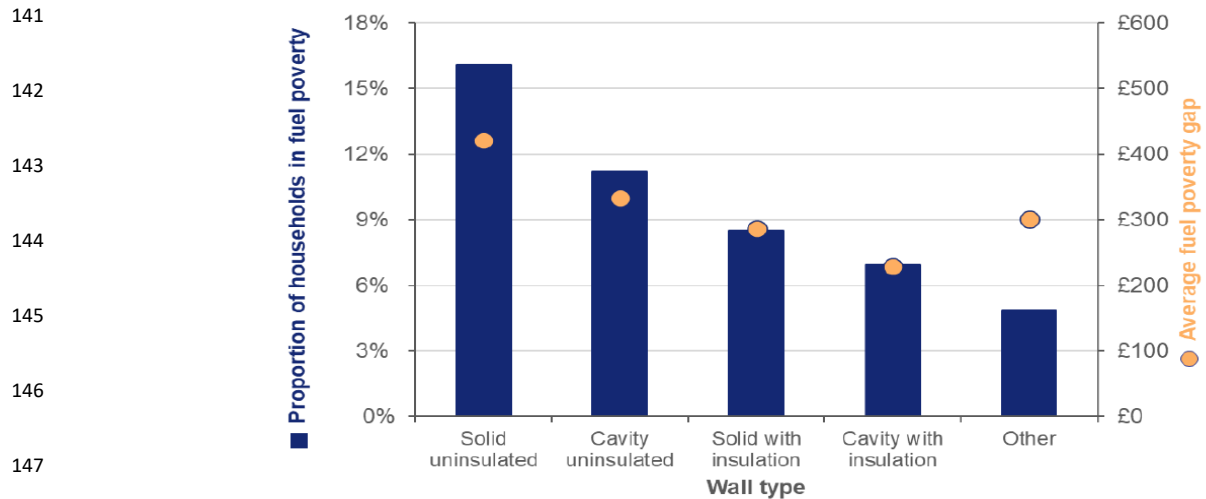
124 classification at approximately 16% of all homes. Figure 5 shows that if residents live in solid uninsulated
 125 homes the average fuel poverty gap is the largest. The fuel poverty gap represents the value or quantity
 126 of money required to move the household out of fuel poverty; for solid, uninsulated homes this is over
 127 £400 per year.



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



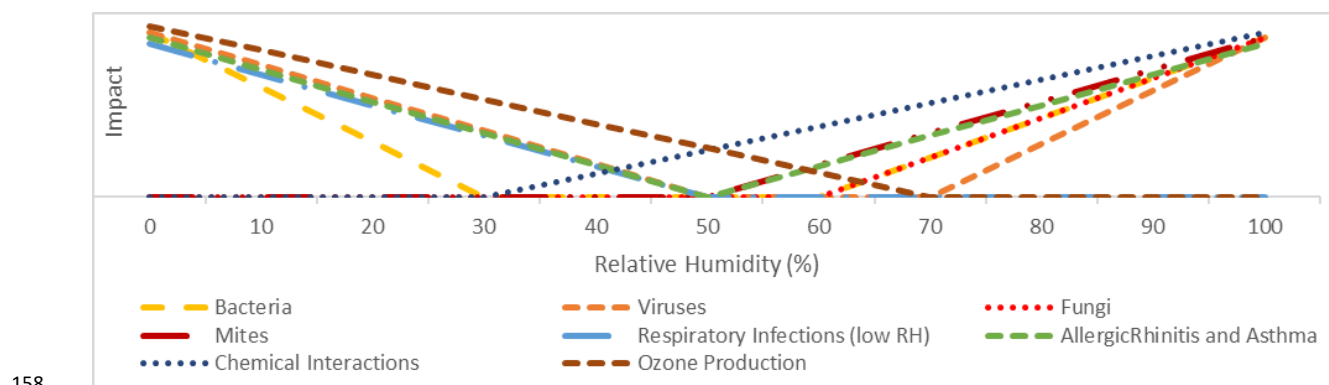
139 **Figure 4.** Percentage of fuel poverty homes in Scotland (by the local authority) (where Aberdeen is
 140 highlighted by an orange arrow) [23].



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

150 **2.3. Indoor Air Quality (IAQ)**

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



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

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

162 Thermal comfort affects all occupants and directly impacts health and productivity [29] which is further
163 exaggerated when succumbing to SBS [30]. SBS was explored by Yu and Crump [31] and Barreca, et al.
164 [32].

