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Energy Procedia 78 (2015) 854 – 859

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Multi-objective optimization for a large scale retrofit program for the housing stock in the North East of England

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Abstract

In this study, a dynamic model was developed to simulate the housing stock in the North East region of England. This model takes input from the English Housing Survey database and uses EnergyPlus as its simulation engine. A range of retrofit options was applied to the housing stock, to examine the possible CO_2 reductions corresponding to different scenarios. By embedding a multi-objective optimization package into the process for making decisions on retrofit solutions, it is possible to identify the most cost-effective combinations of all measures across the housing stock. By ranking the optimal solutions from the lowest to the highest cost, the trend of the uptake of individual retrofit measures could be obtained. The findings will support the development of strategies for retrofitting the housing stock in the region. This framework can be applied to housing stocks at sub-regional or national level.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Dynamic housing stock model; multi-objective optimization; large scale retrofit; energy saving

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]. Although energy efficiency for the whole housing stock

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Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.007

has increased slightly over the years, the average home energy rating remains low and the housing stock could hugely benefit from a wide range of retrofit measures [3]. In order to achieve the UK Government's CO_2 reduction target of 80% by 2050 compared to the 1990 baseline [4], 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.

In general, retrofit measures available in the market can be categorized into three groups:

- Improving the building envelope, e.g. insulating walls, roofs, and windows;
- Improving heating and hot water systems, e.g. upgrading boilers and control systems;
- Installing renewable energy systems, e.g. photovoltaic, biomass boilers, ground source heat pump systems, etc.

When retrofitting a building, there is usually more than one measure that is applicable and the capital cost and energy saving of one measure could be very different from that of another. Consequently, it is of great importance to identify the most cost effective retrofit measures. Applying multi-objective optimization to evaluate the retrofit strategies for a single building by considering multiple and competing objectives, such as cost, energy saving and thermal comfort is well established in the research field of building simulation [5,6]. In contrast, applying multi-objective optimization to a large scale retrofitting program on multiple buildings, particularly on a regional or national scale, is still emerging. With limited resources, maximizing cost benefits and prioritizing the retrofit measures are crucial to the success of making rational decisions on retrofit programs at regional or national level.

This paper describes the application of a multi-objective optimization package for making decisions on a large scale retrofit program. The housing stock in the North East (NE) region of England is chosen as an example in this study. The package has been proved to be able to identify the most cost-effective combinations of all retrofit measures across the representing houses in the NE region. An analysis of the trend of the uptake of individual measures for the optimal solutions is described.

2. Methods

2.1. English housing survey (EHS) data

The English Housing Survey (EHS) is a year-on-year national survey commissioned by the UK 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 [7]. Its database provides detailed information, such as age band, dwelling type, region, dimensions, window area, glazing type, wall construction, roof construction, floor construction, loft insulation and built form, of representative houses in England. This detailed information allows the recorded dwellings to be simulated dynamically in building simulation software such as EnergyPlus.

The 2009 EHS database contains 935 sample dwellings in the NE region of England, and these dwellings represent 1.2 million homes in that region. The 935 dwellings are of 6 different dwelling types, 10 age bands, 8 wall construction types, and 12 loft insulation levels. The distribution of the 935 dwellings in dwelling type, age band, wall construction and loft insulation is shown in Fig. 1. This initial study excludes flats and focuses on the 759 houses recorded in the database, taking no account at this stage of the 1.2 million homes they represent.

2.2. Energy demand of the housing stock

A dynamic housing stock model has been developed, using the English Housing Survey (EHS) 2009 data, coupled to the EnergyPlus dynamic simulation engine [8]. EnergyPlus is a well-recognized and extensively tested fully-integrated building simulation tool and freely available. EnergyPlus takes an input data file (IDF), in which a building model is specified, and a weather file to run a dynamic simulation of a building. 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, different age bands and various fabric constructions. Therefore, an in-house program called the Building Generation Tool (BGT) has been developed to create the IDFs automatically, taking inputs from text files. The detailed description of the model and the validation against a steady-state housing stock model can be found in a previous study [9].

