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Modeling the effect of occupants' behavior on household carbon emissions

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Abstract

Occupants' behavior has proven its significant impact on buildings performance. The research on carbon emissions has therefore recommended the integration of the technical and behavioral disciplines in order to accurately predict buildings carbon emissions. While various models were developed that consider the actions of occupants based on quantitative data, there are little efforts that link the impact of occupants' behavior on selected energy strategies while also consider the economic, technological, and environmental impacts. For this research, a dynamic model will be developed to simulate the interaction of occupants' behavior with various energy efficient scenarios to reduce carbon emissions. The model will help test the effectiveness of certain energy efficient scenarios before implementation. This paper illustrates the structure and the application of the proposed model. The model results show that the behavioral change can contribute enormously to the carbon emissions reduction even without the installation of more energy efficient improvements.

Keywords: Household Carbon Emissions, Occupants Behavior, System Dynamics

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Introduction

Building Services Research Information Association (BSRIA) (2011) reported that the currently used technology is a key reason for creating a gap between the actual and the predicted performance of buildings. Mahdavi and Pröglhöf (2009), and Azar and Menassa (2012) submitted that occupants' behavior affects significantly on the dwellings performance. Occupancy-focused interventions can systematically reduce energy consumption especially for existing buildings where installing energy efficient technologies is demanding, Oreszczyn and Lowe (2010). Therefore, the research in this area has been developed in a multi-disciplinary approach that integrates engineering, economics, psychology, or sociology and anthropology disciplines in order to accurately predict the performance of dwellings when occupied, such as the work of: Gram-Hanssen (2014); Tweed *et al.* (2014); CIBSE (2013); Kelly (2011); Abrahamse & Steg (2011); Yun & Steemers (2011); Bin & Dowlatabadi (2005); Bartiaux & Gram-Hanssen (2005); Moll *et al.* (2005); and Hitchcock (1993). These studies identified the affecting variables, ranked them according to importance, and explained their effects on the household energy consumption.

As a system, the physical components of dwellings are generally reliable. However, the occupants related variables are unreliable, non-linear, and can be irrational. Modeling approaches of energy consumption are quite different from that of occupants' behavior. Although Borgeson and Brager (2008) have used stochastic algorithms to capture the non-linear and unpredictable actions posed by occupants and mapped this with climate data, these models do not sufficiently integrate the occupants' behavioral aspect with energy and carbon emission models.

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The UK Standard Assessment Procedure (SAP) assigns energy rating to dwellings. However, SAP does not fully consider the householders' characteristics in terms of individual occupants' behavior and household size, Building Research Establishment (BRE) (2011). The Inter-governmental Panel on Climate Change (IPCC) (2007) emphasized that "*occupant behavior, culture and consumer choice and use of technologies are also major determinants of energy use in buildings and play a fundamental role in determining carbon emissions*". IPCC (2007) also suggests that energy models should fully incorporate these determinants. Despite BRE Domestic Energy Model incorporates elements of occupants' aspect (such as: number of occupants), they are not explicitly considered, Natarajan *et al.* (2011). Studies of Okhovat *et al.* (2009); Dietz *et al.* (2009); Nicol and Roaf (2005) have given some attention to occupants behavior when evaluating dwellings performance.

Gill *et al.* (2010) estimated how occupants' behavior contributes to variations in dwelling performance using simple statistical computation. Williamson *et al.* (2010) investigated a number of Australian dwellings to test if they meet relevant regulatory standards and revealed that the regulatory provisions do not comprise the variety of socio-cultural understandings, the inhabitants' behaviors and their expectations. The study then suggests that occupants' behaviors should be captured by the standards and regulations.

In this respect, occupancy-focused interventions have been researched which take various forms, such as: continuous occupancy interactions, discrete energy interventions, green social marketing campaigns, and feedback techniques, Allcott and Mullainathan (2010); Carrico and Riemer (2011). Peer pressure, as a continuous interaction technique; considerably affect people behavior towards energy use, Peschiera (2012). This effect varies based on the type of buildings; residential verses commercial, Azar and Menassa (2014). Residential buildings

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tend to have one-social network, however, commercial buildings include multi-social networks representing the different groups of occupants in these buildings. Considering different social groups and the concept of social sub-networks in buildings to represent the multiplicity of cultural attitudes have been addressed by many researches, Mason *et al.* (2007). The discrete occupancy interventions provide opportunities to minimize energy use. Combination of all interventions is required to ensure an improved and sustainable behavioral change over time, Chen *et al.* (2012). Moreover, the concept of variability (occupant's energy intensity over time) was identified to reflect the possibility of an occupant to adopt new energy-use characteristics, Verplanken and Wood (2006). It represents the possibility of a person with strong energy-use attitude to be influenced easier or harder than a person with flexible energy-use attitude. This approved that habits and attitudes of occupants should be considered as main factors when different occupancy intervention techniques are introduced.

Other studies focused more on the classification of occupants' behavior. Barr and Gilg (2006) examined the relationship between different behavioral properties and alternative environmental lifestyles. Clusters of individuals were defined: "committed environmentalists", "mainstream environmentalist", "occasional environmentalists", and "non-environmentalists" with variables relating individuals to each cluster. The Scottish Environmental Attitudes and Behavior (SEAB) (2008) also identified environmental behaviors as: disengaged, distanced, shallow greens, light greens and deep greens. However, Accenture (2010) have introduced eight different categories. The Low Carbon Community Challenge Report (published by the Department of Energy and Climate Change (DECC) (2012)) also has its classification as energy wasters, energy ambivalent, energy aware, and active energy savers. Further similar studies such as Azar and Menassa (2012) and Energy Systems Research Unit (ESRU) (2012) defined frugal, standard, and profligate energy

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consumers. Frugal consumers use energy efficiently. Standard consumers are occupants who do not spend much effort to reduce energy consumption. Profligates are using energy extensively.

For modeling occupants' interaction with dwellings, Stevenson and Rijal (2010) argue that there is a need for a more scientific methodology to link the technical aspect of energy consumption and occupants' behavior in dwellings. There are also previous studies which mainly focus on the interactions of occupants with energy devices in dwellings, Rijal *et al.* (2011); Prays *et al.* (2010); McDermott *et al.* (2010); Haldi & Robinson (2009); Humphreys *et al.* (2008); Kabir *et al.* (2007); Soldaat (2006); Bourgeois *et al.* (2006); Herkel *et al.* (2005); Humphreys & Nicol (1998); Newsham (1994); Fritsch *et al.* (1990); and Hunt (1979). The majority of these studies focused on occupants' behavior to control energy such as using windows for lighting and thermal comfort. Other models have been developed to simulate the occupants' actions based on quantitative data. However, there are little efforts that link the impact of occupants' behavior on selected energy strategies while considering also the economic, technological, and environmental impacts; which this research will focus on.

This research will build on these previous studies and aims to develop a model to simulate the interaction of occupants' behavior with various energy efficient and carbon emissions scenarios. The model will help test the effectiveness of certain energy efficient scenarios before implementation. This paper illustrates the structure and the application of the proposed model.

Model structure

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From the aforementioned discussion, dwellings have two main subsystems which affect each other: the physical (technical) subsystem which represents the dwellings characteristics/parameters and the human (social) subsystem which represents occupants' actions. The variables of the social system include occupants' behavior, occupants' thermal comfort, and household characteristics. The outer environment of the dwellings should also be considered as it has key influences on both the technical and social systems.

