Domestic housing upgrades policy development

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Abstract

Policy formation for the upgrade of domestic sector housing is an increasingly important research area. A major difficulty is to account for the large variations in location, age, climate, construction, occupant use and appliances; and the inclusion of renewable and low carbon technologies.

Detailed simulation tools in a policy context have mostly been applied to representative designs rather than large housing stocks. This paper reports the development of a housing stock modelling tool based on simulation. It establishes a rational approach to refurbishment policy guidance by providing information on energy and emissions implications of upgrade options. It can be applied at any scale from a single dwelling to a national housing stock. The tool is aligned with the UK's Standard Assessment Procedure, which is the regulatory compliance calculation method for dwellings. The paper describes the modelling procedure and presents outcomes from application to the Scottish housing stock.

1 Introduction

Within the UK, buildings are responsible for approximately 40% of carbon emissions and radical upgrades will be required to achieve national targets (a reduction of 34% of 1990 emissions by 2020 and 80% by 2050). The housing stock tends to be old and many buildings have a conservation status and cannot be modified in many respects. Further, upgrade penetration rates are low (typically less than 1%) and upgrade measures are often expensive with payback periods of the order of 10 years or more. Long term energy policy regarding upgrading needs to take into account a variety of factors in addition to emissions reduction to ensure best use of resources.

Appraisal techniques employed to answer relevant questions are mostly based on simple energy balance approaches and/or empirical relationships – such as in the UK's Standard Assessment Procedure (SAP; BRE, 2009). The empirical algorithms employed by SAP rely on historic data (more than 10 years) and do not adequately account for the dynamic behaviour of dwellings. Because of this shortcoming such methods are often unable to accurately represent proposed energy efficiency measures, demand management approaches and local supply options. While dynamic simulation provides an apt solution, it requires a level of operator expertise that may not be available in a policy making context.

To overcome this issue a simplified front end has been developed. This allows a non-expert user to select a specific model from a large pre-simulated set on the basis of simple inputs defining house location, architectural type and year of build; the model resolution may then be enhanced where additional information is available. An upgrade measure may then be selected resulting in the automatic selection of another pre-simulated model. Results from the two models may then be compared to identify the consequences of upgrade choices without the time delay associated with detailed simulation. By repeating the procedure, a user can rapidly determine how various upgrade scenarios impact energy performance and thereby make informed decisions. It is also possible to scale and combine individual models to define estates as a means to quantify the impact of upgrade measures at the community, regional or national level.

The resulting Housing Upgrade Evaluation (HUE) tool is the culmination of several projects addressing the assessment of domestic housing upgrades (Clarke et al 2008a & b, Marnie et al 2006, Clarke et al 2007 & 2005). The intended audience is policy makers, stock owners/managers and designers to enable action planning at the large scale.

2 Stock Modelling

Traditionally results from building simulation and modelling are made realistic by incorporating significant detail on constructional and technical systems. In applying the approach to a large housing stock a number of trade-offs need to be made. Typically, a high level of detail cannot be realised, while variation within the stock makes it difficult to adopt a representative value for many design parameters. The approach adopted within the present study is to pre-establish models for simulation that represent the variation within the stock both now and in the future. These models are based on a national housing stock surveys and information on occupants extracted from large scale survey data available within SAP.

The shift from modelling a single dwelling to a large housing stock means that the detail required in the former case is not required. Since detailed information will not be available for much of the stock (or will be too expensive to obtain) stock-average assumptions must be made (e.g. on infiltration). A reasonable estimate of the energy performance of a stock can be obtained by identifying critical design parameters that are thermodynamically relevant. Upgrade sequences can then be defined by changing the values of these parameters.

While division of a housing stock into architectural types is a relatively straightforward task, it is not a useful exercise in the present context. Two houses belonging to the same architectural type may have substantially different energy performance due to previous upgrade measures, orientation differences, micro-climate effects and so on. Likewise, houses belonging to different architectural types may have similar energy performance (after normalisation for floor area) because they have similar thermodynamic characteristics. The aim in HUE is to organise the design parameters that govern energy performance into distinct thermodynamic prototypes and provide a mechanism to map specific houses to these prototypes.