165 *2.4. Analysis of other modelling by other researchers*

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

175 Multiple simulation steps were also being done for increasing the accuracy of the model. In this work,
176 Heat, Air and Moisture (HAM) models are being elaborated in three steps: semi-infinite wall approach,
177 adiabatic building envelope, and building envelope with heat and moisture internal gains. This basic model
178 then followed with the complex model with adiabatic building envelope with heat and moisture internal
179 gains integrated with validated building energy simulation (BES)[38]. Besides using WUFI Plus, 3D
180 hygrothermal modelling also uses other software such as COMSOL Multiphysics [39] [40]. Some of the
181 simulation software models such as TRNSYS and TAS do not consider relative humidity. The hygrothermal
182 simulation software such as WUFI Plus can consider the humidity and additional loads such as occupancy
183 [41] using Nottingham's weather files. The thermal comfort parameter for relative humidity uses the
184 ASHRAE thermal comfort envelope which has the upper comfort limit of 70%RH using WUFI Plus. The
185 calibration and validation process using the climatic chamber compared with the software model has been
186 completed in Antretter, et al. [42]. The validation using the actual measurement in the real building,
187 compared with the simulation result, has been explored in Coelho, et al. [43] and Francesca, et al. [38].
188 Coelho, et al. [43] addresses the importance of using detailed outdoor weather file and the soil
189 temperature. The real data from the weather station, even if it is not located directly on the premises,
190 will help obtain a more precise result. Using the weather files obtained from WUFI and EnergyPlus

191 database resulted in lower precision. The importance of using multiple geographical locations for
192 simulation is also mentioned in work for simulating the moisture [44].

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

203 **3. Methodology**

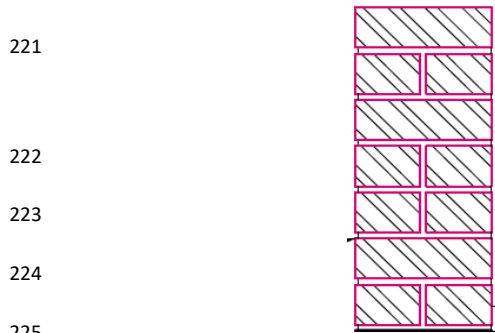
204 *3.1. Modelling Approach and input characteristics*

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

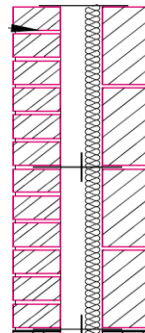
211 **3.1.1 Construction Typology**

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

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



226 **Figure 7a.** 1920s Solid
227 masonry wall.



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

231

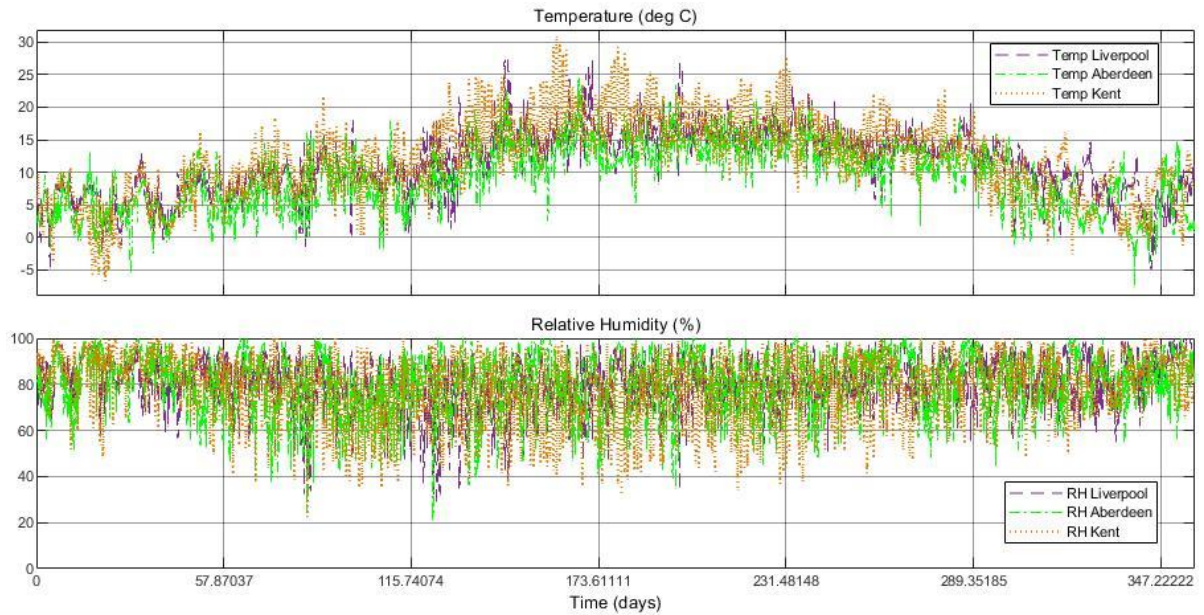
232 **3.1.2. Location environmental conditions**

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

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

242 Figure 8 demonstrate that out of the three locations there is a greater temperature range in Kent
243 compared to Aberdeen and Liverpool. Aberdeen had the coldest temperature reading among the three
244 locations, but Kent had the lowest mean temperature (7.54°C) in 2017 compared with Aberdeen (8.56°C)
245 and Liverpool (8.25°C). The mean temperature of all cities was still below 9 °C. When considering RH
246 Aberdeen had the lowest mean RH (80.57%RH), but all area still had the mean relative humidity above
247 80% (Kent 82.99% RH and Liverpool 82.26%RH).

