DYNAMIC MODELLING OF A LARGE SCALE RETROFIT PROGRAMME FOR THE HOUSING STOCK IN THE NORTH EAST OF ENGLAND

Miaomiao He, Timothy Lee, Simon Taylor, Steven K. Firth, Kevin Lomas

School of Civil and Building Engineering, Loughborough University,
Loughborough, Leicestershire, LE11 3TU, Phone: +44-1509226195, E-mail:
m.he@lboro.ac.uk

ABSTRACT. Housing stock models have long been employed to estimate the baseline energy demand of the existing housing stock, as well as to predict the effectiveness of applying different retrofit measures and renewable technologies on reducing the energy demand and corresponding CO_2 emissions. This research aims to develop a dynamic housing stock model to simulate the hour-by-hour energy demands of 1.2 million dwellings in the North East (NE) of England using the 2008-9 English Housing Survey (EHS) data. The model is validated by comparison to a steady-state energy model. Using the model, new results predicting the impact of a large scale retrofit programme for the NE housing stock are generated.

Keywords: Large Scale Retrofits, Dynamic Housing Stock Model, EnergyPlus, Cambridge Housing Model, North East of England

1. INTRODUCTION

Housing is responsible for more than a quarter of total energy consumption and carbon dioxide (CO_2) emissions in the UK [1]. With less than 1% annual growth rate of new-build homes, it is estimated that 75% of the housing stock in 2050 will have been constructed before 2014 [2]. In order to achieve the UK government's CO_2 reduction target of 80% by 2050 compared to the 1990 baseline [3], large-scale retrofitting (i.e. improving the thermal efficiency and energy system efficiency of dwellings rapidly and at high volumes) of the existing housing stock is expected to play an important role.

Housing stock models have long been developed in the UK to estimate the current energy consumption and CO_2 emissions associated with the existing housing stock, as well as to predict further energy consumption and CO_2 reductions in different scenarios [4]. There are two main approaches, econometric top-down models that work at an aggregated level, and building physics based bottom-up models that work at disaggregated level [5 - 6].

Building physics based models generally try to capture the important factors that influence the energy demand of the buildings, such as total floor area, window area, wall type, floor type, insulation level, air tightness, heating system type and heating system efficiency. The models calculate the heat flows in buildings due to a number of factors including heat transfer through the building fabrics, heat gains from solar radiation, heat transfer from air infiltration and ventilation, and internal heat gains from occupants and their use of household appliances. Consequently, building physics based housing stock models are well placed to estimate the impacts of retrofit measures which directly alter the physical properties of the buildings.

There are two main methods for building physics based housing stock modelling [7]. The archetypes approach is defined as using a number of typical house types to represent the housing stock. A typical house of a certain type, such as a 1940s semi-detached dwelling, might not match any real houses but is considered to be the average house of all houses of that type. The Actual Building Samples approach, on the other hand, models a relatively large number of real houses. With an appropriate weighting, the sample of modelled houses can be scaled up to be representative of a much larger housing stock.

Almost all of the UK building physics based housing stock models are based on steady-state calculations using a version of BREDEM (The Building Research Establishment's Domestic Energy Model) [8]. BREDEM is based on a series of steady-state heat transfer equations and empirical relationships to estimate the annual or monthly energy consumption of an individual dwelling. Therefore, the dynamics of the dwelling and associated energy systems cannot be captured explicitly. A dynamic model, on the other hand, allows the interactions between dwelling, people and the wider energy system to be explored.

As part of the SElf Converving URban Environment (SECURE) project, a £2.1m EPSRC-funded research project which aims to study the energy and resource flows of the North East (NE) region of England, this work sets out to investigate the current and future energy demand and corresponding CO_2 emissions associated with the NE housing stock. The paper describes the development of a dynamic housing stock model and the validation of the dynamic model with an equivalent steady-state model. The dynamic model is used to study the impact of a large scale retrofit programme for the housing stock in the region.

2. METHODS

EnergyPlus has been adopted as the dynamic simulation engine in this study. It is a well-recognised and extensively tested fully-integrated building simulation tool and freely available [9]. Most importantly, EnergyPlus allows simulations to be run in parallel, if these runs are independent, and therefore can reduce the simulation time significantly if a suitable machine with multi-threads is available.

For comparison purpose, the Cambridge Housing Model (CHM) has been chosen as a suitable steady-state housing stock model [10]. It was developed by Cambridge Architectural Research for Department of Energy and Climate Change (DECC) to underpin the 2012 Housing Energy Fact File and Energy Consumption in the UK, and to inform housing policy decisions. The model uses EHS 2009 data (see next section), coupled to a SAP-based energy calculator, to estimate energy consumption and CO_2 emissions for all homes in England, broken down by final use.

2.1 The English Housing Survey (EHS) Data

One of the biggest challenges for the development of a dynamic physics based housing stock model lies in the data that it requires to construct the model. As can be expected, the more levels of detailed information a model can use, the more representative the results are. However, the levels of detail are often limited. The

English Housing Survey is a year-on-year national survey commissioned by the Department for Communities and Local Government (DCLG). It collects information about people's housing circumstances and the condition and energy efficiency of housing in England [11]. Its database provides detailed information of representative houses in England which are useful for dynamic modelling, such as age band, dwelling type, region, dimensions, window area, glazing type, wall construction, roof construction, floor construction, and loft insulation.