In HUE the governing design parameters for energy performance are divided into two categories relating to building and systems. The scope of this paper is restricted to the building side parameters although work is ongoing to extend the approach to include pre-constructed system components. These prototypes were then simulated under long term weather influences that typify the range of possibilities and the results are stored in a format that supports rapid access. An actual house may be related to a thermodynamic prototype via the level of its governing design parameters and system selections. When a given dwelling (prototype) is upgraded it is then reassigned to another prototype allowing the rapid estimation of the energy/emissions impact.

It is hypothesised that the energy performance of any dwelling, existing or proposed, can be expressed as a function of the following 7 design parameters.

Exposure

This is represented within the prototypes as exposed area expressed as a fraction of the total floor area. The range of the exposure parameter is from 0.5 to 3.

Insulation

This is the area weighted sum of the U-values of exposed surfaces normalised by the total floor area. Although dynamic simulation does not require recourse to steady-state parameters such as the U-value, it is a useful metric to define insulation levels. The range of the insulation parameter is from 0.19 to 6.05.

Air tightness

This is determined from the number of designed air flow openings (service openings, chimney stacks, passive trickle vents etc.) and the type of terrain following guidance provided within SAP. The range of the ait tightness parameter is from 0.1 to 1.5 air changes per hour.

Capacity position

This parameter governs the position of thermal capacity within the construction. For construction systems where capacity lies on the inside of the insulation layer, it results in a slow response system and *vice versa*. This parameter is of importance because some modern heating systems (e.g. underfloor heating) work efficiently only with fast response buildings and should not be recommended for older dwellings. This parameter has two values corresponding to capacity located at the inside and outside of the insulation layer.

Solar ingress

This parameter takes into account the different levels of heat gain (and loss) due to fenestration systems and is determined by normalising the total window and roof light area by floor area. Dwellings with the same ratio of window surface to floor area have the same solar ingress. While this conjecture will be compromised by solar shading and orientation, when integrated over a large estate, the impacts will tend to cancel out. The range of this parameter is from 0.15 to 0.3.

Occupancy

This parameter governs the level of internal gains, fresh air requirements, hot water use and small power loads. The approach adopts the SAP approach where gains are given as a function of total floor area. The range of this parameter is from 0.7 to 2.2 W/m^2.

Living area fraction

All dwelling models are divided into 2 zones corresponding to a living and sleeping area. These zones are controlled to different temperatures and have different occupancy and use profiles. Different dwellings are said to have the same living area fraction if the fraction of the living zone area to total floor area is the same. The HUE tool may be readily adapted to include additional zones if required. The range of this parameter is from 0.25 to 0.75.

Resolution of design parameters

Once the governing design parameters have been identified, the next step is to determine the levels of representation in each case. Capacity position has 2 available states. For the other parameters, limiting ranges are obtained from observation of the existing and extrapolation of building regulations into the future. Once the limiting range has been established for a particular parameter, it is divided into several discrete levels. The number of levels for each parameter is dependent on its relative impact on energy performance as well as consideration of the balance between loss of information and too many discretisation levels (Kotsiantis and Kanellopoulos 2006). The aim is to ensure that the discretisation levels provide good prototype representation of estates and this was measured in terms of annual heating energy demand.

The number of levels for air tightness and insulation corresponds to UK building regulation evolution: 5. levels for both were chosen. Exposure levels were selected by following principal architectural types: detached, semi-detached, end-terraced, mid-terraced, top floor flat, ground floor flat and mid-floor flat. Because semi-detached and end-terraced, and top and ground floor flats, are similar in terms of this parameter, this resulted in 5 levels. Initially, there were 5 levels of solar ingress, corresponding to a 10% difference between levels. Because the difference between the other design parameters was around 15%, this was subsequently reduced to 3 levels. Because of the lack of data on occupancy levels and living area fractions, and given the importance of these two parameters, 5 levels were chosen for both. Because all simulation results are normalised by floor area, they are scalable to dwellings of any size.