248



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

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

247 **3.2. Model Input Parameters**

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

253 **3.3. Model Detailing and Assumptions**

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

Table 1. Model Parameters.

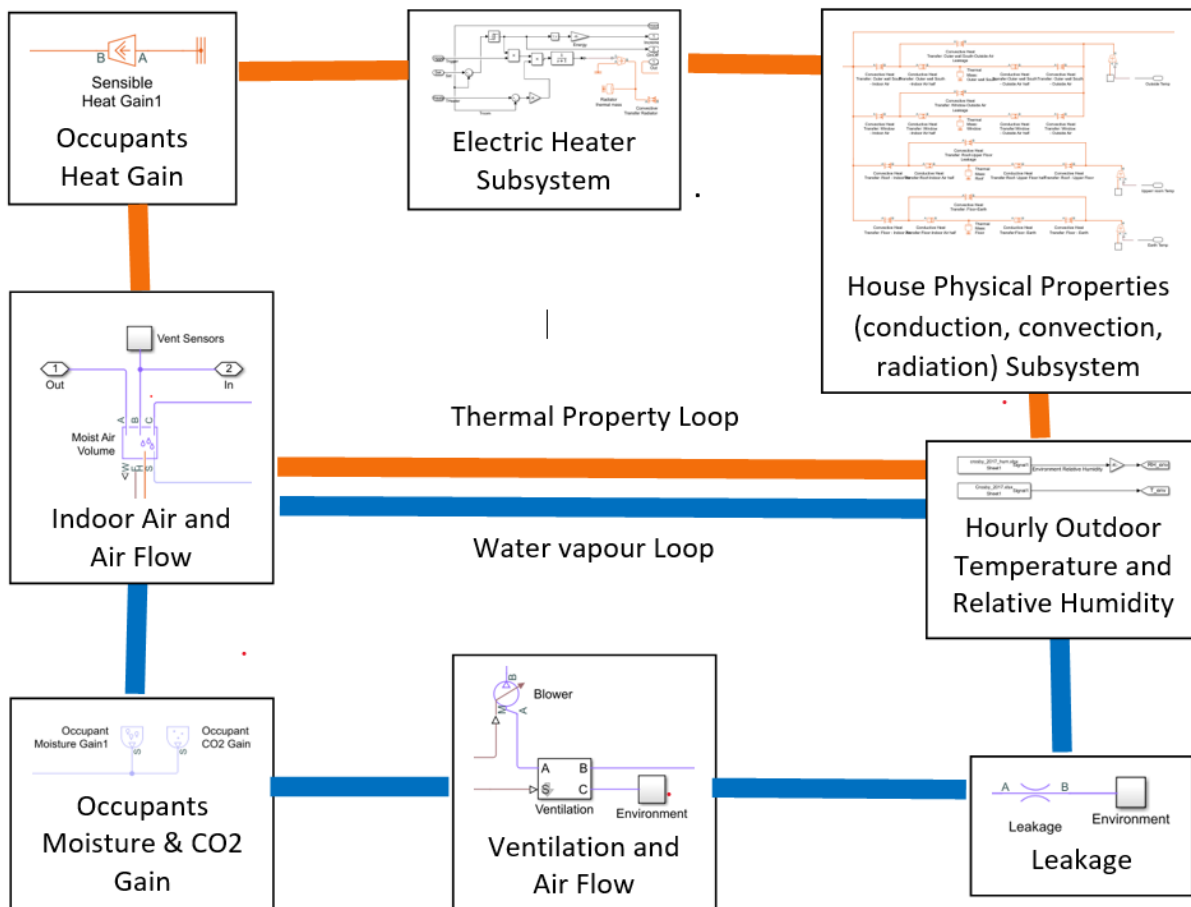
General				
<i>Input Parameter</i>		<i>Value</i>		
Number of Occupants		2 and 4		
Sensible heat per occupant, (W)		100		
Ventilation area, (m ²)		0.01		
Flow (m/s)		0.05 and 0.025		
Room Dimensions				
<i>Input Parameter</i>		<i>Value</i>		
Room Volume (m ³)		31.84 (4.35 x 3.05 x 2.4)		
Window Area (m ²)		2.8314		
Door Area (m ²)		3.4		
Housing Typology Characteristics				
<i>Typology Description</i>	<i>Specific Heat Capacity (J/(kg K))</i>	<i>Thermal Conductivity (W/mK)</i>	<i>Wall Thickness (m)</i>	<i>Density (kg/m³)</i>
1920s house solid brick wall	800	0.98	0.215	1920
2010s house internal blockwork concrete block	1000	0.51	0.1	1400
2010s house insulation	1500	0.022	0.09	30
2010s house outer facing brick	800	0.98	0.1025	1920

