DYNAMIC ENERGY MODELLING OF UK HOUSING: EVALUATION OF ALTERNATIVE APPROACHES

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ABSTRACT

Models of UK houses have been created at nine levels of detail, to study the impacts on the computed energy consumption. The results will inform an evaluation of alternative methods of large-scale dynamic stock modelling. The levels reflect the shortage of suitable data at one end of the scale and the effort involved in implementing a detailed model at the other.

Simulations using EnergyPlus showed that a built form based on the true building footprint, along with the inclusion of window frames and a separately-zoned living area, brought the computed annual energy demand within about 10% of the best estimate. Higher accuracy was associated with the inclusion of complete zoning, sophisticated ground floor heat loss and high levels of architectural detail.

INTRODUCTION

The combination of increasing urbanization and the need to reduce CO_2 emissions has led to the emergence of the SECURE project (SECURE 2013). Its aim is to study the energy and resource flows of a whole English region and to determine the extent to which it can be self-supporting.

The region of interest is the North East, with a population of 2.6 million living in about 1.1 million homes. It includes several large towns and cities including Newcastle, Gateshead, Durham, Sunderland and Middlesbrough, along with large rural areas with low populations. One major area of study is the energy consumption and corresponding CO_2 emissions associated with the homes in the region, and the prospects for demand reduction through energy efficiency measures and low-carbon energy systems.

Current approaches in bottom-up domestic stock modelling in the UK typically employ steady-state or quasi-steady state calculations to compute energy demands on a monthly or yearly basis as reviewed by Kavgic et al. (2010). Examples are BREHOMES (Shorrock and Dunster 1997), UKDCM (Boardman et al. 2005), DECarb (Natarajan and Levermore 2007), CDEM (Firth et al. 2010) and the CAR housing model (CAR 2013, Hughes et al. 2013). Typical uses are to estimate emissions and evaluate the potential impact of large-scale refurbishment strategies.

However, steady state methods are not appropriate for studying the transient behaviour that can arise in a range of important circumstances, such as short-term changes in the weather or disruptions to parts of the energy supply. There are also aspects of net flows of gas, electricity and other resources that require a fully time-dependent approach to capture important behaviours. Examples are district heating, heat storage, the charging of electric cars, embedded electricity generation, and the behaviour and management of smart grids.

MODELLING APPROACH

Having established that there is a case for dynamic modelling of the building stock, an approach needs to be established. There are two main methods of carrying out stock modelling. One is to represent sets of dwelling types by well-specified models known as "archetypes". These may not match any specific real dwelling but are nevertheless assumed to behave in an average way such that when the behaviours (e.g. energy consumptions) of the archetypes are combined in proportion to the population in the region of interest, the total is an accurate reflection of the housing stock. An example is the CDEM model of Firth et al. (2010) which used 47 archetypes based on building age band and house type, the latter using the archetypes defined by Allen and Pinney (1990). Archetype approaches have also been used by, among others, Parekh (2005), Zhao et al. (2011), Famuyibo et al. (2012) and Mavrogianni et al. (2012).

An alternative stock modelling approach is to model relatively large numbers of samples of real dwellings. This "actual building samples" approach, referred to hereafter as ABS, was used by Swan et al. (2013) to supply the ESP-r dynamic modelling tool from an existing database of nearly 17,000 real Canadian houses. However, the database did not contain sufficient geometrical data to create a detailed floor plan layout (Swan 2010), leading to the need for a "rectangularization process" to create simple models consistent with the value available for the floor area.

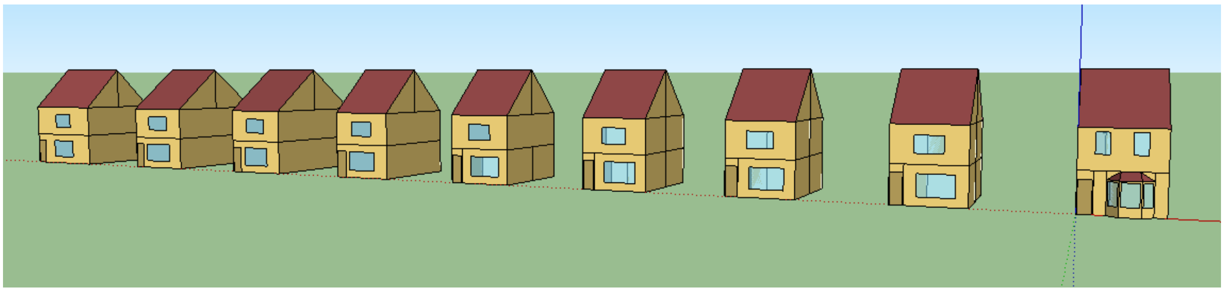

Figure 1 Variants of the Allen and Pinney period terrace

An attempt was made to use a single thermal zone in line with the finding of Purdy and Beausoleil-Morrison (2001) that the impact of such an approach on the modelling accuracy was small. But when combined with the rectangularization process, this approach led to a loss of accuracy in the model of Swan et al., and as a result a zone was used on each floor.