In order to minimize computational complexity, the approach adopted for simulating the thermal behavior of the houses was to determine the heating demand. Post-processing was then used to account for fuels and heating systems. The optimization study was therefore restricted to retrofit measures related to improving the building fabric, including cavity wall insulation, internal solid wall insulation, external solid wall insulation, loft insulation, and double glazing. All possible individual or combined retrofit measures have been applied to each of the 759 houses identified in the EHS 2009 database. However, not all measures are applicable to all houses; for example, double glazing is not an option for houses that are already fully double glazed. Consequently, the original 759 houses increased to 2097 houses with all possible options of retrofit measures applied. The energy demand of the original 759 houses and the retrofitted 2097 houses has been estimated by the dynamic housing stock model.

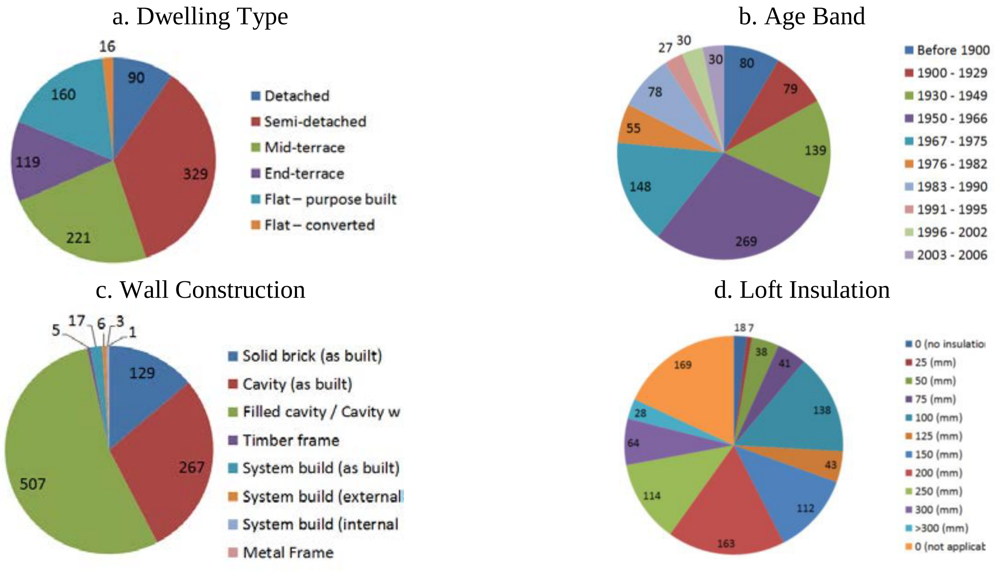

Fig. 1. Distributions of 935 dwellings in dwelling type, age band, wall construction and loft insulation.

2.3. Costs of retrofit measures

Despite there being multiple price guide books and references available, no single source of cost information could be found that covers all retrofit measures and the range of figures varies widely from different sources [10]. Table 1 shows the costs of retrofit measures used in this study. These costs were carefully chosen to reflect the real costs in the market. Most of the costs are taken from Energy Saving Trust (EST) [11], except the cost of double glazing which is taken from a report from the Retrofit for the Future project by the Technology Strategy Board (TSB) [12].

2.4. Multi-objective optimization

A multi-objective optimization package has been applied to identify the most cost-effective combinations of all measures across the housing stock. The algorithm selected in this study is an implementation of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) first proposed by Deb et al. [13]. The same implementation has been used in a previous study to optimize the design of fenestration on a façade of a building [14].