259

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

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

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



280

281 **Figure 9.** Overview of the Simscape MATLAB Model

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

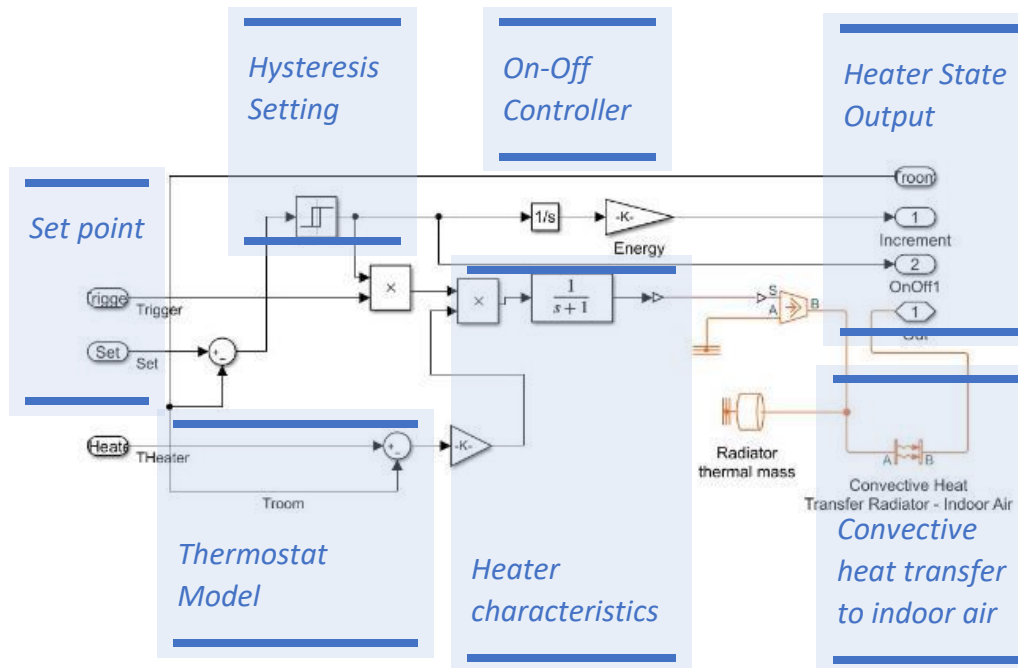


Figure 10. Simplified electric heater model in the Simscape simulation.

289

290 This model uses the following assumptions:

291 • The heater is a model of the convective panel electric heater. The temperature of the panel when
 292 switched on is 40 °C. Dimensionally, the panel heater is 0.9 x 0.4 m² with a mass of 46.7 kg and
 293 radiator specific heat capacity is 447 %J/(kg K) and the heat transfer coefficient is assumed to be
 294 100 %W/m²K

295 • Occupants are simulated to be present all the time (24 hours) and having the same activity level.
 296 The amount of moisture produced to use the approximation of occupants being at a low activity
 297 or resting and as per BS 5925:1991 [51] and the ASHRAE Handbook Fundamentals - 2017 [52] RH
 298 is no greater than 70%. Each occupant is assumed to produce a 50 g/h moisture level as per BS
 299 5925:1991 standard (as the value is 40 g/h for resting and 55 g/h for heavy activity) . The model
 300 uses this single figure to represent the effect of human respiration with the different metabolism
 301 rate and other activities such as cooking.

302 • The solar heat gain is simplified in this model and not calculated using the weather files as
 303 temperature and humidity are.

304 • There is no air conditioning used in this model, the thermal set point is applied as a threshold for
 305 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 CO₂ level is below 1000 ppm for 2 and 4 occupants. This model uses the CO₂ gain per occupant value of 0.01 g/s and the CO₂ 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 °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 °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.