The most expedient approach to use in the SECURE project is not currently clear, since both methods have advantages and disadvantages. In broad terms, the choice is between creating a large number of models for which the built form and internal details are estimated, or a small number for which these aspects are represented precisely. In addition, there are many other aspects to consider, such as the ability to incorporate future technical developments, data availability both now and in the future, and the software development effort and computing resources required.

One important contributor to the decision is the level of detail required in the building models to achieve sufficiently accurate results. If more detail is required than available in the databases that would be used for an ABS approach then an archetype basis might be preferred. Even if the data are available, computing resource issues (speed and storage) or the effort required to construct the ABS models might make such an approach impracticable, or at least expensive. These points are studied in the present paper.

A further consideration, not considered here but the subject of planned work in the future, is the ability of the dynamic behaviour of an archetype model to represent that of a real population of dwellings. In the current work this would be the clusters of 400-1200 homes in a Lower Layer Super Output Area.

PARAMETRIC ANALYSIS

A modelling exercise was carried out to provide information about the impact of different levels of detail on the energy consumption and run time of a set of house models.

The levels were chosen to represent both data availability and variations in detail used to represent houses, and so capture some of the important issues that will be taken into account when choosing between an archetype or ABS approach.

The dwelling types simulated were two-storey north-facing houses based on the period terrace, semi-detached and detached house archetypes defined by Allen and Pinney (1990). Nine variants of each of these designs allowed the impact of modelling detail on annual energy consumption and run time to be assessed. The variants are listed below and illustrated in Fig. 1 for the period terrace, with the level of detail increasing from left to right.

The details of the variants are as follows:

1. The simplest case, using just the ground floor area (GFA) from the building database to define a square building footprint, so that the wall lengths are the square root of the GFA. Each floor forms a single zone (Hopkins 2011). Window area is distributed equally between the (front and rear) exposed walls; windows are placed centrally in each surface. Front and rear external doors are placed on the left of the house when viewed from the front.
2. A rectangular building footprint with an aspect ratio of 1.6 is calculated from the GFA, with the length of the front façade shorter than the front-to-back distance. All other assumptions are the same as Variant 1.
3. As Variant 2 but with the aspect ratio of the base rectangle adjusted to ensure the area of the party walls is correct. This level of modelling is omitted for detached buildings because they have no party wall.
4. The footprint of the actual building is used. This might be taken from digital mapping data, for example, as done by Zhao et al. (2011). The result is precise lengths of all outer walls.
5. Simple window frames and dividers are added, replacing wall area (so that the glazed area remains constant). The aim is to determine the need for detailed glazing.
6. A “living zone” is introduced to the ground floor. This reflects the multi-zone model of the UK Standard Assessment Procedure (SAP) which defines two zones: the living area and the rest of dwelling, for which different space heating schemes are applied. The “true” living area, as defined by Allen and Pinney (1990), is used here to ensure the subsequent comparison provides the greatest value.

7. Each dwelling is fully internally zoned (each individual room is a thermal zone). Many studies have used exemplar houses at this level of sophistication in which buildings are sufficiently well described that detailed occupancy, lighting and appliance load schedules may be investigated.
8. Rather than the simple monthly ground temperature approach (a ground temperature object with a temperature setting of 14 C, following the default used by DesignBuilder), the EnergyPlus ground slab pre-processing tool is used. This departure from default options, while only requiring seven additional EnergyPlus objects, would force a significant increase in the computational complexity since monthly internal temperatures must be first estimated and passed as parameters to the slab object.
9. Most of the detail described by Allen and Pinney (1990) is represented, including correctly sized windows and bay windows where present.