Evaluation of upgrade scenarios

This is a two stage process. First, existing dwellings are mapped to prototypes based on the notional level of their governing design parameters. Second, the proposed upgrade is defined and this is used by HUE to automatically select another prototype based on the levels of the upgraded design parameters. The performance implication of the upgrade is then apparent from the difference between the immediately available performance data for each prototype. The tool user is able to accept or discard particular upgrades plans on cost or performance grounds. Within HUE these prototypes are referred to as *base case*, *upgrade* 1, 2 etc.

In this manner, pre-constructed simulation results are used to define the performance of a housing stock as summations of various prototypes, with upgrade impacts immediately apparent without the time delay associated with the standard simulation approach. This is achieved by defining an estate consisting of scaled prototypes. This estate can be modified by replacing prototypes and/or modifying the scaling factors. This allows the user to mix and match upgrade options as part of a rational planning process.

3 HUE Formulation

Building upgrade appraisal

The ESP-r system (URL1) was used to quantify the energy performance of standard house designs – the HUE prototypes. Simulations were conducted over long term weather conditions that typify the UK. It was assumed that ESP-r predictions were of acceptable accuracy on the basis of outcomes from extensive previous validation studies (Strachan et al 2007). In practice validation would need to be an integral and ongoing activity.

The construction prototypes were established as permutations of discrete levels of principal design parameters that may be adjusted as part of an upgrade: exposure (5), level of insulation (5), air tightness (5), capacity position (2), solar ingress (3), occupant density (5) and living area fraction (5). If each of these parameters can exist at the number of levels indicated in parentheses then the total number of prototypes is 18,750 (= 5 x 5 x 5 x 2 x 3 x 5 x 5). This means that any possible dwelling, existing or planned, will correspond to a unique combination of these parametric permutations and is therefore represented by a unique prototype. Dwellings can only have the stated levels of each design parameter, i.e. there are only 5 levels of exposure a dwelling can have and so on.

In order to generate the 18,750 prototypes, a seed model was created. Assumptions underlying this model correspond to an average dwelling as determined from relevant publications (Bartholomew and Robinson 1998, BRE 2009, CIBSE 1999, Scottish Homes 2009, Shorrock and Utley 2003). The principal design parameters of this model are then assigned values when the prototypes are generated.

This seed model was modified by applying appropriate parametric adjustments in order to generate the 18,750 prototypes. For this purpose, a computational environment was developed that replaces parameters in the seed model files as required. These replacements are made according to rules that ensure that external surface area ratios, insulation levels, air tightness levels and window sizes are typical of the housing stock as taken from house condition survey data (Scottish Homes 2009). Occupancy levels were taken from a statistical model of average occupancy in the UK (SAP 2009).

The entire prototype set was simulated using hourly weather collections spanning 30 years for 75 locations. Results from these simulations were subjected to a multiple linear regression analysis (Weisberg 1985) to obtain regression equations that express prototype energy demand as a function of weather parameters.

The final results dataset, comprising the regression equation coefficients for each prototype, is used by HUE to determine the energy demand of a given prototype when placed in a given weather context. This is a simple process requiring only the multiplication of the regression equation coefficients by weather parameters to obtain the energy demand.

The correlation coefficient value (R^2) for the regression equations generally exceeded 95%. This is to be expected since they correspond to time series simulation data. The regression equations thus capture the richness of the simulations they are built upon and provide a reasonable proxy.

HUE data flow and operation

Figure 1 summarises data flow within the HUE tool. Solid line boxes show major files, processes or milestones; dotted line boxes show UNIX shell scripts and programs applied to the data; and chain line boxes show supporting files and databases. The first group is highlighted in yellow with subordinate detail highlighted in blue. In the following explanation references to elements in this figure are given in parentheses.

The environment for prototype generation consists mainly of Unix Bash Shell scripts that copy model files and perform string and character substitution using the *Sed* stream editor (model generation scripts). It has been ensured that the same data model input files are reused as input to more than one model. This is made possible by the modular nature of the ESP-r data model structure.