The outer environment such as the climatic variables (*e.g.* external temperature, rainfall) affect on the dwellings' heating and ventilation. The occupants' reactions to these effects vary depending on many determinants such as cultural, economic and demographic. This creates a complex system with multi-causal relationships and interdependencies. The variables can be "soft" and/or "hard" with a non-linear changeable behavior over time including multiple feedback loops. Therefore, the proposed model in this research will test various strategies to reduce household carbon emissions considering different occupants' behaviors. The modeling approach adopted for this research uses System Dynamics (SD) methodology.

The first stage of the methodology reviews the literature and published datasets for energy consumption and CO_2 emission in dwellings to identify the model's variables, boundary, and reference modes. 'Reference mode' is the past record of the model variables and how its future trend might be. It is used to validate the results of the proposed model. For this stage, the reports of the UK Department of Energy and Climate Change, metrological department, Office of National Statistics, and Building Research Establishment have been reviewed. The qualitative data used for the model was collected via interviews with energy experts to

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develop the relationships among variables with no empirical data and/or evidence of relationships, and also to ascertain the correctness of the initial relationships drawn.

SD modeling requires developing Causal Loop Diagrams (CLDs) and Stock-Flow Diagrams (SFDs) for the studied system. CLDs show how each variable relate with one another. The details of the CLDs developed for this model can be found elsewhere; Motawa and Oladokun (2015). SFDs covert these CLDs into model formula to simulate the relationships among the identified variables. The SFDs are the central concepts of dynamic systems theory, Sterman (2000). The proposed model consists of six modules as shown in Figure 1: dwelling internal heat, population/household, occupants' thermal comfort, household energy consumption, climatic-economic-energy efficiency interaction, and household CO_2 emissions. The feedback relationships among these modules represented by the identified loops show the complexity of the system. This paper will focus on the part of the model which simulates the effect of occupants' behavior to achieve thermal comfort. The SD environment "Vensim" was used for the simulation of the developed modules.

Insert Figure 1

Occupants Thermal Comfort Module

To estimate thermal comfort, the following parameters are required: wet bulb globe temperature, effective temperature, resultant temperature, and equivalent temperature. Fanger (1970) used basic heat balance equations with empirical studies for skin temperature in order to develop the Percentage People Dissatisfied and the Predicted Mean Vote parameters that can measure thermal comfort, ISO (1994). In addition, the Chartered Institution of Building Services Engineers (CIBSE) (2006a; 2006b) identified comfort measures in certain areas of

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the dwellings for certain occupants' activity, clothing levels, and temperature. The guide of CIBSE (2006b) identifies for bedrooms in winter, for example: clothing level of 2.5 clo., an operating temperature of 17 – 19^{0}C, and occupants' activity of 0.9 met. In addition to specific studied parameters, this module also employs the criteria set out by CIBSE (2006b). These criteria and parameters for estimating occupants' thermal comfort include: 'perceived dwelling temperature', Humidex value, clothing, windows opening within the dwelling, occupants' metabolic build-up, dwelling internal temperature, 'probability of window opening', and 'probability of putting on clothing' by occupants based on the qualitative data collected at the model conceptualization stage. The stock-flow diagram developed to represent the relationships among these criteria and parameters is shown in Figure 2.

Based on these criteria and the developed stock-flow diagram, Equations 1 and 2 below formulate the "occupants' comfort" and "occupants' metabolic build-up". For example, the 'occupants comfort' stock is accumulated by the inflow 'perceived dwelling temperature' which depends on the windows opening within the dwelling, clothing, occupants' metabolic build-up, and Humidex value. 'Humidex value' was driven by the relative humidity extracted from the Humidex chart (shown in Figure 3) and the dwelling internal temperature. These degrees of comfort have been qualitatively represented by the use of lookups within the model. The relative humidity is the driving data within this module (summary is shown in Table 1). The lookups in Figures 4 and 5 show the 'probability of putting on clothing' and 'probability of window opening' based on the qualitative data collected at the model conceptualization stage, details of the data collection for this stage can be found elsewhere, Oladokun (2014). Examples of the developed SD equations are shown in equation 3:5 for the calculation of the Humidex value and occupants' comfort. The main output of this module

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determines the level of occupants' comfort as a key variable to find the overall carbon emissions as will be discussed next.

Insert Figure 2

Insert Figure 3

Insert Table 1

Insert Figure 4

Insert Figure 5

$OC\ (t) = INTEGRAL\ [PDIT, OC\ (t_0)]$ ……………………………………………………………(Eq. 1)

$OMB\ (t) = INTEGRAL\ [OAL + PDIT, OMB\ (t_0)]$ ………………………………………………(Eq. 2)

$HV = IF\ (DIT < 21\ :AND:\ RH < 45), THEN\ (DIT), ELSE\ (NDHS)$ ………………(Eq. 3)

$NDHS = IF\ (DIT < 30\ :AND: RH > 25), THEN\ (NDHS), ELSE\ (SDHS)$…………(Eq. 4)

$SDHS = IF\ (DIT < 36\ :OR: RH > 50), THEN(SD), ELSE(GD)$ ……………………(Eq. 5)

Household Carbon Emissions Module

The household carbon emissions module simulates end uses of energy, namely; (hot water, space heating, lighting, cooking, and appliances). The developed SFD for 'space heating', as an example, is shown in Figure 6. The Figure illustrates the interrelationships among few key variables simulated to calculate the amount of space heating. In addition to 'Occupants' behavior', there are: rate of space heating, space heating energy, effect of energy efficiency on space heating, effect of energy bills on energy consumption, setpoint temp, dwelling internal temp, Space Heating Energy Consumption, energy to carbon conversion, and energy to carbon conversion factor. As indicated by the SD equations (6:10), adding these end uses of household energy consumption results in the calculation of the 'Average annual household

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energy consumption'. Multiplying 'households' by this 'average annual energy consumption per household' results in the calculation of the total annual household energy consumption. Table 2 shows the data driving this module. The conversion factor 'energy to carbon conversion' is then used to determine carbon emissions. For the developed model, this factor is assumed for the conversion of energy from electricity source only. Ideally, a factor for each different fuel source should be identified separately then aggregated for all end uses of energy.

Insert Table 2

Insert Figure 6

$$RSH = (SHE * EEESH / EEBEC *1.14 - 0.15 * FORECAST(SHE * 0.53, 39, 450)) * (0.60*ST) / DIT) \quad \ldots \quad (Eq.\ 6)$$

$$SHEC(t) = INTEGRAL\ [(RSH - ECC), ISHE\ (t_0)] \quad \ldots \quad (Eq.\ 7)$$

$$ECC = SHEC * ECCF \quad \ldots \quad (Eq.\ 8)$$

$$AAECH = CEC + HWEC + LEC + SHEC + AEC \quad \ldots \quad (Eq.\ 9)$$

$$TAHEC = AAECH * HO / 10^{\wedge}6 \quad \ldots \quad (Eq.\ 10)$$

The model uses the three behavioral classifications: 'frugal', 'standard', and 'profligate'; adopted from ESRU (2012) and Azar and Menassa (2012). An assumption was informed to formulate the algorithm for energy consumption relative to the frugal, standard, and profligate behaviors based on the data published in the Intertek (2012) report. Further work is underway to consider more occupants' behavior variables such as: "occupants' social class influence" and "occupants' cultural influence"; which are currently assumed exogenously

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variables for this model. External environment variables such as energy securities and political uncertainties are also considered exogenously variables at this stage of the research.

Behavior Analysis of Occupants Thermal Comfort Module

A baseline scenario has been designed to run the proposed model assuming that the existing trends of energy consumption are continuing until 2050. The 'standard' occupant's behavior is assumed for the 'baseline' scenario. The dwelling internal temperature is assumed to be 19ºC as an average degree for the whole dwelling.