In the EHS, dwellings are categorised into 11 age bands, 9 regions, 6 dwelling types, 2 glazing types, 15 types of wall construction, 3 types of roof construction, 3 types of floor construction and 11 different thicknesses of loft insulation, as detailed in Table 1 and 2.

TABLE 1. Categories of age band, region, and dwelling types in the EHS.

Age Band	Region	Dwelling Type
Before 1900	North East	Detached
1900 - 1929	Yorkshire and The Humber	Semi-Detached
1930 - 1949	North West	Mid-Terrace
1950 - 1966	East Midlands	End-Terrace
1967 - 1975	West Midlands	Flat - Purpose Built
1976 - 1982	South West	Flat - Converted
1983 - 1990	East of England	
1991 - 1995	South East	**Glazing Type**
1996 - 2002	London	Single Glazing
2003 - 2006		Double Glazing
2007 -		

TABLE 2. Categories of wall construction, roof construction, floor construction and loft insulation in the EHS.

Wall Construction	Roof Construction	Loft Insulation
Stone: granite or whinstone (as built)	Pitched, slates or tiles	0 (mm)
Stone: sandstone (as built)	Thatched roof	25 (mm)
Solid brick (as built)	Flat roof	50 (mm)
Stone/solid brick (external insulation)		75 (mm)
Stone/solid brick (internal insulation)		100 (mm)
Cob (as built)		125 (mm)
Cob (external insulation)		150 (mm)
Cob (internal insulation)	**Floor Construction**	200 (mm)
Cavity (as built)	Slab on ground, screed over insulation	250 (mm)
Filled cavity / Cavity with insulation		300 (mm)
Timber frame	Suspended timber, insulation between joists	>300 (mm)
System build (as built)		
System build (external insulation)		
System build (internal insulation)	Suspended concrete floor, carpeted	
Metal Frame		

There are two main built form types for all the dwellings in the EHS, a rectangle or an L-shape. The built forms are represented by either one or two rectangles depending upon the shapes of the dwellings. For a rectangular dwelling, one main rectangle with width and depth is used to describe the built form of the dwelling. But for an L-Shape, an additional rectangle with width and depth is also used, which is attached to the main rectangle. The location of the additional part is categorised into twelve different positions, namely, front left, front centre, front right, back left, back centre, back right, left front, left centre, left back, right front, right centre, and right back. In addition, the width and depth of the living room area are recorded.

The complexity of the housing stock represents a challenge for the development of a dynamic housing stock model. Not only does each dwelling have unique dimensions and window areas, the same form of construction of houses built in different age bands may have different thermal properties.

2.2 North East Housing Stock

This study focuses on the NE region of England. The 2008-9 EHS database contains 935 sample dwellings in the NE which are representative of about 1.2 million homes in that region. The distributions of the 935 dwellings among 6 dwelling types, 10 age bands, 8 types of wall construction, and 12 loft insulations are shown in Fig. 1.

There are 759 houses and 176 flats. This study initially focuses on the modelling of the 759 houses, including 90 detached houses, 329 semi-detached housed, 221 mid-terrace houses and 119 end-terrace houses. Each house is assumed to be East/West facing, considering the average effect of a number of houses that are represented by this particular one.