Two objectives are optimized: the energy demand of the housing stock, estimated by the dynamic housing stock model; and the costs of installing retrofit measures, calculated using the figures in Table 1. In order to deal with the large search space, the optimization approach is decomposed into two stages. Firstly, an exhaustive search is run for each individual house to find its Pareto-optimal energy-cost trade-off (the search space for this typically being a maximum of a few tens of solutions per house). Constraints such as over-heating risk can be considered at this stage, so that only solutions meeting the constraints are passed to the next stage. Secondly, to find the trade-off for the housing stock, the space of Pareto-optimal solutions over all houses is searched using NSGA-II.

A parametric tool called jEPlus [15] 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 the original 759 houses and the potential retrofitted 2097 houses takes about 6 hours in a dual-core PC with 4 threads.

Table 1. Costs of retrofit measures.

Retrofit Options	Criteria	Cost	Sources
Loft Insulation	Detached	£395	EST [11]
(0 to 270mm)	Semi/End	£300	
	Mid	£285	
Loft Insulation top up	Detached	£265	EST [11]
(100mm to 270mm)	Semi/End	£220	
	Mid	£215	
Cavity Wall Insulation	Detached	£720	EST [11]
	Semi/End	£475	
	Mid	£370	
Solid Wall Internal Insulation	External wall area	£87/m^2	EST [11]
Solid Wall External Insulation	External wall area	£157/m^2	
Double Glazing	Window area	£261/m^2	TSB [12]

3. Results and discussion

3.1. Pareto optimal

The output set of non-dominated solutions, i.e. the Pareto optimal set, was derived from the set of all solutions generated over an optimization run. The parameters, such as random initialization number, which might affect the results of the optimization runs, have been extensively tested. The outcomes from the tests will be reported in another paper [16]. The run found 398 solutions in the trade-off, which are plotted in the objective space, i.e. energy demand and cost, in Fig. 2.

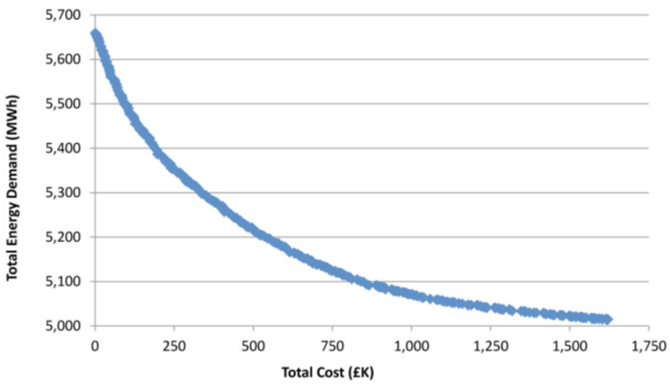

Fig. 2 The Pareto optimal set found by the optimization, plotted in objective space.

The total heating energy demand of the 759 houses without applying any retrofit measures is about 5,660 MWh. Providing a total investment of £250,000, a maximum 310 MWh reduction in total heating energy demand (5,350 MWh) can be achieved through applying the optimum combination of retrofit measures to the houses. The cost-effective ratio of the investment can be defined as: $R = ER / C$, where R is the cost-effective ratio (kWh/£), ER is the total energy reduction (kWh) and C is the total cost (£). The cost-effective ratio of the initial £250,000 investment is 1.24 kWh/£. Increasing the investment to £750,000, a maximum further 230 MWh reduction can be made, which gives a cost-effective ratio of 0.46 kWh/£ for the additional £500,000 investment. If all suitable measures are applied to all houses, it will cost a total of £1,620,000, reducing the total energy demand to 5,015 MWh. The further additional investment of £870,000 only gives a cost-effective ratio of 0.12 kWh/£.

3.2. Data analysis

Analyzing the Pareto optimal solutions in detail provides insights into the uptakes of individual or combined retrofit measures during the optimization process. Fig. 3 shows the number of installations for each individual retrofit measure for all the solutions on the Pareto front.