The perceived dwelling temperature as a model of occupants' comfort will be the output of this module. However, the input data includes the average relative humidity and the average dwelling internal temperature. The perceived dwelling temperature as produced by the model in Figure 7 is determined based on the Humidex chart in Figure 3. It is clear that the increased pattern of the perceived dwelling temperature resembles the pattern of the average dwelling internal temperature. To obtain better comfort level, the model assumes two occupants' actions to respond to this increase of the perceived dwelling temperature: putting on higher thermal resistance clothes or opening windows. Relevant qualitative data was collected to model the probabilities of these two actions. As shown in Figure 8, the model results indicate that the probability of putting on higher thermal resistance clothes declines over the years, while the probability of occupants opening windows increases as the perceived dwelling temperature increases. This is consistent with the global climate warming predictions.

As the perceived dwelling temperature increases, the pattern of occupants' comfort and occupants' metabolic build-up grow over time, as shown in Figures 9 and 10. Consequently,

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a decline in the quest for hot water usage and more space heating is expected. Logically, these growths would reach a saturation level considering the two aforementioned actions of occupants to regulate comfort. Artificial ventilation may be possibly used more if the two occupants' actions fail to achieve a satisfactory comfort level.

Insert Figure 7

Insert Figure 8

Insert Figure 9

Insert Figure 10

Behavior Analysis of Household Carbon Emissions Module

The output of the Occupants Thermal Comfort Module is a key input to this module. For the example given in this paper of space heating as one of the components of Household carbon emissions, the behavior of this module will be discussed.

Figure 11 shows the model results of 15MWh as an average space heating per household for the first four decades. An increase in space heating energy has been observed until 2004, and then a decline is observed. The initial growth is possibly because occupants raise the internal temperature to get better thermal comfort. In 2010, the bad weather conditions led to another sharp increase. As the results show, the space heating energy will continue to decline until 2050 mainly because of the energy efficiency improvements in order to comply with building regulations. This decline can be also linked to the increasing energy costs from 2004 as noted by Summerfield *et al.* (2010) and the milder winters (Palmer & Cooper, 2012).

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Table 3 illustrates the expected decrease in household carbon emissions in years 2020 and 2050 compared with the year 1990 emissions. It is expected that there will be a reduction of 49.73 million tones of CO_2 by the year 2020 (about 29%). Therefore, based on the assumed 'baseline' scenario, the reduction of 34% targeted by the 2008 Climate Change Act will not be achieved. For the year 2050, the model results show a reduction of 83.73 million tones of CO_2 (about 48%) which also suggests that the conditions of the 'baseline' scenario are not sufficient to achieve the reductions of 80% targeted by the 2008 Climate Change Act.

Having discussed the model results for the baseline scenario, the following section discusses a scenario of occupants' behavior change over time due to potential more concern about carbon emissions reduction.

'Behavioral Change' Scenario

As the major assumptions of the 'baseline' scenario are not sufficient to achieve the UK target reduction in carbon emissions, further proposals should be considered. For the developed model, occupants' behavioural change is assumed as more concern from occupants towards energy consumption is expected. Therefore, 'frugal' behaviour is assumed rather than the 'standard' behaviour; i.e. attitude of more energy saving. This may make occupants maintain a reduced internal temperature. The dwelling internal temperature is therefore set at 18.5ºC. With the ongoing increase in energy prices, energy bills will be assumed higher by 5% over the 'baseline' scenario values. The household energy efficiency is assumed similar to the 'baseline' scenario. The same effects of the 'average household size' and the 'number of households' are also anticipated as generated by the model based on the historical record.

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Analysis of the results of the 'Behavioral Change' Scenario

The total household carbon emission is shown in Figure 12 for the behavioral change effect in comparison with the baseline scenario. Table 3 shows the household carbon emissions in 2020 and 2050 compared with the year 1990. The analysis reveals that there is substantial reduction in the energy consumption under the 'behavior change' scenario which emphasizes Janda's (2011) comment *'buildings don't use energy; people do'*. A total of 40.95% and 58.47% reduction in carbon emissions relative to 1990 base is expected by this behavioral change by the year 2020 and 2050 respectively. This is actually a decent percentage showing the high impact on energy consumption by occupants' behavior even without the effect of more advanced energy efficiency improvements. With the effect of more energy efficient technologies installed in dwellings, the target of 80% reduction may be achieved.

Insert Figure 11

Insert Figure 12

Insert Table 3

Model evaluation

SD models should be first qualitatively evaluated by experts in the field. Sterman (2000) highlighted that model structure should be consistent with relevant descriptive knowledge of the system and conforms to basic physical laws. The level of aggregation of the model should be also appropriate.

Fifteen experts from energy and SD backgrounds took part in the model evaluation process; brief details about them are shown in Table 4. The interviewees of each field have an average of 17.5 and 18.4 years of experience on issues relating to household energy and system

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dynamics respectively. The interview started with a description of the research, its aim, objectives, and the purpose of the evaluation process. The interviewees were then given the final CLDs and the SFDs together with the assumptions made for each module. The 'baseline' scenario and other trial scenarios (including the 'behavior change' scenario) were then simulated and the main outputs from the model were presented. Furthermore, the system dynamics experts have had additional scrutiny to test the model behavior, structure, and equations and assess their appropriateness and conformity with the general rules of SD modeling.

Insert Table 4

Martis (2006) suggest that models should be adequately evaluated against the criteria of: logical structure, clarity, comprehensiveness, practical relevance, applicability, and intelligibility. A scoring scale attributed for evaluating the criteria is shown in Table 5 and the evaluation results are shown in Table 6.

Insert Table 5

Insert Table 6

The logical structure assesses the model consistency with the properties of the real system. The mean score of 4.07 (which is above average) indicates that the model has an acceptable logical structure to mimic the real system. The respondents also agree that the model has enough clarity and practical relevance on issues relating to energy consumption and carbon emissions with a mean score of 4.2 for both criteria. A mean score of 4.00 was given to the model comprehensiveness which shows that the model captures the important variables that

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influence energy and carbon emissions and is capable to address the problem under study. With the assumptions made for the current version of this model, a mean score of 3.87 and 3.73 were given to Applicability and intelligibility of the model. While they are still above average, the relatively low scores can be improved by further development of the model to deal with these assumptions. This was clearly addressed in the feedback through highlighting few exogenous variables to be considered endogenous, and through expanding the model boundary to include other excluded variables. Their feedback was recorded for further data collection and modeling.

The evaluation also aims to validate the SD model by conducting a number of structure-oriented tests (e.g. dimensional consistency, parameter assessment, boundary adequacy, structure assessment, integration error, and extreme conditions). There are also a number of behavior pattern tests (e.g. family member, surprise behavior, behavior reproduction, behavior anomaly, system improvement, and sensitivity analysis). Sterman (2000) concluded that a model is behaviorally validated if its results show similarity with the behavior patterns of the real system. Due to space limitation, one test of each group will be presented in this paper. The full details of model evaluation can be found elsewhere; Oladokun (2014).

Among the main evaluation tests, there is the ‘extreme conditions test’ which evaluates how the model responds to the variation of variables values. The model was run under the extreme values of few key variables. For example, the variables of ‘insulation factor’ and ‘% increment of energy bills’ were selected to show the sensitivity of the model. The two variables are varied between 0% and 100%. Figure 13 and Figure 14 show the model results that indicate the model behavior still make sense without any plausible or irrational response to the extreme values.