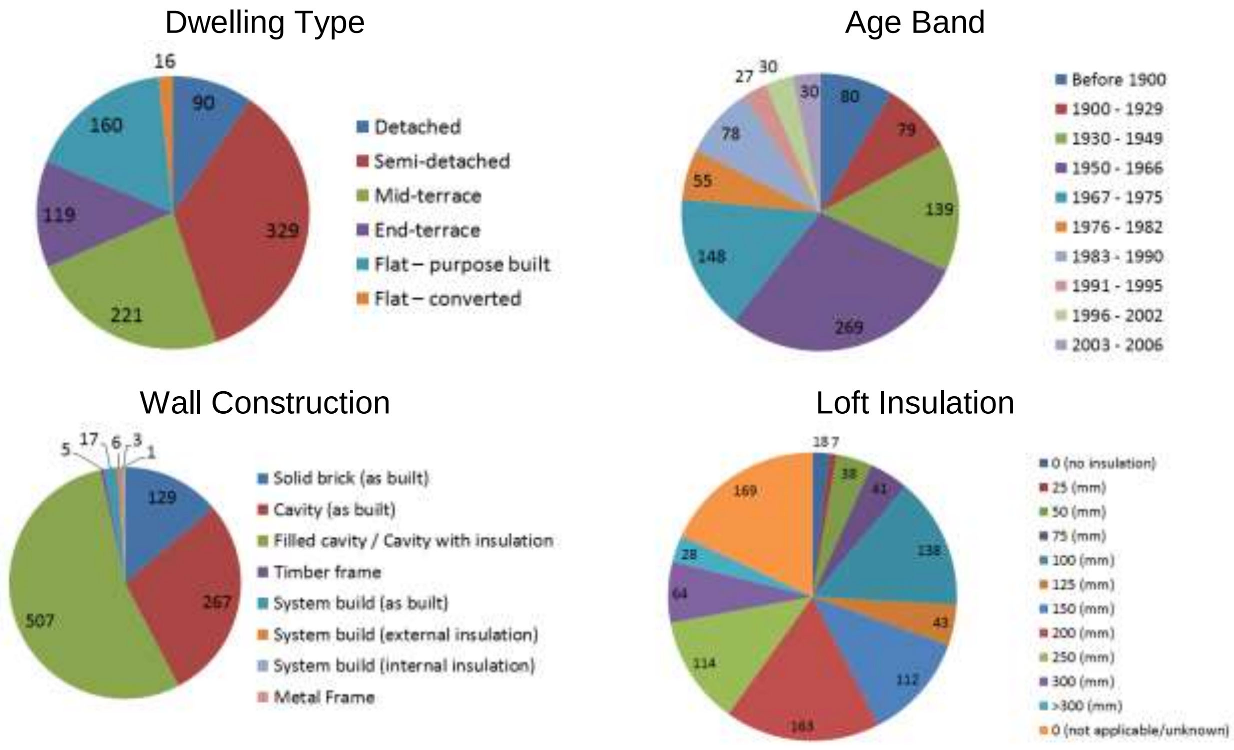

FIGURE 1. Distributions of 935 dwellings in dwelling type, age band, wall construction and loft insulation.

2.3 Dynamic Housing Stock Model Generation Tool

EnergyPlus takes an input data file (IDF), in which a house model and a weather file are specified for a single simulation of a single dwelling. Although there are tools currently available to create IDFs, none of them is suitable to simulate a relatively large number of real houses with individual dimensions and various fabric constructions in different age bands. Therefore, an in-house programme called the Building Generation Tool (BGT) for running EnergyPlus simulations was developed to create the IDFs automatically for the 935 dwellings which are recorded in the EHS database.

Both the rectangular and L-shape built forms are captured in the BGT. Although, as discussed in the previous section, in the EHS database the relative location of the additional rectangle to the main one is specified into 12 different positions, in this tool it is assumed that in all cases the additional rectangle is attached to the back left of the main one, which is the location in the majority of cases. Each dwelling is modelled as containing two separate zones: the living area and the rest of the dwelling. This configuration was shown in a previous study [7] to be able to bring the predicted annual energy demand within about 10% of the best estimate using individual room zones. A diagram of a rectangular and an L-shape dwelling is shown in Fig. 2.

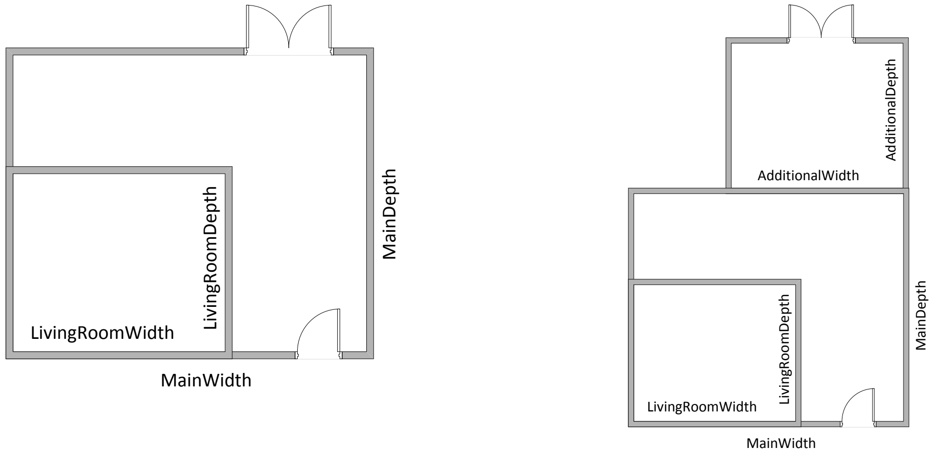

FIGURE 2. Diagram of a rectangular and an L-shape dwelling.

The U-values of wall, roof, and floor stated in SAP Table S6, S9, S10 and S12 are used as references to construct the building fabrics in different age bands. Table 3 shows the construction of solid wall as built for different age bands as an example.

Windows are added to the external walls appropriately according to the total single or/and double glazing window area of each dwelling recorded in the CHM housing data. There are 3 types of window frame as recorded in the EHS: wood, metal and uPVC. SAP uses the overall U-value of glazing and frame in the calculation of window heat loss, as shown in Table 4. Based on the overall U-values in SAP, the BGT creates detailed construction of glazing and frames with matching U-values. A similar approach is applied to doors.

TABLE 3. Construction of solid wall as built for different age bands.

Age Band	SAP U-values (W/m^{2}K)	E+ U-values (W/m^{2}K)	E+ Wall Construction
Before 1900 1900 - 1929 1930 - 1949 1950 - 1966	2.10	2.06	Brick 225mm Plaster 13mm
1967 - 1975	1.70	1.67	Brick 225mm Air layer 50mm Plaster 13mm
1976 - 1982	1.00	1.00	Brick 225mm Air layer 50mm PIR 5mm Plasterboard 13mm
1983 - 1990 1991 – 1995	0.60	0.60	Brick 225mm Air layer 50mm PIR 20mm Plasterboard 13mm
1996 - 2002	0.45	0.44	Brick 225mm Air layer 50mm PIR 30mm Plasterboard 13mm
2003 - 2006	0.35	0.36	Brick 225mm Air layer 50mm PIR 40mm Plasterboard 13mm
2007 -	0.30	0.30	Brick 225mm Air layer 50mm PIR 50mm Plasterboard 13mm

TABLE 4. Overall U-values of window (SAP Table 6e).