Bash scripts are also used to pre-process the model, including invocation of ESP-r’s shading and insolation module (shading analysis) and the linking of weather files at simulation run time (linking models to weather files). The *Awk* tool is used to generate summary weather information from ASCII versions of ESP-r’s weather files (generation of summary weather files). This summary includes the averaged weather parameters that, in conjunction with regression coefficients, are used to generate prototype energy demand. Additional scripts are generated (generation of super computer scripts) that allow the models to be run on a high performance computer (HPC). The serial queue was used on the HPC and simulations for each weather year were directed to separate processors using ESP-r’s batch processing facility. Results from the simulation were collated using *Perl* (post processing scripts). These results were then processed by a bespoke multiple linear regression analysis tool to create the final results database comprising the regression coefficients sets for each house prototype. HUE accesses this results database as well as the summary weather file.

From information about a housing stock (house condition survey data), the architectural form and age banding of dwellings may be established and a link made to relevant prototypes. This action allows the underlying prototype to be inferred and relevant regression coefficients selected for combination with corresponding weather parameter values to generate energy demand. Results are then normalised by prototype floor area to allow scaling to the real case.

The user has the option to fine tune the model at this point by changing default inferences through a SAP-like interface. This allows changes to insulation levels, glazing areas, hot water usage, heat generation equipment, renewables specifications and other standard SAP inputs.

Using intermediate statistical equations is favoured because the simulation engine is then segregated from users who are not required to define a detailed model and can concentrate on upgrade options evaluation in real time. For the purpose of stock modelling the level of detail required is reduced because the differences between similar buildings within a housing stock will be at least of the same order as the performance impact of increasing the resolution of the input model. That said, a fall-back position is also supported: the user may assess a given building at an enhanced level of detail by accessing the underlying ESP-r, model, implementing any required modifications and then following a standard simulation approach.

Supply technology appraisal

Once energy demand for the dwelling is determined, space conditioning and hot water systems are selected. These are determined from information on system type, age band and fuel type in accordance with CIBSE and SAP defaults (BRE 2009, CIBSE 1999), the BRE Domestic Energy Fact File (Shorrock and Utley 2003) and the Carbon Trust's Building Market Transformation project database (MTP 2006). Energy requirements for hot water are determined from standard domestic system capabilities and water usage rates (BRE 2009).

Once the energy demand has been determined, it is met by means of traditional and/or renewable energy systems. For many systems, a simple seasonal efficiency figure is used to map energy demand to supply. In other cases a pseudo-dynamic systems model is used, e.g. for solar water heating (Samuel et al 2011). For mechanical ventilation with heat recovery a prototype selection is automatically made with lower levels of air tightness. As a fully dynamic analysis is possible within ESP-r, future work will implement an approach on the systems side similar to that taken for the building, i.e. the *a priori* production of regression equations for prototype models based on dynamic simulation. This will give users access to whole-system, dynamic simulation results on the basis of prototype model manipulations.

To map energy performance to cost and carbon emissions, relevant factors are taken from SAP that is applicable to the UK. Such conversions may be redefined for non-UK contexts or for alternative assumptions relating to user behaviour or national fuel mix. Unit costs and standing charges are embedded within the tool; again these are based on SAP.

Renewable options are selectable at this point; those supported for electricity generation include PV, micro wind turbines, micro CHP and micro hydro, while those supported for heating include solar thermal, flue gas heat recovery, mechanical ventilation with heat recovery and waste water heat recovery. Power production predictions for these technologies are, at present, based on steady-state formulations.

Tool Applicability and Availability

A typical application of HUE proceeds by selection of a weather context, a house type and age band. From these rudimentary inputs, the governing design parameters are inferred and a representative prototype chosen. As appropriate, the prototype energy demand is modified by a relevant efficiency to give the energy consumed. Upgrades are then proposed, new prototypes automatically selected and the appraisal process repeated. Finally, the performance results for the base case and upgrade scenarios are collated and presented along with the available power from local micro generators.

The entire model generation, simulation and results post-processing environment is freely available within the Open Source ESP-r distribution.

4 Tool Verification

Tool verification was undertaken as a two-step inter-model comparison: by comparing outputs from HUE and ESP-r and then by comparing outputs from HUE and SAP.