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Insert Figure 13

Insert Figure 14

The behavior anomaly test is a main test that evaluates how implausible behavior arises should the assumptions made in the model altered, Sterman (2000). In order to conduct this test, a loop knockout analysis was carried out on one of the loops in the occupants' thermal comfort module to test its effect on the model output. Figure 15 shows the results of the test which indicates that no anomaly or erratic behavior was noticed when the simulation was performed.

Insert Figure 15

Conclusions

A dynamic model is introduced in this paper to simulate occupants' behavior effects to reduce carbon emissions in dwellings. The systems theory has been followed for the model development to consider the interrelationships among the technical, occupants' behavior and the external environment of buildings. A number of factors have been used to represent occupants' behavior based on: Humidex value for different degrees of comfort, the 'probability of putting on clothing' and the 'probability of window opening' within the dwelling, and occupants metabolic build-up. Further work is underway to consider other occupants' behavior variables such as: "occupants' social class influence" and "occupants' cultural influence" which are currently assumed exogenously variables for this model. Furthermore as a limitation to this proposed model, external environment variables such as energy securities and political uncertainties are also considered exogenously variables at this stage of the research. It is also proposed to consider, in further details, the impact of different

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dwelling types on the model results and also the situation of having different temperature degrees within the dwelling units instead of the assumption of one average degree for the whole dwelling. The model can test the effectiveness of certain energy efficient scenarios for the changes in occupants' behavior. It is concluded that carbon emissions can be vastly reduced by changing occupants' behavior even without the installation of more energy efficient improvements. With the effect of more energy efficient technologies installed in dwellings, the target of 80% reduction set by the UK Climate Change act 2008 can be achieved.

Notation

The following symbols are used in this paper:

AEC = Appliances Energy Consumption;

AAECH = Average Annual Energy Consumption per Household;

CCF = Carbon Conversion Factor;

CEC = Cooking Energy Consumption;

DIT = Dwelling Internal Temperature;

EEBEC = Effect of Energy Bills on Energy Consumption;

EEESH = Effect of Energy Efficiency on Space Heating;

ECC = Energy to Carbon Conversion;

ECCF = Energy to Carbon Conversion Factor;

GD = Great Discomfort;

HWEC = Hot Water Energy Consumption;

HO = Households;

HV = Humidex Value;

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ISHE = Initial Space Heating Energy;

LEC = Lighting Energy Consumption;

NDHS = No Discomfort from Heat Stress;

OAL = Occupants Activity Level;

OC = Occupants Comfort;

OMB = Occupants Metabolic Build-up;

PDIT = Perceived Dwelling Internal Temperature;

RSH = Rate of Space Heating;

RH = Relative Humidity;

ST = Setpoint Temp;

SD = Some Discomfort;

SDHS = Some Discomfort from Heat Stress;

SHE = Space Heating Energy;

SHEC = Space Heating Energy Consumption;

TAHEC = Total Annual Household Energy Consumption.

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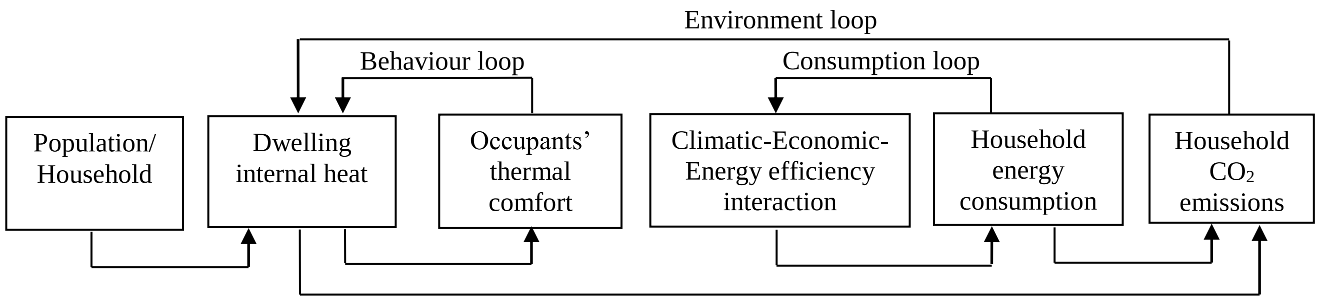


Figure 1: Household Energy Consumption modules

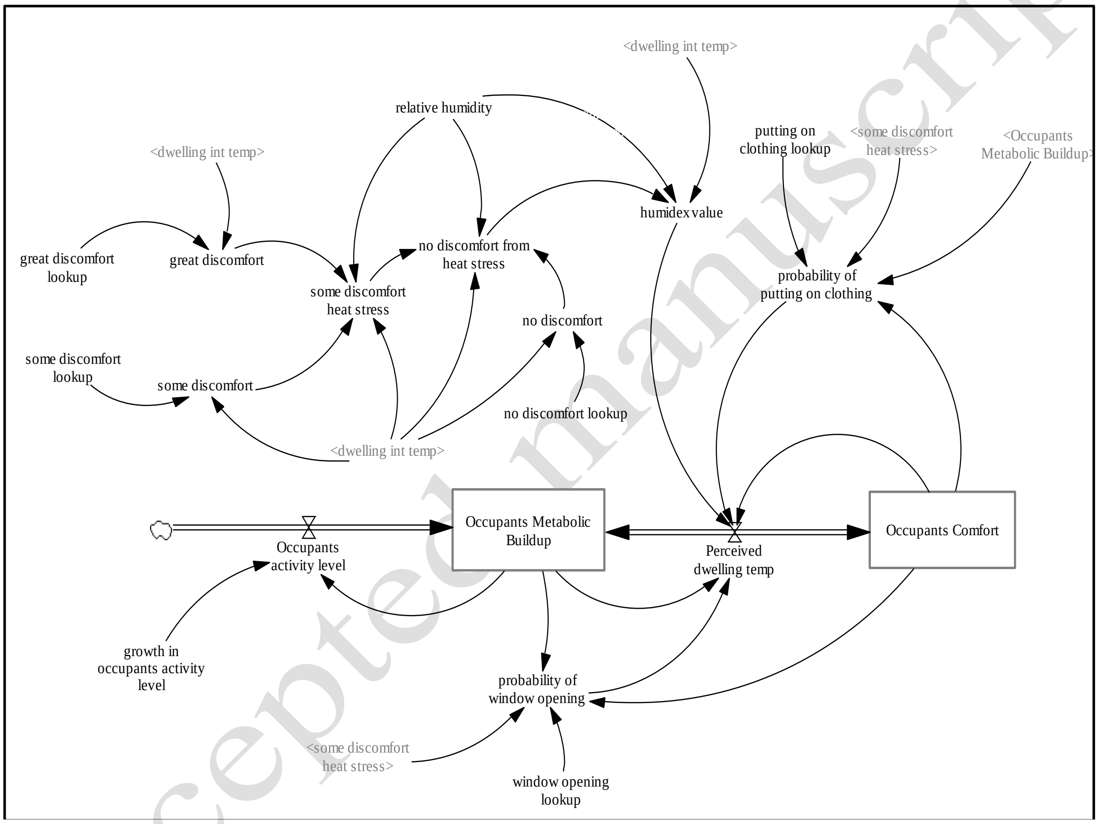
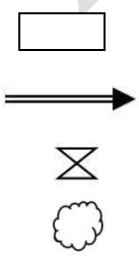