U-values (W/m2K)	Wood	Metal	uPVC
Single Glazing	4.80	5.70	4.80
Double Glazing (air filled)	3.10	3.70	3.10

Demand temperatures and heating hours are recognised as the main determinants of building energy consumption in housing stock modelling, as highlighted by a local sensitivity analysis on the Community Domestic Energy Model carried out by Firth et al. [12]. Among the 27 primary input parameters, the heating demand temperature is the most sensitive parameter, followed by the length of the daily heating period. However, demand temperature and heating duration vary considerably between household and there is limited recent data on either of these parameters. The BREDEM sets the default heating demand temperature in the living room to be 21 °C, with heating periods on weekdays of 7:00 to 9:00 and 16:00 to 23:00, and at weekends 7:00 to 23:00. The CHM reduces the heating demand temperature in the living room to 19 °C but keeps the heating period the same as that in BREDEM, trying to take into account the variation in behaviour of households. A recent study by Huebner et al. [13] suggested a demand temperature of 19.5 °C and average heating duration of 10 hours both for weekdays and weekends as opposed to 9 hours for weekdays and 16 hours for weekends in both BREDEM and CHM. For the purpose of consistency in the comparisons discussed in the next section, the DHSMGT keeps the same setting of demand temperatures and heating hours as CHM for all houses. However, this tool allows different settings of demand temperatures and heating hours for each individual house if such data are available.

In the EHS, the number of occupants and the occupied hours, as stated by the householders, are recorded for each dwelling. The occupied hours are divided into 7 groups: Home All Day (include weekdays and weekends); Home Weekday 9am – 12pm; Home Weekday 12pm – 2pm; Home Weekday 2pm – 5pm; Home Weekday evening; Home Weekend day; and Home Weekend evening. The CHM takes the number of occupants as recorded in the EHS, but a standard pattern of occupied hours the same as the heating hours. The BGT also takes the same number of occupants but implements two options for setting occupied hours. One is to set the standard pattern for all dwellings, the same as in the CHM. The other one varies according to the occupied hours recorded in the EHS, but in a slightly less detailed way. It is assumed the occupants are always at home during the weekend and the day is only divided into morning and afternoon, so instead of having 7 groups, the tool only provides 4, Home All Day, Home Morning, Home Afternoon, and Not At Home.

3. RESULTS

A parametric tool called jEPlus [14] has been used in this study to run simulations in EnergyPlus in parallel and to extract outputs. Each simulation takes about 30 seconds to run; therefore running a full set of simulations for 759 houses takes about 1.5 hours in a dual-core PC with 4 threads.

3.1 Comparisons with CHM

Inter-model comparison is a useful way to test a model when real measured data are not available. Shorrock et al. [15] carried out inter-model comparisons using ESP-r, SERI-RES, HTB2, BREDEM-8 and BREDEM-12 to model a typical UK semi-detached house. Yilmaz et al. [16] extended this study by including SAP 2009 and EnergyPlus to the comparisons. The conclusions stated that the EnergyPlus prediction was similar to that from ESP-r, an expected result as both are dynamic simulation software, and the SAP 2009 prediction was comparable to the predictions by BREDEM as their core calculation engines are similar. More importantly, this study demonstrated that SAP 2009 consistently predicted higher heating demands than EnergyPlus.

Since both the BGT and the CHM take inputs from the EHS database and simulate each dwelling individually, the results from both models are comparable. Extra care has been made to ensure that both models have the same boundary variables, e.g.

heating set point temperatures, weather data, occupancy profiles, and infiltration and ventilation rates.

Fig. 3 shows the comparisons of heat demand of the 759 houses predicted by EnergyPlus and CHM. As can be seen from the graph, for each individual house, the prediction by CHM is higher than that by EnergyPlus, although the degrees of difference among all houses vary.