Detailed models of two houses were subjected to ESP-r simulation, with and without upgrades, and the results compared to corresponding HUE predictions. A detached house and a middle floor flat were modelled using ESP-r; details of the models were taken from a previous study (Clarke et al 2005 supplemented by information taken from building regulations). Governing design parameters of the simulation models were used to manually choose corresponding prototypes: that the annual heating energy predictions from ESP-r and HUE were within 5%. Upgrades addressing thermal insulation and air tightness were then introduced to the ESP-r models and corresponding prototype selections made within HUE. Results from ESP-r were within 7% of those from HUE. Automated comparisons were also made between results from direct ESP-r simulation of the prototypes and the results generated by the corresponding regression equations. The majority of the results (~95%) were within 10%, with no case differing by more than 15%. Figure 2 shows comparisons of the annual heating demand from 10 randomly selected prototypes. From the above tests it was concluded that the agreement between explicit ESP-r simulation and the regression equation approach of HUE was satisfactory.

Equivalent models were created within HUE and SAP for all predominant Scottish house types as listed in Table 1. Information was taken from the latest Scottish House Condition Survey (Scottish Homes 2009) and supplemented by data from Clarke et al (2005). It was observed that, on average, the differences were within 10% for heating energy use and 7% for total energy use. Differences were greater for low energy houses. This is because the steady-state algorithms used within SAP (based on historic building data) under-predict the energy consumption of low energy houses because of their disregard for thermal capacity effects. Figure 3 shows the heating energy demand for semi-detached houses as detailed in the Scottish House Condition Survey.

5 Application to the Scottish Housing Stock

Background and context

There are around 2,344,000 dwellings in Scotland of which 4% are vacant and 2.5% are due for demolition. The majority of dwellings are either houses (63%) or flats (37%). Over 40% of all dwellings were built within the last 37 years, with 24% constructed between 1945 and 1965. The 2009 Scottish House Condition Survey (Scottish Homes 2009) identified 7 predominant house types: Detached, Semi-detached, Terraced, Tenement Flat, Four-in-a-Block, Conversion and Tower/Slab Block.

The condition of the Scottish housing stock is generally poor, with 13% of houses affected by dampness or condensation (URL4). In addition, 62% of Scotland's social housing currently falls beneath the new Scottish Housing Quality Standard (URL4). Penetration of upgrades and improvements is generally low. For example in 2002 around 87% of dwellings had whole house[1] central heating, with a further 8% having partial central heating. This represents a 6% improvement since 1996, with the number of dwellings with no central heating down from 13% to 5.5% (Clarke et al 2005). Dwellings without whole house heating will

[1] Whole house in this context means the total occupied space and excludes areas that are normally unoccupied, e.g. box rooms, lofts, storage space etc.

have areas with a high risk of condensation, mould growth and hypothermia. This raises concerns about fuel poverty[2] and the health-related problems associated with poor energy performance.

The assessment of energy use for the purposes of the Scottish House Condition Survey is based on two calculation methods; National Home Energy Rating (NHER) (URL2) and SAP. NHER covers all energy use in the home, including cooking and electrical appliances, and allows for regional and geographic climate variations. SAP covers the energy used by space heating (with auxiliary equipment), hot water and lights for standardised dwelling use. It uses a single UK weather source from East Yorkshire. Both rely on steady-state calculation methods.

Upgrading strategy

Due to practical constraints, any upgrading strategy should focus on low cost technologies in the first instance. These should require less capital for installation and have higher potential estate penetration. This ensures that the return on investment is maximised. Upgrades should be phased over time in a manner that accommodates technical advance. Furthermore, the useful lifetime of structural upgrades (insulation and infiltration improvements) is longer than system upgrades. This means that if the energy and emissions benefits of improvements are similar, structural improvements should be preferred over system improvements. The two most effective measures to improve thermal performance of a dwelling are reducing fabric and ventilation heat loss. Both were assessed in this study.

Table 1 shows stock decomposition into architectural types and age banding. Only predominant architectural types are listed since these comprise around 90% of the stock. For each type the frequency column gives the number of units of that type as a percentage of all dwellings in Scotland. The base column gives energy use in kWh/m^2. Columns Imp1 to 3 list the energy use for improvements 1, 2 and 3. The first two are improvements to insulation level while the last is an improvement to air tightness. These improvements result from increasing insulation by one and two levels (imp1 and imp2) and by improving the air tightness by one level (imp3).