Figure 2: SFD for occupants thermal comfort module



Stocks represent accumulations

Flows represent the changes to stocks

Flow rate

Cloud represents either Source/sink of the flow

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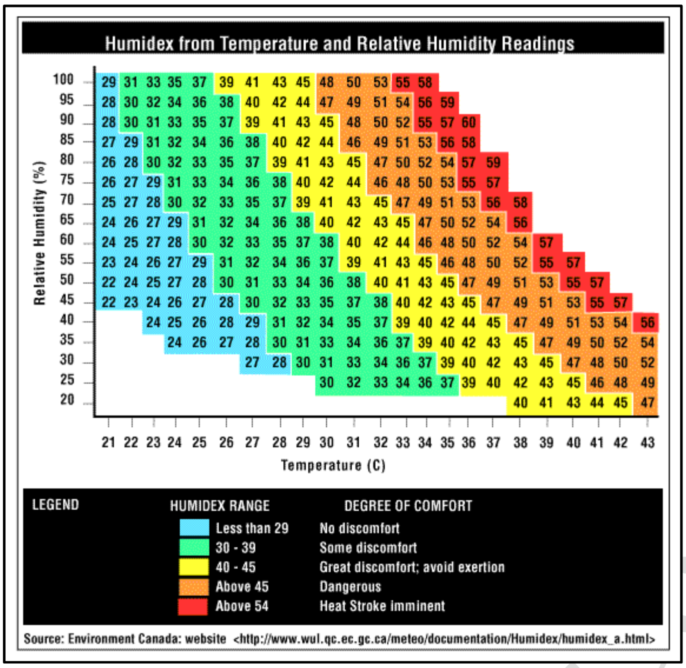

Figure 3: Humidex chart (Source: Canadian Centre for Occupational Health and Safety)