Area	Simulation Result			ASHRAE Global Thermal Database II						
	Temperature (°C)	Relative Humidity (%)	Indoor Air Velocity (m/s)	Temperature (°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 °C with a standard deviation of 1.93. The mean air

332 velocity value is 0.07 m/s with a standard deviation of 0.06. Our simulation shows that for the average
333 temperature between 22 °C and 23 °C with the indoor air velocity of 0.05 m/s, the RH is between 38.7%
334 and 40.63%. The average RH value deviation is less than 2%, so it justifies our simulation result.

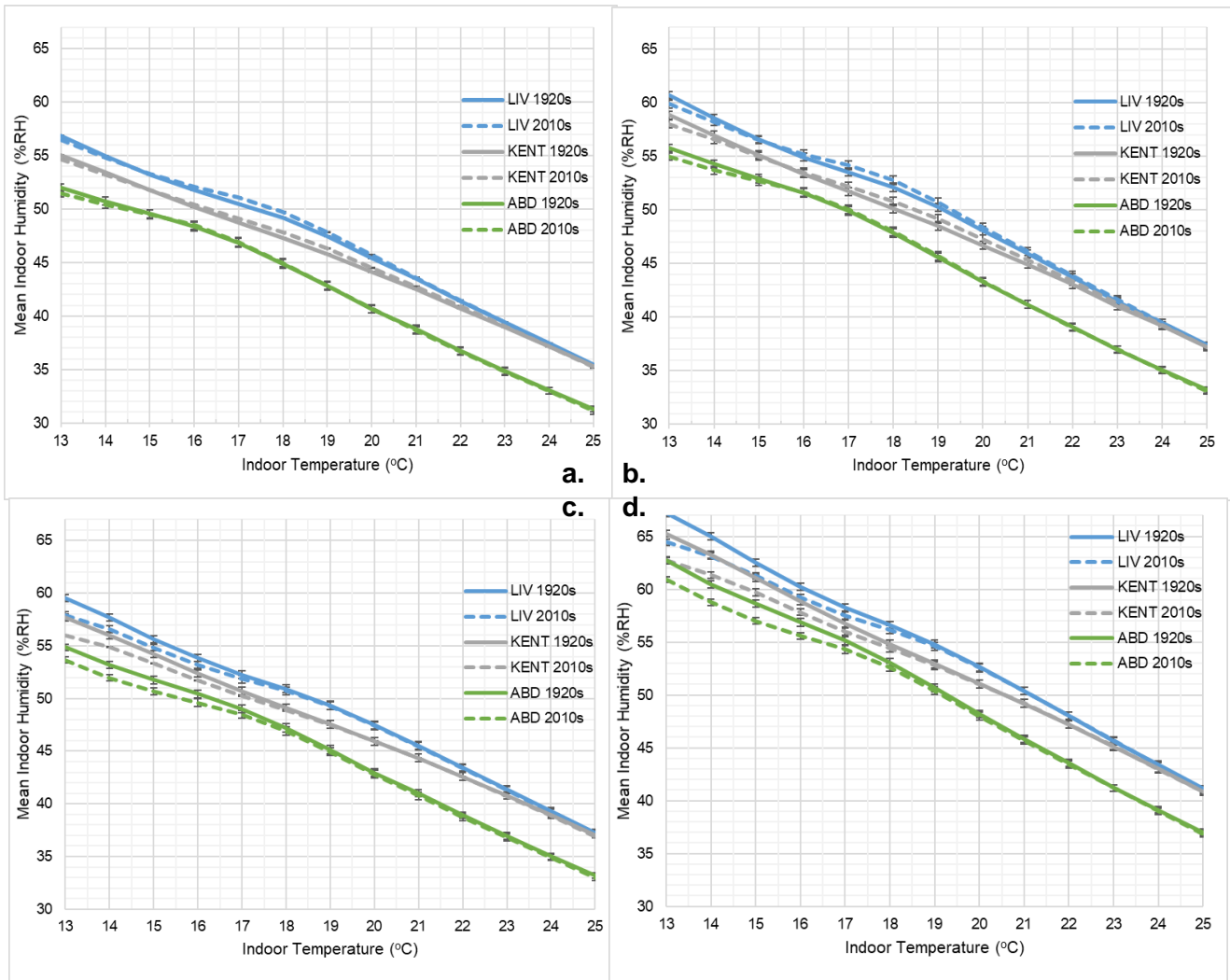
335 **4. Results and Discussion**

336 Simulations were completed to compare the performance of the housing location and construction
337 typologies with 2 and 4 people inside a room over 24 hours as demonstrated in Figure 11. The ventilation
338 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
339 CO₂ levels, a ventilation rate of 0.05 for 2 occupants inside the room will reach about 650 - 700 ppm;
340 whereas for 4 occupants inside the room, CO₂ levels will reach about 900 to 950 ppm. Both of which are
341 still considered within the healthy region. By comparison, when the ventilation rate is halved to 0.025, the
342 CO₂ level will rise to 900 - 950 ppm for 2 occupants and with 4 occupants these levels rise to an unhealthy
343 level of 1400 - 1450 ppm. Besides simulating the CO₂ values, this work will also focus on relative humidity
344 levels and if they can be considered healthy. What is demonstrated is that the annual mean indoor
345 humidity is among the value range with no negative health effects, based on the simulation as outlined in
346 H.M.Government [25] except the case of 4 occupants with a ventilation rate of 0.025.