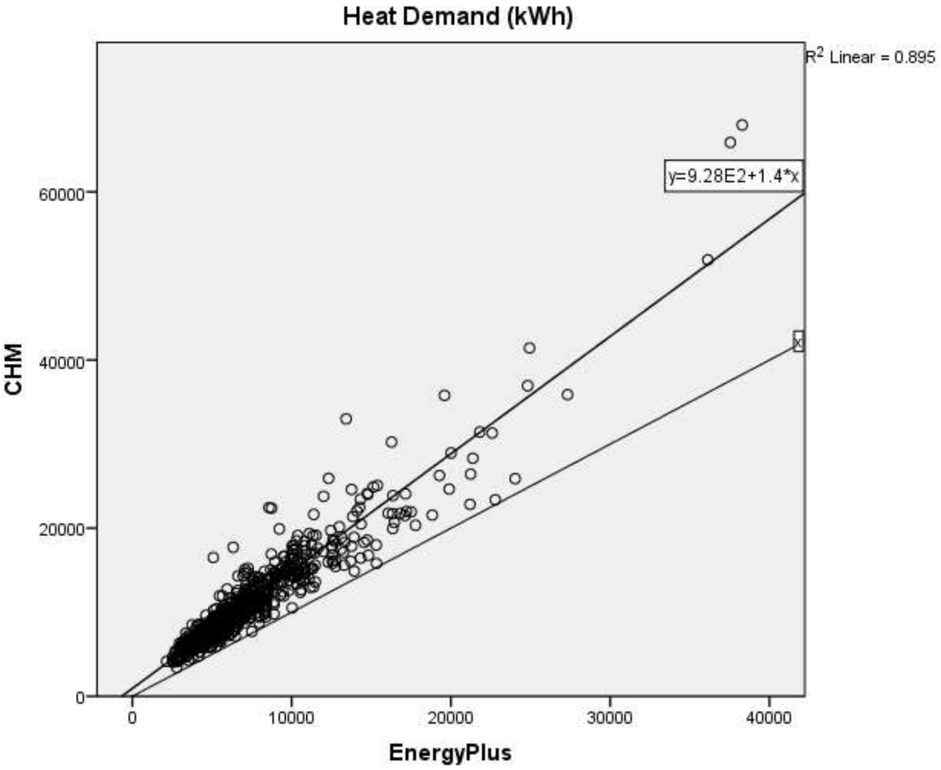

FIGURE 3. Comparisons of heat demand of 759 houses predicted by EnergyPlus and CHM.

Fig. 4 presents a histogram of frequency showing the percentage of difference in heat demand prediction of all houses. The percentage of difference is defined as

$$Percentage\ of\ Difference = \frac{CHM\ Heat\ Demand - EnergyPlus\ Heat\ Demand}{CHM\ Heat\ Demand} * 100\% \quad (1)$$

The mean of the percentage of difference is 34.4% with a standard deviation of 9.37%.

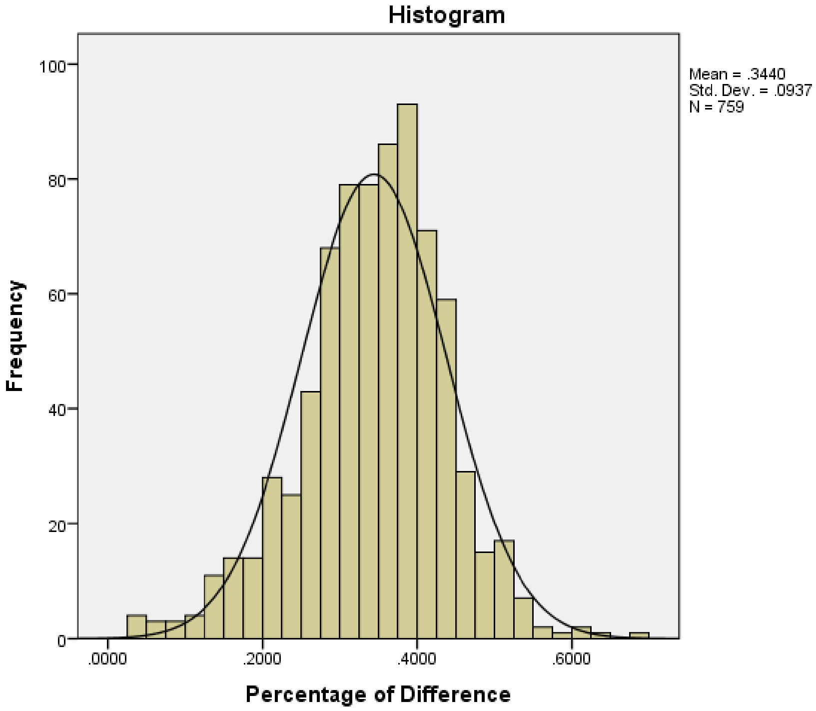

FIGURE 4. Histogram of frequency showing the percentage of difference in terms of prediction in heat demand for the 759 houses.

3.2 Retrofit Options

In this section, the BGT was employed to examine the total heat demands of the existing housing stock when applying different retrofit options to the eligible houses. Five measures were selected, namely, loft insulation, cavity wall insulation, solid wall internal insulation, solid wall external insulation and double glazing. Fig. 5 shows the number of eligible houses for retrofitting in the existing housing stock in the NE. There are 954,000 houses in which the loft insulation is less than 300mm, and can be topped up with loft insulation of 400mm. There are 308,000 houses were built with unfilled cavity walls, 128,000 houses with uninsulated solid walls, 209,000 houses with some or all windows with single glazing.