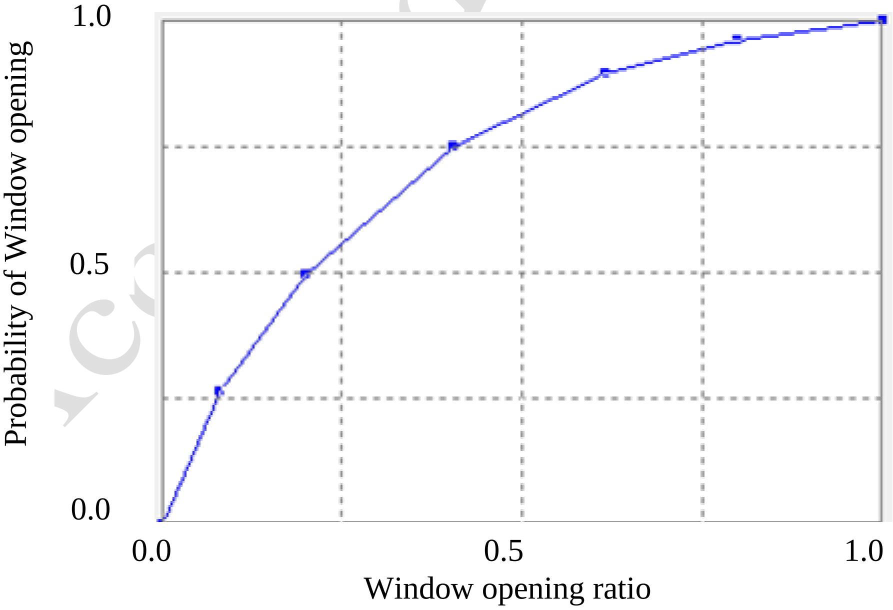

Figure 4: Window opening lookup

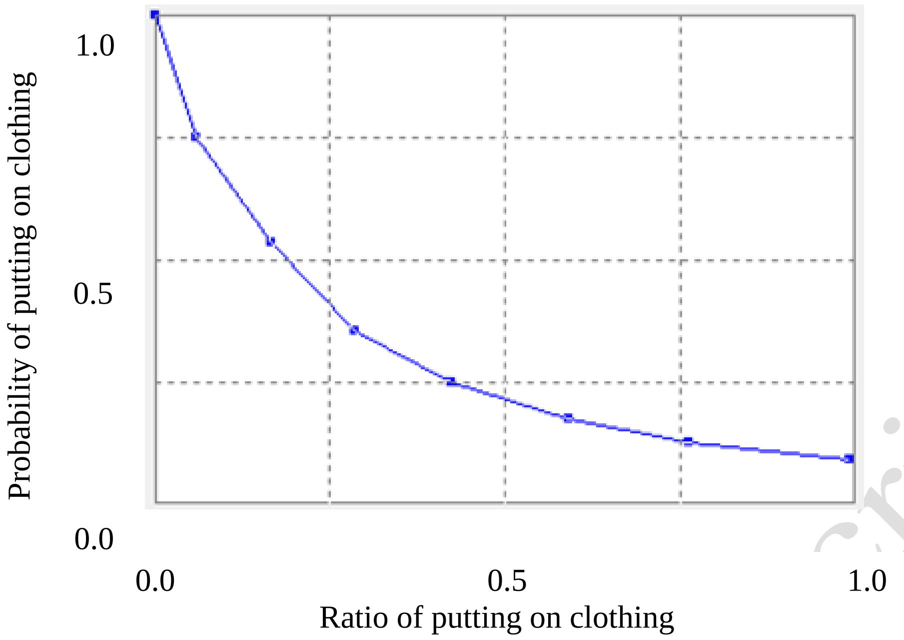

Figure 5: Putting on clothing lookup

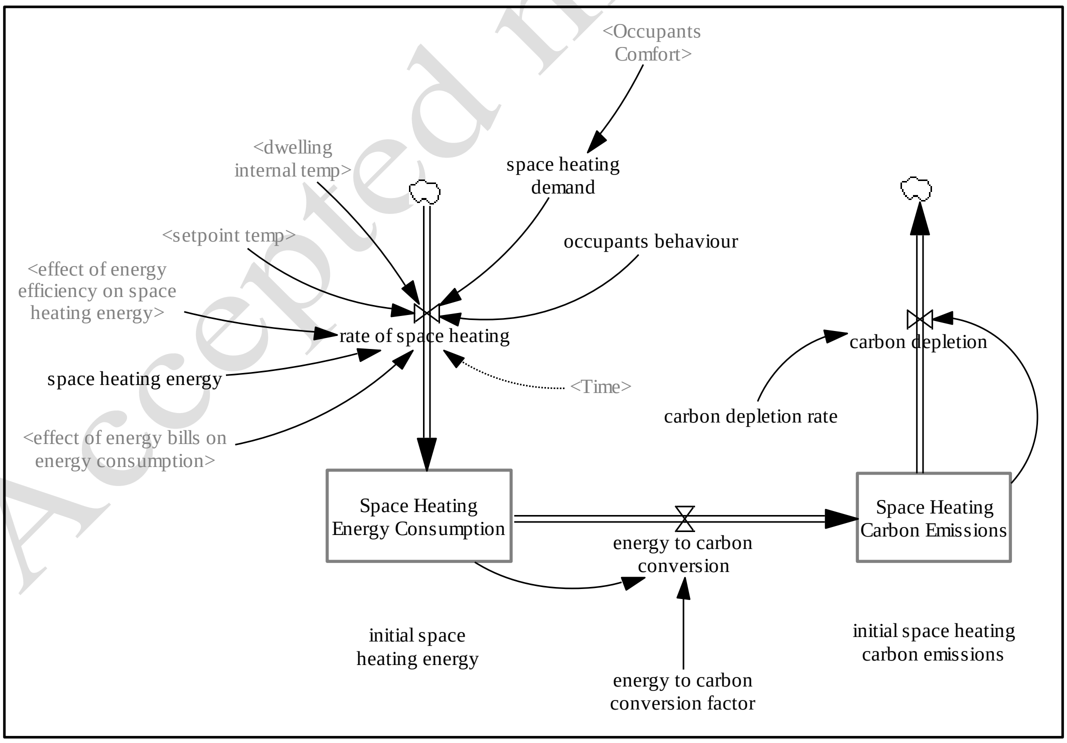

Figure 6: SFD for space heating energy consumption and carbon emissions

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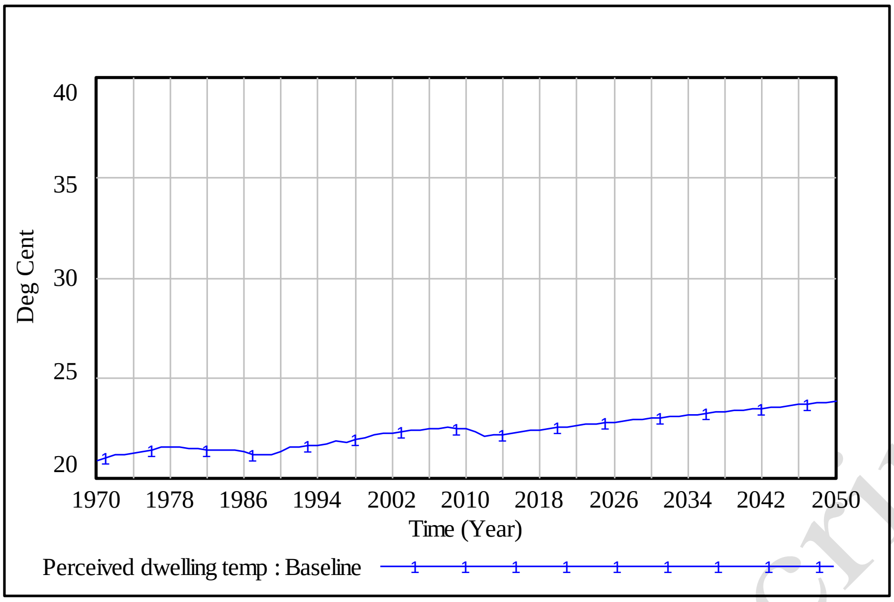

Figure 7: Perceived dwelling temperature under the 'baseline' scenario

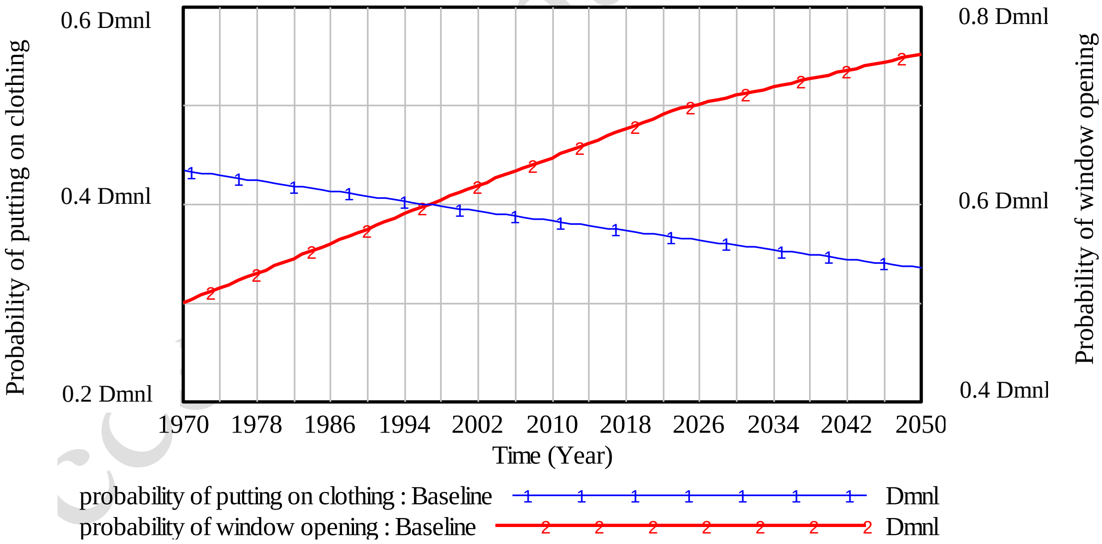

Figure 8: Probabilities of putting on clothing and window opening under the 'baseline' scenario

**Dmnl – dimensionless.*

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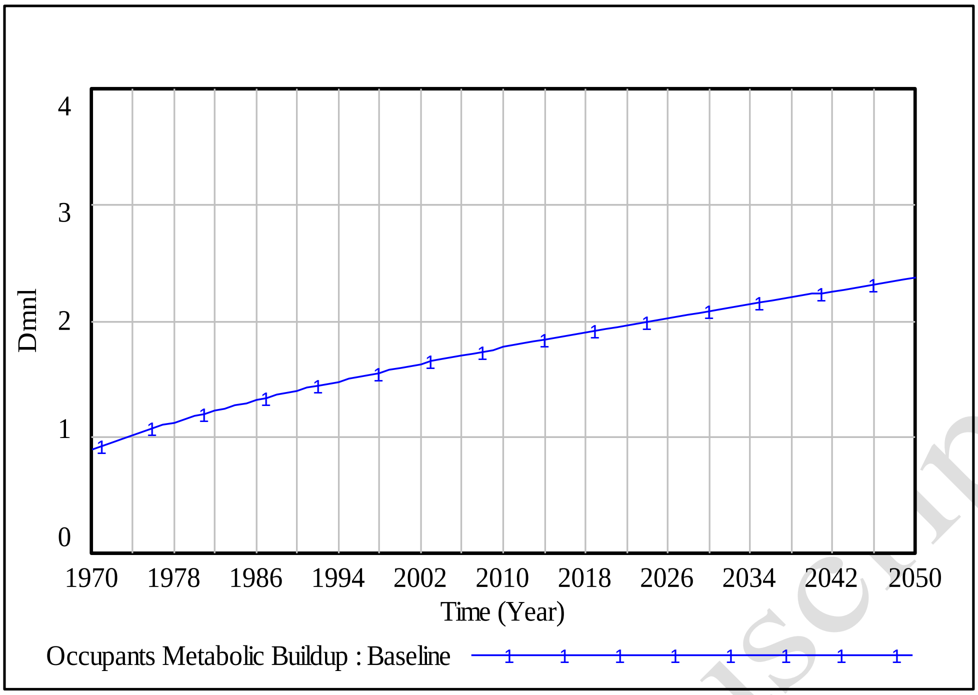