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

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

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



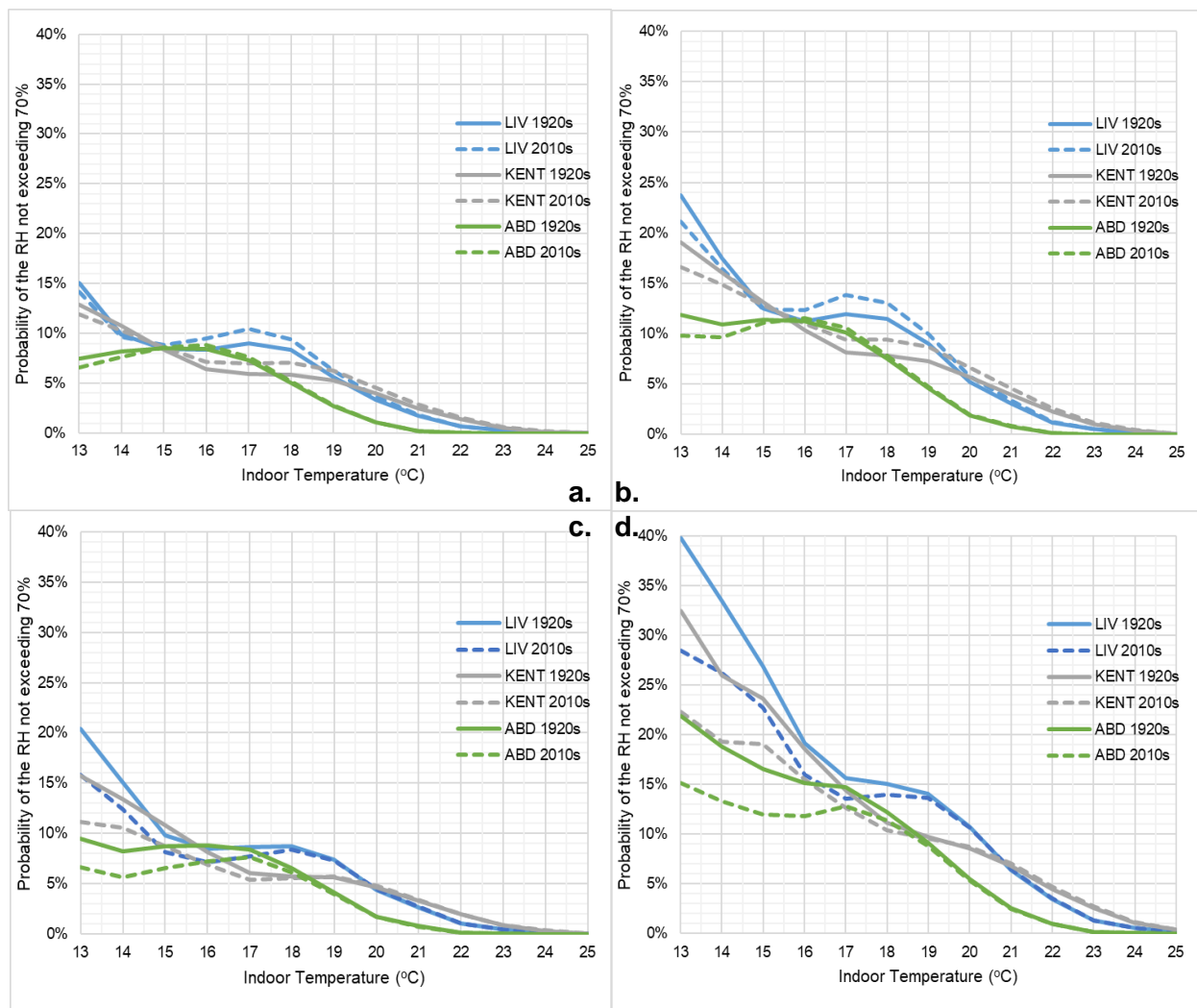
368 **Figure 11.** Comparison of mean indoor relative humidity (% RH) for the 1920s and 2010s housing
 369 typologies in Liverpool, Aberdeen and Kent over the entire year of 2017 with **a.)** 2 occupants and flow
 370 0.05m/s, **b.)** 2 occupants and flow 0.025, **c.)** 4 occupants and flow 0.05m/s and **d.)** 4 occupants and flow
 371 0.025.