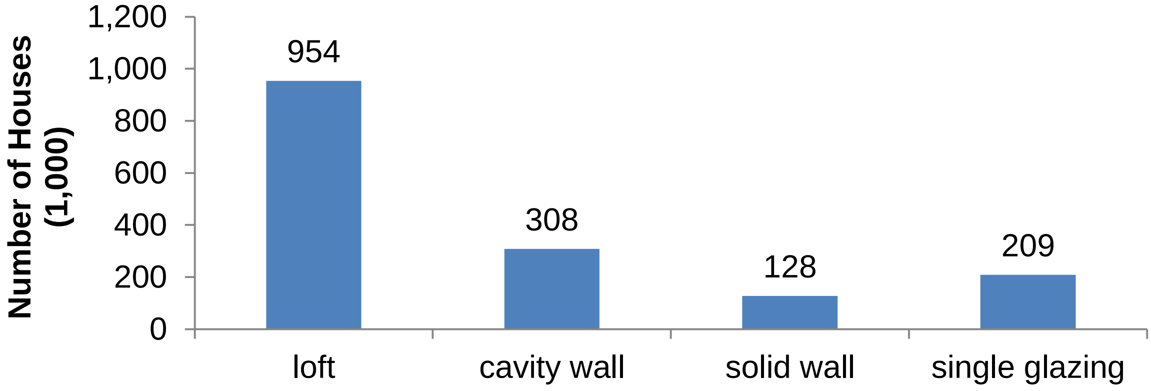

FIGURE 5. Number of eligible houses for retrofitting in the NE.

Fig. 6 shows the total heat demand predictions by applying individual retrofit options, compared to that of the base case. It appears that solid wall internal insulation/solid wall external insulation offers the largest reduction in total heat demand, by 5.7%. Cavity wall insulation reduces the total heat demand by 5.4%. Loft insulation reduces the total heat demand by 1.7%. Double glazing only reduces the total heat demand by 0.6%.

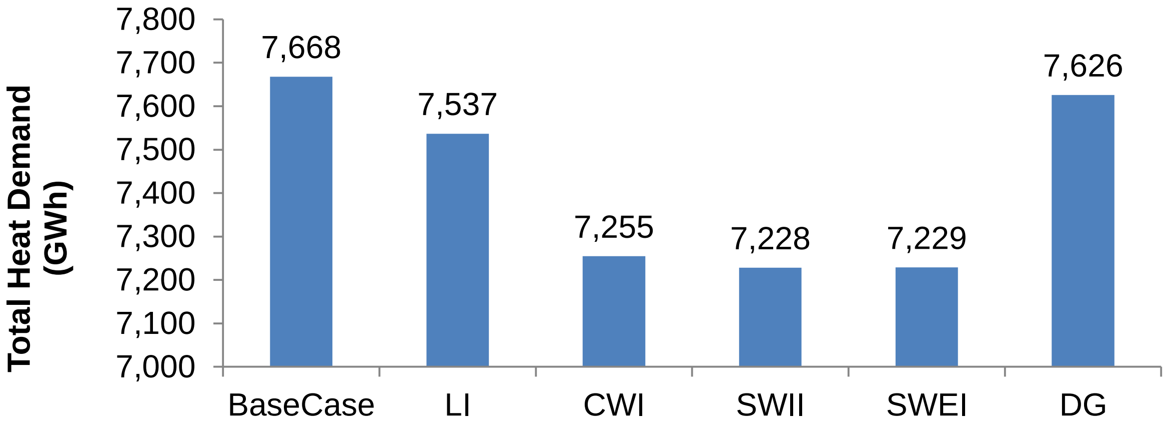

FIGURE 6. Total heat demand predictions by applying individual retrofit option.

Fig. 7 shows the cumulative total heat demand when applying loft insulation, cavity wall insulation, solid wall internal insulation/solid wall external insulation and double glazing in sequence. Applying loft insulation to all the eligible houses, it reduces the total heat demand by 1.7%, from 7,668 to 7,537 GWh. Adding cavity wall insulation to all the eligible houses reduces the total heat demand by another 5.6%, from 7,537 to 7,112 GWh. Adding either solid wall internal insulation or solid wall external insulation further reduces the total heat demand by another 6.3%, and finally adding double glazing reduces by another 0.9%. Overall, applying this range of retrofit options can reduce the total heating demand by 13.9%.

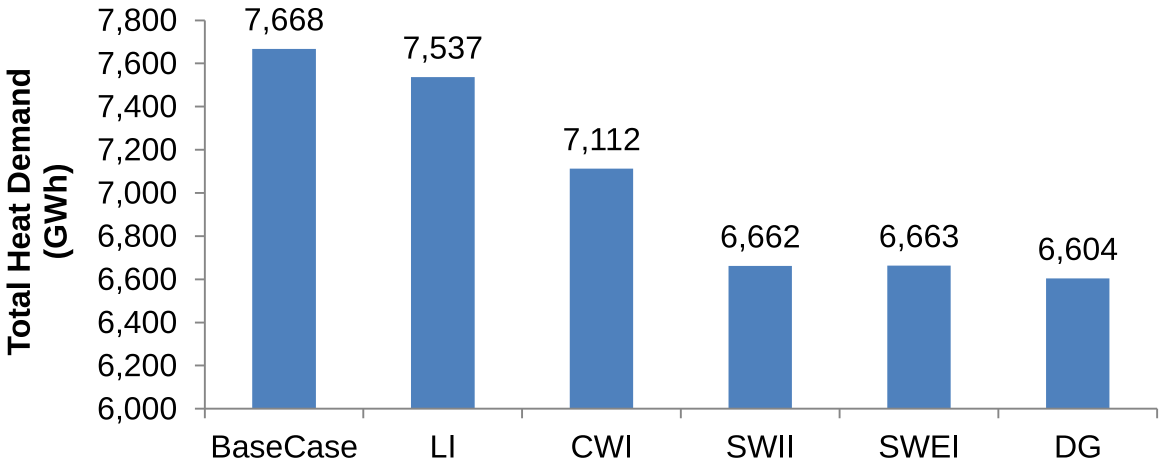

FIGURE 7. Cumulative total heat demands through applying a sequence of retrofit options.