Figure 9: Occupants metabolic build-up under the ‘baseline’ scenario

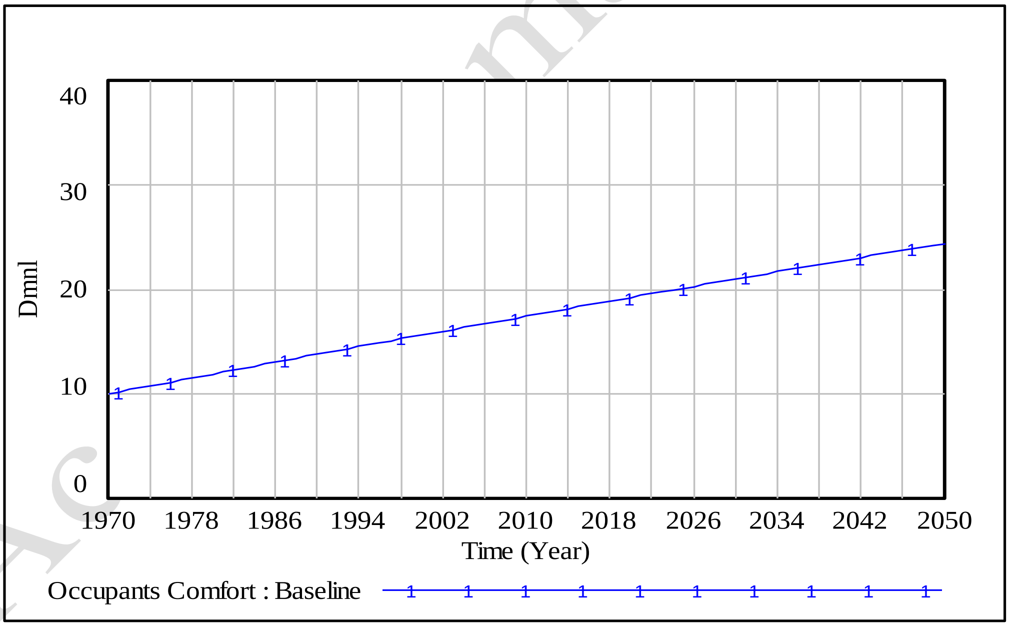

Figure 10: Occupants comfort under the ‘baseline’ scenario

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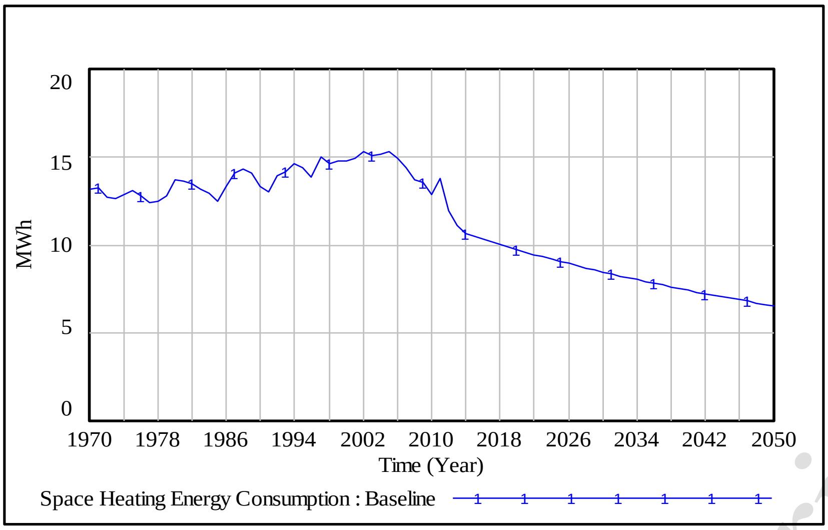

Figure 11: Average space heating energy consumption per household

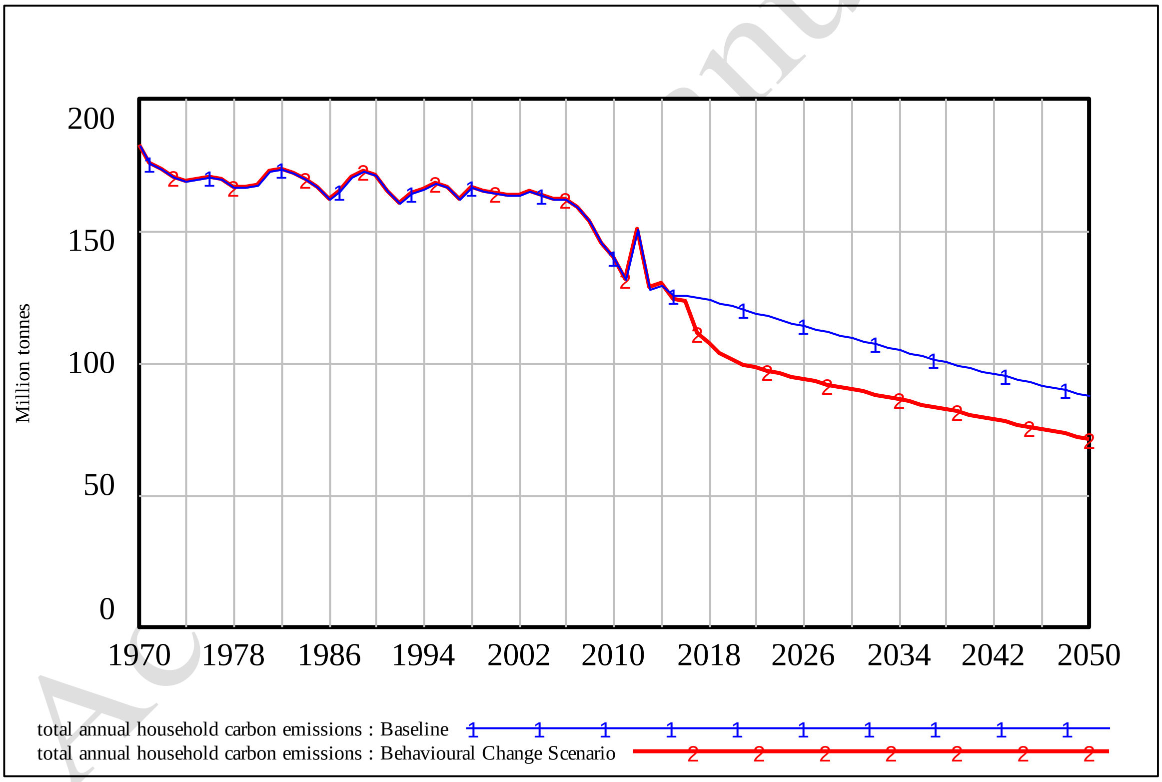

Figure 12: Total annual carbon emissions for the UK housing stock for the baseline and the 'behavioural change' scenarios

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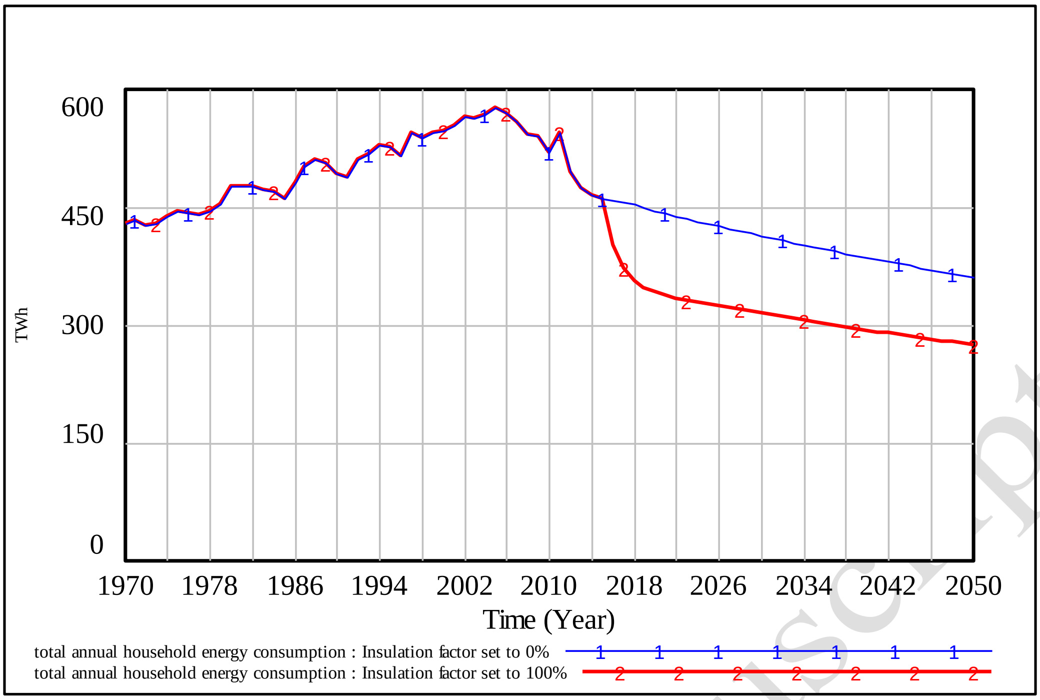