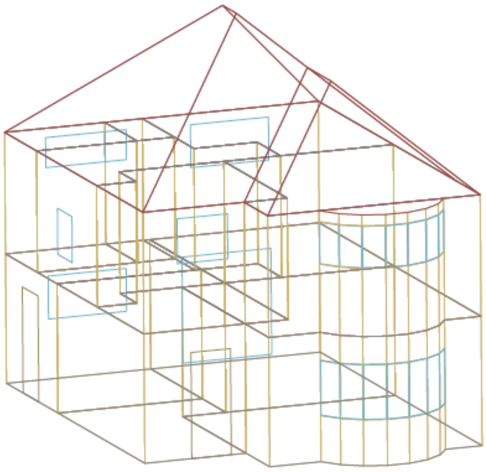

Figure 2 Detached house, Variant 9

The level of detail included in Variant 9 is illustrated in Fig. 2, which depicts the Allen and Pinney detached house.

The effects of these changes on the building envelopes of the three house types are shown in Table 1.

It is worth noting that although the gross exposed wall area (that is, the area of wall plus windows) of the period terrace is smaller than that of the semi-detached, its conditioned floor area and volume are both larger.

METHODOLOGY

The dynamic thermal modelling tool adopted was EnergyPlus because it is well-regarded, well supported and capable of operating at a range of levels of complexity. Version 7.1.0.012 was used, with the same weather file, for Leicester, UK, in all simulations.

The annual heating energy demand was determined for the three defined house types, detached, semi-detached and period terrace, using the variations defined in the previous section. Solid wall construction was assumed in all simulations.

Table 1

External Envelope Details

Property	House type	Variant				
		1	2	3	4-8	9
Gross exp wall area / m^2	Terrace	66.9	52.9	47.5	62.8	63.0
	Semi	110.2	96.4	97.7	97.3	103.4
	Detached	137.2	140.8	-	141.7	144.7
Party wall area / m^2	Terrace	66.9	84.7	94.4	105.1	105.1
	Semi	30.7	38.3	38.9	33.4	33.4
	Detached	0.0	0.0	-	0.0	0.0
Floor area / m^2	Terrace	86.1	86.2	86.2	86.3	87.5
	Semi	85.3	83.0	85.4	83.2	85.5
	Detached	100.0	99.8	-	100.0	102.8
Volume / m^3	Terrace	219.5	219.7	219.8	216.0	222.1
	Semi	200.4	195.0	200.5	195.6	201.0
	Detached	242.4	242.0	-	242.5	249.3

The same convective heat transfer algorithms, TARP for internal surfaces and DoE-2 for external, were used for all simulations. The choice was not crucial, because the main aim in the present work was to compare the effect on the results of changes in the level of detail being modelled. The appropriate choice of convection heat transfer algorithm will be the subject of future work.

The infiltration was kept constant in all simulations at 0.7 ach (air changes per hour) in conditioned areas and 3.0 ach in the roofs.

In all cases a heating schedule was used in which the heating is switched on between 7 and 9 a.m. and 4 and 11 p.m. during the week and between 7 a.m. and 11 p.m. at weekends. In the later variants (6 onwards), two setpoint temperatures were used: 21 C in the living room and 18 C elsewhere. In the earlier variants which did not have a defined living area, a floor area-weighted mean temperature was calculated using the area of the living room used subsequently. This temperature was close to 18.5 C for each house type.

Heating was modelled using an ideal loads system which supplied precisely the energy required to maintain the setpoint temperature in each zone during the heating period.

For simplicity, there were no casual gains from either occupants or lighting and appliance usage, making the heating schedule the only aspect of occupancy included.

RESULTS

Energy demand

The annual space heating energy demand for the nine variants of the three house types is shown in Fig. 3.

Several features are worth noting. First, the period terrace and the semi-detached house have similar energy consumptions at all stages. This can be attributed to a balance between two heat loss mechanisms. While the semi-detached house suffers greater fabric heat loss due to its larger exposed area, the higher volume of the terraced house leads to higher ventilation heat loss.

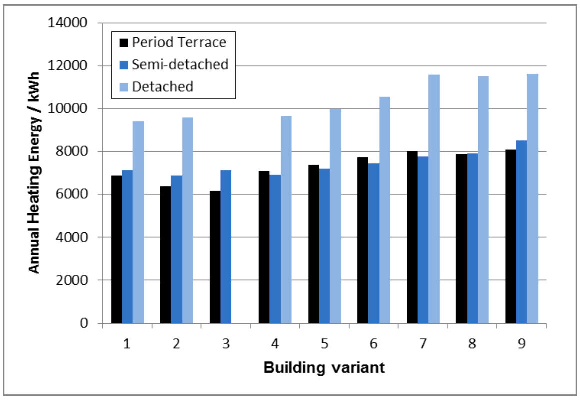

Figure 3 Annual heating energy demand

Second, the range of the values of annual heating energy consumption resulting from the changes between the variants is about 21% of the mean value for the semi-detached and detached houses, and slightly higher at about 27% for the period terrace.