The solutions on the Pareto front are ranked from 1 to 398 according to the increment of total cost, which is shown on the x-axis. Solution No.1, for example, is the solution with the minimum cost (0 in this case), and none of the measures is installed. Solution No. 398 is the solution with the maximum cost, and in this case, all the suitable measures for all houses are installed. Each line between Solution No.1 and No.398 shows the trend of the installation of a particular measure when the total cost increases. The prioritization is in the installation of loft insulation, followed by the installation of cavity wall insulation, which is not surprising, considering that loft insulation is the cheapest, and cavity wall insulation second cheapest, among all selected measures and their energy savings are relatively high. Solid wall external insulation and solid wall internal insulation are two exclusive measures, both of which can only be applied to houses with solid wall construction. Due to the lower cost of solid wall internal insulation, up to Solution No. 325, the installation of solid wall internal insulation is increasing; however, solid wall external insulation has a better performance in terms of reducing heat demand in some cases, and therefore, at the higher cost end of the solutions, the installation of solid wall external insulation starts to pick up, which corresponds to the decrease of solid wall internal insulation. The installation of double glazing also only starts to happen towards to the high cost end of the solutions due to the high cost and the smaller savings from individual installation.

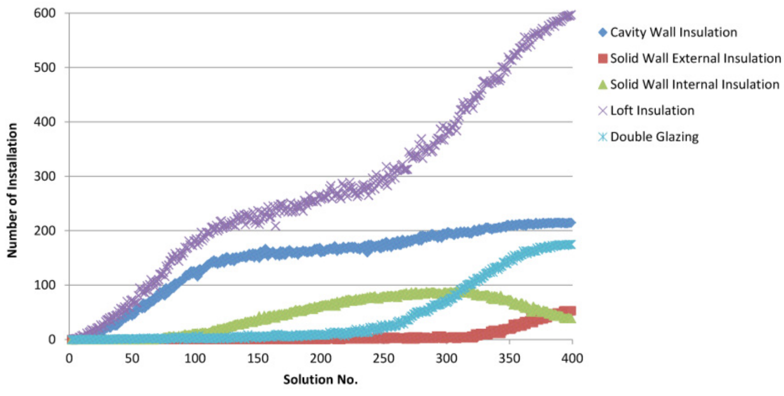

Fig. 3 Counts of individual measures for the Pareto solutions.

4. Conclusions and further work

When resources are limited, as is often the case in the real world and particularly in a large scale retrofitting programme, it is important to identify the most cost-effective measures that can be applied to the most suitable houses. By applying the multi-objective optimization package, it is possible to derive the Pareto optimal solution set that demonstrates the trade-off between the energy demand and cost. The findings show that the cost-effective ratio decreases sharply for a significant increase in investment. The initial £250,000 investment could result in a cost-effective ratio of 1.24 kWh/£, while the cost-effective ratio of an additional £500,000 investment drops to 0.46 kWh/£. Retrofitting all houses with the expensive measures for a further additional £870,000 causes the cost-effective ratio to fall to 0.12 kWh/£.

The analysis of the Pareto optimal solutions set can be difficult, particularly where there is a large number of an individual or combined retrofit option to consider. A simple approach based on ranking the solutions and counting the number of installations of individual measures, whether they are applied on their own or in combination with other measures, has been used in this study to examine the trend of installation for each measure across the whole cost range. While it is not surprising the uptake of loft insulation shows a much faster trend, followed by cavity wall insulation, it is interesting to notice the uptake of double glazing only begins towards the higher cost end, and the uptake of solid wall internal insulation starts to drop and later overtaken by solid wall external insulations at the higher cost end.

When running all the dynamic simulations, the overheating hours for living room and bedroom have been recorded, and in future work they will be added as the constraints in the optimization process. Furthermore, the ability to predict dynamic demand at regional or sub-regional level by the dynamic housing stock model needs to be further investigated.

Acknowledgements

This work was funded under UK EPSRC grant EP/I002154/1 (Self Conserving Urban Environments – SECURE). SECURE is a consortium of four UK universities: Newcastle, Sheffield, Exeter and Loughborough. Website: https://www.secure-project.org/

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