3.3 Cost Consideration

Cost is obviously an important factor when considering the deployment of different retrofit options. There are a few price guide books or references available; however, no single source of cost information could be found that covers all options and the range of figures varies widely from different sources [17]. Table 5 lists the costs used in this study and the sources.

TABLE 5. Costs for retrofit options.

Retrofit Option	Criterion	Cost	Source
Loft Insulation (loose fill)	Ceiling area	£14/m^2	Retrofit for the Future project data analysis report
Cavity Wall Insulation	Detached	£625	The Greener Homes Price Guide (BCIS, 2008)
	Semi/End	£400	
	Mid	£300	
Solid Wall Internal Insulation	External wall area	£87/m^2	Solid wall insulation supply chain review (EST, 2009)
Solid Wall External Insulation	External wall area	£157/m^2	
Double Glazing	Window area	£261/m^2	Retrofit for the Future project data analysis report

These costs are chosen with great consideration and are intended to reflect the real costs in the market. The prices from Retrofit for the Future data analysis report [18] are taken from individual installations although the sample size is quite small. The price for loose fill loft insulation is derived from a sample size of 6 and the price for double glazing is from a sample size of 10. The figures from Solid wall insulation supply chain review by Energy Saving Trust are thought to most reliable as they are based on a wide survey of realistic installed costs from 2009. The Greener Homes Price Guide [19] published by the Building Cost Information Services (BCIS) provides guideline costs for a range of home improvement measures; however, some of the quoted prices are quite high compared to other sources. For example, for cavity wall insulation, the price for a detached house with a floor area of 250 m^2 is quoted as £850. This is adjusted to £625 as a floor area of 250m^2 is larger than that of an average detached house.

Fig. 8 shows the costs for different retrofit options for the housing stock in the NE. Cavity wall insulation costs the least, followed by double glazing, followed by loft insulation, followed by solid wall internal insulation, and solid wall external insulation costs the most.

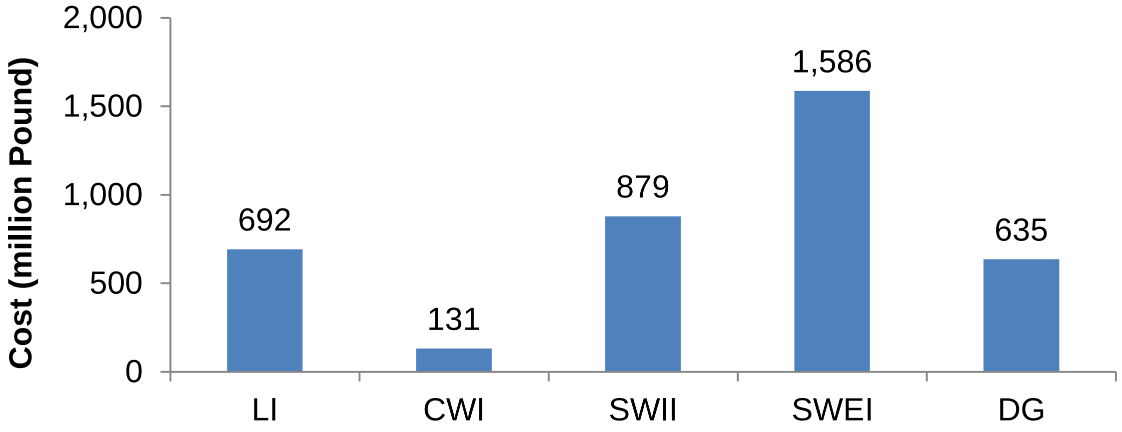

FIGURE 8. Costs for adopting different retrofit options for the NE housing stock.

4. DISCUSSION AND CONCLUSIONS

Despite both the CHM and BGT taking the same inputs from the EHS database, the predictions of total space heating demands by the two models are very different, due to the different calculation/simulation engines. The findings are consistent with other studies [15-16] in the sense that the dynamic simulations have lower demand predictions than the steady-state calculations. Attempts were made to examine individual cases, trying to identify reasons for the discrepancy in predictions by the models. However, due to the large number of assumptions and empirical relationships employed in the steady-state model, as well as the complex heat transfer process simulated by the dynamic model, no firm conclusions could be made. One interesting point related to the heat gain and heat loss through the windows predicted by these two models. The models suggested similar heat gains through the windows, but while the dynamic model suggested the heat loss through the window is about half of the heat gain, the steady-state model suggested it is twice the heat gain. As in the steady-state model, the heat loss through windows is proportional to the overall heat loss calculation; this might suggest the overall heat loss calculation in the steady-state is over estimated

Combing the reductions on space heating demand through applying individual retrofit options and the associated costs, for the housing stock in the NE, cavity wall insulation appears to be the most cost effective measure. Solid wall insulation offer a slightly higher percentage on space heating demand reduction, but the cost is significantly higher. Despite providing nearly the same demand reductions, solid wall external insulation costs nearly twice the amount for solid wall internal insulation. The costs for loft insulation and double glazing are similar; however, insulating lofts for all eligible houses can provide 1.7% demand reduction, while changing all the windows to double glazing can only provide 0.6%.