Figure 13: Total annual household energy consumption under 'insulation factor' set to 0% and 100%

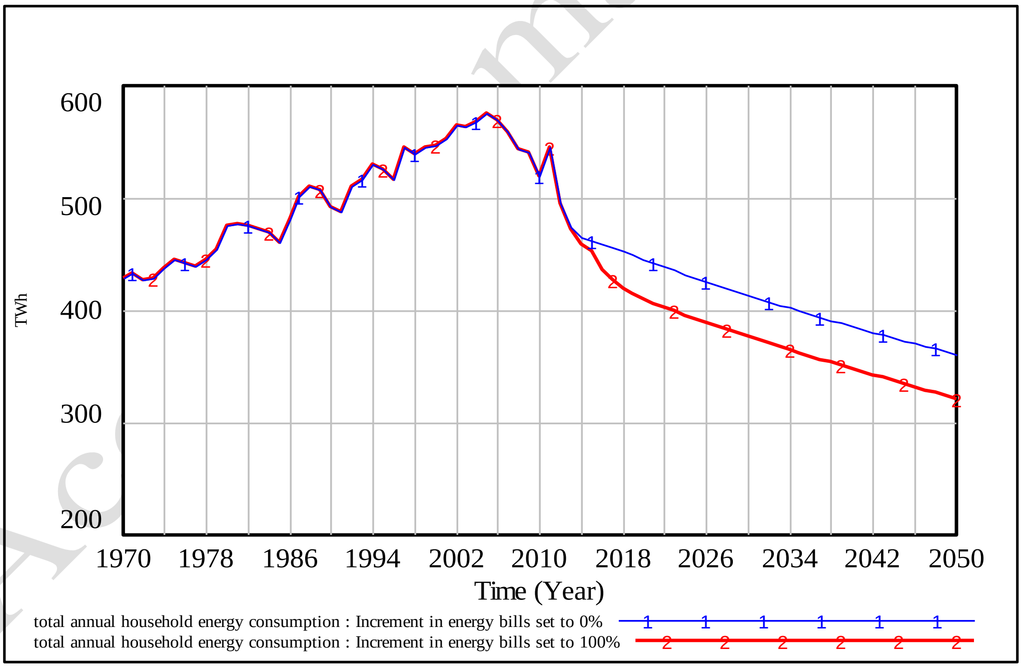

Figure 14: Total annual household energy consumption under 'increment in energy bills' set to 0% and 100%

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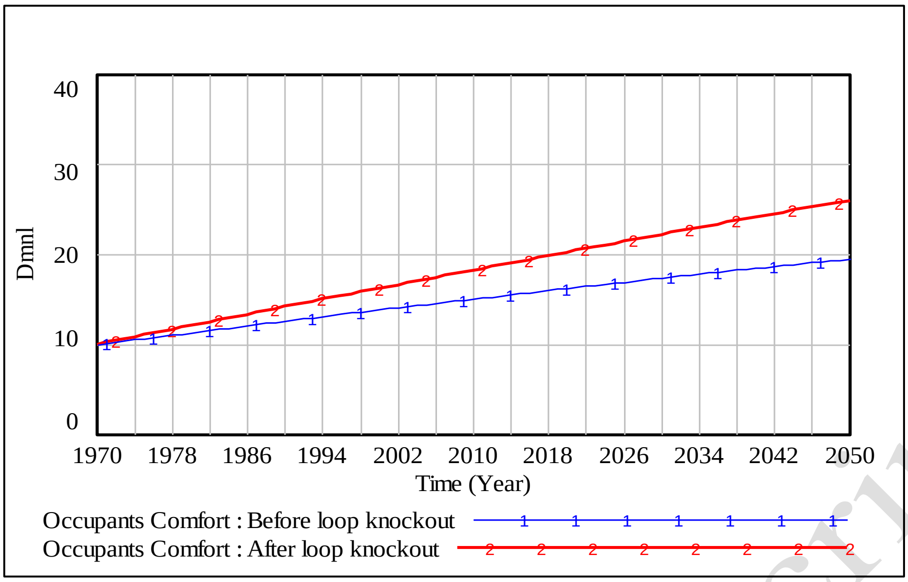

Figure 15: Effect of loop knockout on occupants' thermal comfort module

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Table 1: Sample data for relative humidity (adapted from: Met Office, 2013)

Variable	Unit of Measurement	Minimum	Maximum	Mean	Standard Error	Standard Deviation
Relative humidity	Percentage	67	94	85.09	1.32	8.67

Table 2: Sample data for household energy by end-uses (adapted from: Palmer & Cooper, 2012)

Variable	Unit of Measurement	Minimum	Maximum	Mean	Standard Error	Standard Deviation
Space heating	MWh	10.14	15.84	13.54	0.18	1.19
Hot water	MWh	3.03	6.64	4.78	.17	1.10
Cooking	MWh	0.48	1.36	0.86	0.04	0.28
Lighting	MWh	0.55	0.69	0.65	0.01	0.04
Appliances	MWh	1.07	2.39	1.92	0.06	0.37

Table 3: The household carbon emissions by end-uses for the baseline and the 'behavioural change' scenarios for the year 2020 and 2050 relative to 1990

	(1990)	(2020)				(2050)			
	Tonnes of CO_2	Baseline		Behavioural change		Baseline		Behavioural change	
		Tonnes of CO_2	*(%)	Tonnes of CO_2	*(%)	Tonnes of CO_2	*(%)	Tonnes of CO_2	*(%)
Space heating	94.47	53.19	-43.70	43.76	-53.68	32.46	-65.64	24.35	-74.22
Hot Water	44.15	32.09	-27.32	25.64	-41.93	25.71	-41.77	21.03	-52.37
Cooking	7.93	4.21	-46.91	4.75	-40.10	4.16	-47.54	4.81	-39.34
Lighting	6.04	5.50	-8.94	4.64	-23.18	4.61	-23.68	3.84	-36.42
Appliances	18.43	26.29	+42.65	22.19	20.40	20.35	+10.42	16.99	-7.81
Total	**171.01**	**121.28**	**-29.08**	**100.98**	**-40.95**	**87.28**	**-48.96**	**71.02**	**-58.47**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

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Table 4: Brief details about experts participated in model evaluation

Category	**Classification**	**Number of experts**
Organisation Type	Public Private	6 9
Academic Qualification	Bachelor's degree Master's degree PhD	4 9 2
Years of Experience in Household Energy related issues	6-10 11-15 16-20 21-25	2 3 6 1
Years of Experience in System Dynamics Modelling	11-15 16-20	1 2

Table 5: Evaluation scores

	'excellent'	'above average'	'average'	'below average'	'poor'
Score	5	4	3	2	1

Table 6: Evaluation results

Criteria	**Score**					**Mean**
	5	**4**	**3**	**2**	**1**	**Score***
Logical structure	4	8	3	0	0	**4.07**
Clarity	5	8	2	0	0	**4.20**
Comprehensiveness	3	9	3	0	0	**4.00**
Practical relevance	4	10	1	0	0	**4.20**
Applicability	2	9	4	0	0	**3.87**
Intelligibility	2	7	6	0	0	**3.73**

**Mean Score* $=(5*n_5 + 4*n_4 + 3*n_3 + 2*n_2 + 1*n_1)/(5+4+3+2+1)$ *where* n_5, n_4, *…. correspond responses relating to each score of 5, 4, …. respectively.*

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