The reducing trend in energy consumption for the period terrace in Variants 1 to 3 can be attributed to a decreasing exposed area and increasing party wall area as shown in Table 1. The trend reverses in Variant 4, where although the party wall area increases slightly, the exposed wall area rises sharply.

There is a general trend in all three house types for the annual energy consumption to increase with variant number from 4 to 7, with some levelling off afterwards.

Run time

Figure 4 shows the impact of the model complexity on computer run time. The value returned by EnergyPlus is actually an elapsed time and so depends on other processes being carried out by the computer. The data presented should therefore be seen as indicative rather than precise.

All simulations were performed on the same machine (an HP ProBook 6460b running a Core i5-2520M CPU at 2.5GHz with 8GB RAM). The execution time is shown for each variant of each building. The main increases in execution time occur with Variant 7 (internal zoning) and, for the detached house, Variant 9 (high levels of detail including a complex bay window).

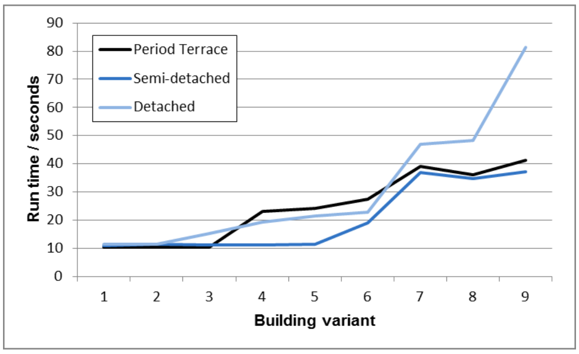

Figure 4 Simulation run times

DISCUSSION

Impacts of changes in detail

The main aim of the present work was to examine the impact of variations in the level of modelling detail on the annual energy demand and also on the run time. Variant 9 can be taken as the most accurate representation of the three Allen and Pinney houses, and the discrepancies in the energy consumption values for the earlier variants therefore give a measure of their performance.

Table 2 presents the degree by which the earlier variants underestimate the energy consumption predicted by Variant 9.

Table 2
Underestimation of Variant 9
energy consumption

Variant	Period Terrace	Semi-detached	Detached
1	14.9%	16.2%	19.1%
2	21.4%	19.0%	17.6%
3	23.9%	16.1%	-
4	12.7%	18.8%	16.8%
5	8.9%	15.3%	14.0%
6	4.6%	12.3%	9.1%
7	1.2%	8.5%	0.4%
8	2.6%	6.9%	0.9%
9	0.0%	0.0%	0.0%

By Variant 6, all results are close to being within 10% of the Variant 9 value. Variant 6 is the point at which a separately-zoned living area is introduced.

Figure 4 shows that some sharp rises in computational run time occur after Variant 6. Although these figures are approximate, as mentioned earlier, the indications are that if run time was an issue, Variant 6 could represent a good compromise if suitable data were available to allow its calculation.

Feasibility of the ABS approach

The discussion so far has covered energy consumption and run time but, as noted earlier, the choice of level of detail will have many other consequences. While high detail levels may be achievable for an archetype approach because the number of models can be low enough to allow manual data collection, the same is not true of the ABS approach, and this section of the discussion will focus on the feasibility of implementing the latter method.

The higher levels of detail may require data that are unavailable or impracticable to obtain for the numbers of models required by the ABS approach, so that inference methods become necessary. This could considerably increase the modelling effort because robust algorithms that produce realistic outputs, e.g. of room shapes and sizes, will be required.

In this context, it is interesting to consider the possibilities offered by the English Housing Survey (EHS) database as presented in association with the Cambridge Housing Model (Hughes et al. 2013, CAR 2013).

This database contains data for 16,150 UK dwellings, intended to be representative of the English housing stock of about 22.3 million homes. It includes the age band, tenure type, dwelling type (detached, semi-detached, etc.), number of occupants, information on windows and heating system and the number, height and floor area of storeys. There is also a regional code, allowing the 935 dwellings in the North East of England, which is the focus of the SECURE project, to be identified.