5. FURTHER WORK

The scope of this study is limited by the number of retrofit options that have been applied to the housing stock in the NE. However, it is important that the proposed method has been tested thoroughly in a small pilot study before applying a wide range of options. Further study will include more retrofit options such as cavity wall insulation with external insulation and low E triple glazing, as well as renewable options such as heat pumps, biomass, wind turbines, PV, etc. in order to have a full picture of the potential demand reduction.

When resources are limited, as often in the real world, it is important to focus all the available resources on the most cost-effective retrofit measures. An optimization package is under development aiming to examine the most cost-effective combinations of all possible retrofits options that can be applied to all the houses at regional or sub-regional level. The findings will support development of long term policy to encourage the take-up of certain combinations of retrofit options in the region.

The ability to predict dynamic demand at regional or sub-regional level by the BGT needs to be further investigated. Other potential outputs which might be of great interests from the model include overheating hours in the future climate, which could become an important constraint for intensive retrofitting.

ACKNOWLEDGEMENTS

This work was carried out as part of the Self Conserving Urban Environments (SECURE) project which was funded by the Engineering and Physical Science Research Council (EPSRC) under their Sustainable Urban Environment programme (grant EP/I002154/1). SECURE is a consortium of four UK universities: Newcastle University, the University of Sheffield, the University of Exeter and Loughborough University. The project website is https://www.secure-preject.org/

REFERENCES

1. DECC, Energy Consumption in the United Kingdom, https://www.gov.uk/government/statistics/energy-consumption-in-the-uk [last accessed Sep 2014]

2. J. Ravetz, *State of the stock: what do we know about existing buildings and their future prospects? Energy Policy*. **36**, pp. 4462-4470 (2008).

3. Department of energy and Climate Change. Climate change act 2008. London: Department of Energy and Climate Change, The Stationary Office (2008).

4. S. Natarajan and G. J. Levermore, *Predicting future UK housing stock and carbon emissions*, *Energy Policy*. **35**, pp. 5719-5727 (2007).

5. M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, and M. Djurovic-Petrovic, *A review of bottom-up building stock models for energy consumption in the residential sector*, *Building and Environment*. **45**, pp. 1683-1697 (2010).

6. T. Lee and R. Yao, *Incorporating technology buying behaviour into UK-based long term domestic stock energy models to provide improved policy analysis*, *Energy Policy*. **52**, pp. 363-372 (2013).

7. S. Taylor, D. Allinson, S. Firth and K. Lomas, “Dynamic energy modelling of UK housing: Evaluation of alternative approaches”, in 13th Conference of International Building Performance Simulation Association, Chambery, France, pp. 745 – 751 (2013).

8. BRE, BREDEM, available from: http://www.bre.co.uk/page.jsp?id=3176 [last accessed Sep 2014]

9. EnergyPlus Energy Simulation Software, available from: http://apps1.eere.energy.gov/buildings/energyplus/ [last accessed Sep 2014]

10. Cambridge Housing Stock Model, available from: https://www.gov.uk/government/publications/cambridge-housing-model-and-user-guide [last accessed Sep 2014]

11. English Housing Survey, available from: https://www.gov.uk/government/collections/english-housing-survey [last accessed Sep 2014]

12. S. K. Firth, K. J. Lomas and A.J. Wright, *Targeting household energy-efficiency measures using sensitivity analysis*, *Building Research & Informaiton*. **38:1**, pp. 25-41 (2010).

13. G. M. Huebner, M. McMichael, D. Shipworth, M. Shipworth, M. Durand-Daubin and A. Summerfield, *Heating patterns in English homes: Comparing results from a national survey against common model assumptions*, *Building and Environment*. **70**, pp. 298-305 (2013).

14. Y. Zhang, "'Parallel' EnergyPlus and the development of a parametric analysis tool", in Proc. of the 11th IBPSA Conference, Glasgow, UK, July (2009).

15. L.D. Shorrock, J.E. Dunster, C.F. Seale, H. Eppel and S.Z. Lafferty, *BREDEM: Testing monthly and seasonal versions against measurement and against simulation models*. *Proc. CIBSE A: Building Serv. Eng. Res. Technol.* 17(3), pp. 135-140 (1996).

16. S. Yilmaz, D. Allinson, S. Taylor and K. Lomas, "A parametric analysis of the energy savings predicted by different thermal models: implications for the UK Green Deal", Building Simulation and Optimization Conference, UCL, London (2014).

17. S. M. Porritt, "Adapting UK Dwellings for Heat Waves", Ph.D. thesis, De Montfort University, Leicester, UK (2012).

18. Technology Strategy Board, Retrofit Revealed, The Retrofit for the Future projects – data analysis report, available from: https://www.innovateuk.org/retrofit-analysis [last accessed Sep 2014]

19. BCIS, *The Greener Homes Price Guide*. Number ISBN 978 1 904829 67 6. The Building Cost Information Service London (2008).