372 Figure 12 a, b and c demonstrate the probability of the relative humidity exceeded 70%, all the results
373 show the value below 25%. Only in Figure 12 d, for a dwelling with 4 occupants and ventilation flow 0.025
374 has the relative humidity exceeded 70% value above 25%. Besides CO₂ level, the value of the RH makes
375 IAQ conditions unhealthy. The graph displayed in Figure 12 a - d are not linear because of the humidity
376 change due to the heater effect. The use of a heater will decrease the indoor relative humidity. The 2010s'
377 dwelling tends to have higher humidity compared to the 1920s' dwelling. This happens due to the
378 difference in the heater state. In 1920s' dwelling, the desired temperature has to be achieved with the
379 heater activated, while in the 2010s' dwelling, the temperature still can be reached with no heater as
380 2010s' dwelling has better insulation to maintain the indoor temperature.

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

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

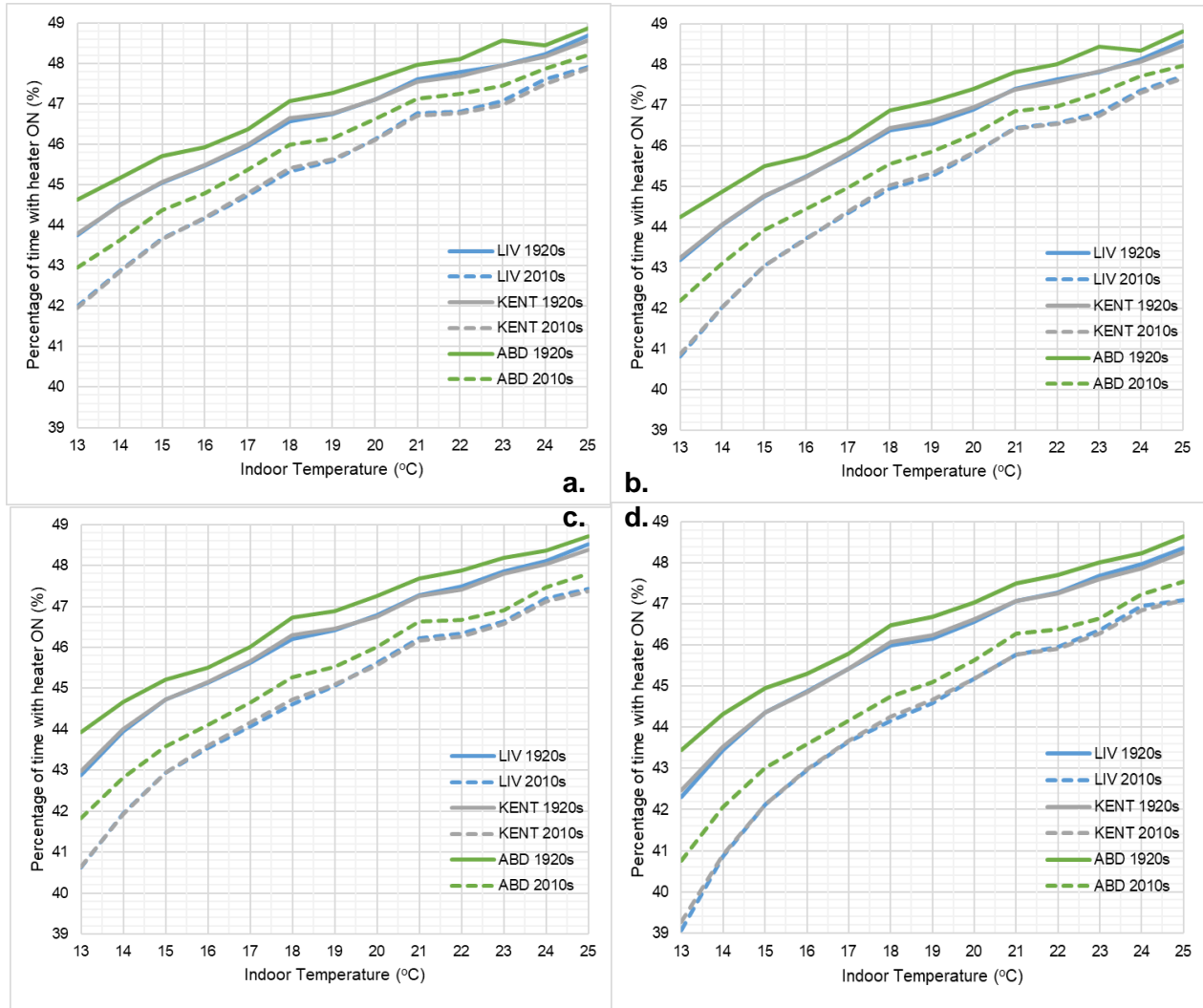
392 Figures 12 c and 12 d shows that the 2010s' dwelling typology beginning to show the superior result
393 compared to the 1920s'. The probability of the RH exceeds 70% can be lowered down while still conserve
394 the energy for indoor heating. The correlation values between the probability of the relative humidity
395 exceeded 70% in Figure 12 c and the percentage of the heater activated is shown in Figure 13 c is similar
396 with the 2 occupants. In 1920s' dwellings, for Liverpool, Kent, and Aberdeen, the values are -0.9694, -
397 0.9903, and -0.9405. For the 2010s' dwellings, for Liverpool, Kent, and Aberdeen, the values are -0.9624,
398 -0.9754, and -0.8564. The two groups have negative correlation values with the dwellings in Kent have
399 the biggest inverse values.