The database does not define the building geometry, so an element of simplification would be necessary as in the work of Swan et al. (2013). However, the data that are provided do allow some clues to the built form. The available data from which the built form must be derived are house type, ground floor area, exposed perimeter, party wall area and height. From this, it is clear that the total exposed wall area can be derived, thus allowing one of the most important features of the built form to be represented. By making reasonable assumptions, the data provided allow a basic footprint shape to be inferred. Total window area together with further reasonable assumptions allows the fenestration to be defined.

But the situation is less clear-cut for aspects of the building for which data availability is more limited. An example is the internal zoning of a dwelling. It should be possible to automatically determine a likely room layout for a given built form, so that each room can be defined as a zone. But the problem is not trivial, and the programming effort will be considerable. At the same time the results will be debatable because an automatic approach is unlikely to get zoning exactly right. This would not matter if the impact on the energy consumption were small, but in that case the zoning would be best left at the current default level. So the sensitivity of the modelling results to a change from default to full zoning is an important issue.

The results suggest that the introduction of zoning does have an impact on the annual energy consumption, supporting the work of Purdy and Beausoleil-Morrison (2001). An important future task will be to understand the reasons for this. Possible reasons are greater thermal mass due to more internal walls, or differences in the utilization of solar gain. Depending on the cause, it may be possible to retain simple zoning and account for the difference by an alternative method. For example, if the explanation were the additional thermal mass provided by extra zones, it would require much less development effort to place a concrete block with the required thermal properties in a single-zone model than to program an algorithm to define zones automatically.

If this is not possible, and automatic zoning is required, some interesting issues are raised. It would be easier to zone an archetype because it would probably be feasible to perform the task manually. But since the precise positioning must be rather arbitrary (since the majority of buildings represented by an archetype will differ from it in matters of detail), the result from an automatic method that behaves according to reasonable rules should be no worse. There would be other advantages of full zoning, including the ability to study zonal heating controllers and summer overheating risk. The additional computing cost of full zoning would, however, be considerable.

Future work

The initial phase of future work will concentrate on the feasibility of the two alternative modelling approaches. The main tasks are to determine methods for representing built form using the available data in the EHS database as described above, and to assess the operation of an archetype approach when performing dynamic modelling.

When the approach has been decided, the main focus will be the methods to be used for modelling occupancy, the appropriate representation of heating systems, and the creation of a software tool to create and run dynamic simulations at the appropriate level of detail.

Occupancy will need to be modelled whichever approach is chosen. Within a dynamic building modelling tool like EnergyPlus, human behaviour appears in the form of schedules related to the numbers of people present and the operation of windows, HVAC (extract vents, heating and hot water systems), and, crucially, lights and appliances.

The behaviour of occupants can have a profound impact on energy consumption, as shown by many studies. A recent example is Gill et al. (2011) who measured energy and water consumption in a low-energy housing development. They found space heating and electricity consumption per unit area varying by factors exceeding 3 between similar dwellings.

Methods for modelling occupancy include the creation of synthetic demand data, closely matching real data for individual dwellings, e.g. Yao and Steemers (2005), Richardson et al. (2010). More recently, Goldstein et al. (2010a, 2010b) demonstrated the use of "personas" to represent individuals' energy use in non-domestic buildings.

The complexity of heating system modelling, and the lack of the highly detailed data that would be needed to support it, means that further investigations of the modelling approach will focus on small increases in the level of detail, to capture the main differences between the behaviour as modelled in the present work (with near-instantaneous temperature increase) and the realities of systems in existing occupied homes.

CONCLUSIONS

A study has been carried out of the effect of variations in modelling detail on the energy consumption of three UK house types. The work was prompted by the need to decide on a modelling approach for the SECURE project which will apply dynamic thermal modelling to the housing in a UK region.

An overall trend of increasing energy consumption with increasing detail was found, with the most detailed modelling producing the highest energy consumption. Simulation run times also increased with the level of detail, with the effect most marked for the detached house.

It was possible to omit complete internal zoning, sophisticated ground floor heat loss calculations and detailed architectural features and still achieve energy consumption values within about 10% of the high-detail results. The run times for this detail level were less than three times the base case values.

Whether the levels of modelling detail required for this level are achievable using actual buildings samples (ABS) approach will be tested by further work on constructing dwelling models from the EHI database.

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