400 **Figure 12.** Comparison for the probability of indoor RH becoming >70% RH 1920s and 2010s housing
 401 typologies in Liverpool, Aberdeen, and Kent over the entire year of 2017 with a.) 2 occupants and flow
 402 0.05m/s, b.) 2 occupants and flow 0.025, c.) 4 occupants and flow 0.05m/s and d.) 4 occupants and flow
 403 0.025.

404 When the outdoor temperature reduces and there is a requirement of a heater for this 'optimum' indoor
 405 temperature to be reached. In terms of RH, the correlation between the probability of the relative
 406 humidity exceeded 70% in Figure 12 a and the percentage of the heater in the 'on' state shown in Figure
 407 13 a is negatively correlated. This result shows that the decrease in the use of the heater will increase the
 408 probability of the relative humidity exceeded 70%, particularly the dwellings in Kent have the most
 409 significant inverse correlation values. Therefore, the lower the annual temperature in the area will benefit
 410 more from reducing the minimum indoor temperature setpoint to 16°C. This judgement is based on the

411 annual temperature of Liverpool in 2017, which is 8.247 °C warmer than the annual temperature of Kent,
 412 which is 7.535 °C. Aberdeen has the lowest inverse correlation among the other two cities due to its
 413 annual temperature value, which is the warmest compared to Kent and Liverpool. The annual
 414 temperature of Aberdeen in 2017 was 8.559 °C, as shown in figure 8.



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

418 This trend shows that to minimize the probability of the indoor relative humidity not exceeding 70%, the
 419 location will not give significant value if the temperature inside the dwelling is maintained at least 16°C in
 420 the house with 4 occupants. The house typology will have a significant impact on thermal comfort when
 421 the temperature set point is below 16°C. When the temperature set point is above 20°C, the dwelling

422 typology becomes no longer important to the comfort but only give the impact in the energy usage. The
423 indoor temperature is demonstrated to be efficient in the range between 16°C - 20°C. Therefore,
424 recommending 16°C temperature set point to become the minimum set point for comfort standard
425 temperature would be desirable.

426 Outlined in Figure 13 a, the energy used for the heating in the dwelling is represented by the percentage
427 of the heater activated. The more percentage value, the more energy spent to reach the desired indoor
428 temperature. The heating energy usage represented by the heater on state percentage over the year can
429 be compared between different set point and different housing typology. To reach the indoor
430 temperature set point of 13 °C, the Liverpool 1920s' house heater must be turned on for about 44%
431 throughout the year, while the Liverpool 2010s' house heater will be on for about 42%. The result will be
432 proportional to about a 1% difference in the 25°C set point. To reach the comfort temperature of 16 °C
433 for example, the heater in the Liverpool 1920s' house will be turned on 45.5% in a year, but it only needs
434 44% in a year for the 2010s' house in Liverpool to reach the minimum temperature of 16°C. With the same
435 temperature setting in the Aberdeen 1920s' house typology, it needs higher on time which is 46% due to
436 the lower outdoor temperature. However, lowering the temperature from 18 °C to 16 °C for example will
437 decrease more than 1% of the heating energy.

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

443 Based on the simulation result where 2% of heating energy can be conserved by the 2010s, dwelling
444 typology and with the assumption of 16,500 kWh - 22,000 kWh on annual heating energy consumption
445 per household per year, the energy-saving per house per year will be in the range of 330 - 440 kWh. If it's
446 multiplied by the number of '1920s' homes which are approximately 36.6% of the total dwellings
447 (approximately 8.76 million homes), the total energy conservation across the UK will reach about 2.89 -
448 3.85 billion kWh. The carbon reduction per year can reach approximately 635.8 - 847 thousand tonnes
449 with 220 gCO₂eq/kWh.

5. Conclusion

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451

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

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

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

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

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

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