The governing insulation parameter is the total UA value of the dwelling and may be achieved in practice by modifications applied to the wall or roof components separately or together. Improvement to air tightness can be as achieved through window upgrades and/or draught proofing. Table 2 lists the energy use in TWh per annum for each of the dwelling types and their proposed upgrades (identified by trial and error).

The dwellings to be targeted first would be the ones that are most energy intensive. This is indicated by the ‘base / (frequency * floor area)’ column in Table 2, which indicates the impact in terms of its energy consumption when normalised by its floor area and prevalence in the stock. Inefficient dwellings are highlighted in Table 2 if they have an impact index greater than 0.55.

After implementing the first phase of improvement measures (imp1), it was determined that the annual space heating energy demand was reduced by 13 TWh (or 31% of the national heating energy demand (URL3)). In the second phase of upgrades (imp2), the annual heating energy savings increased to 22 TWh (46% of national heating demand). Finally in the third phase (imp3), the energy saving increased to 29 TWh (60% of national heating demand).

[2] Fuel poverty is defined to be present if fuel bills are greater than 10% of a household’s disposable income.

6 Conclusions

Detailed dynamic thermal simulation has been applied to a set of prototype models representative of the Scottish housing stock. The outcomes have been encapsulated in a tool that supports policy makers concerned with the development of upgrade strategies for the domestic sector or those concerned with enacting energy rating schemes.

The tool can be applied to any housing stock on the basis of statistical information. The tool supports implementation of low and zero carbon technologies and provides information on the potential energy savings associated with such technologies. The underlying prototype models can be readily adapted as additional information about the building stock becomes available. The tool can be used to inform users about which upgrades provide best value for money and the order in which upgrades should be implemented. Further work will involve the development of a regression based database for HVAC and renewable energy systems in order to allow for dynamic demand-supply matching.

The tool was applied to the Scottish housing stock in order to devise an effective upgrade scenario. It was seen that heating energy demand can be reduced by up to 60% by the phased deployment of fabric upgrades. At current upgrade rates (approximately 1%) it will take 70 years to reach half the stock. Clearly, the issue of capital investment is paramount.

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Table 1 Scottish houses by energy use kWh/m^2.

Built form	Age band	Frequency %	Base	Imp 1	Imp 2	Imp 3
Detached	pre-1919	3.9	267	186	127	94
	1919-44	1.9	268	187	128	94
	1945-1964	1.8	222	155	107	79
	1965-1982	5.4	223	127	83	60
	post 1982	5.5	190	108	71	51
Semi-detached	pre-1919	1.9	252	217	140	99
	1919-44	3.8	253	218	141	99
	1945-1964	4.9	212	183	119	85
	1965-1982	4.2	219	153	90	72
	post 1982	3.9	131	77	72	52
Terraced	pre-1919	1.9	265	179	129	104
	1919-44	1.9	266	180	130	105
	1945-1964	6.2	222	151	110	89
	1965-1982	5.1	200	128	94	69
	post 1982	4.7	170	109	80	59
Tenement	pre-1919	8.3	263	171	133	103
	1919-44	1.9	265	172	134	104
	1945-1964	4	221	145	113	88
	1965-1982	3.6	183	120	93	73
	post 1982	3.3	157	103	80	63
4-in-block	pre-1919	1	370	227	158	121
	1919-44	3.7	372	228	159	121
	1945-1964	2.2	305	188	132	101
tower/slab	1945-1964	1.3	223	162	132	100
conversion	pre-1919	1.9	338	197	153	129

Table 2 Scottish houses by total heating energy use TWh per annum.

Built form & floor area	Age band	Frequency % (f)	Base	Base / (f*floor area) or impact index	Imp 1	Imp 2	Imp 3
Detached $141m^2$	pre-1919	3.9	3.44	0.63	2.40	1.64	1.21
	1919-44	1.9	1.68	0.63	1.17	0.80	0.59
	1945-1964	1.8	1.32	0.52	0.92	0.64	0.47
	1965-1982	5.4	3.98	0.52	2.27	1.48	1.07
	post 1982	5.5	3.45	0.45	1.96	1.29	0.93
Semi-detached $87m^2$	pre-1919	1.9	0.98	0.59	0.84	0.54	0.38
	1919-44	1.9	1.96	0.59	1.68	1.11	0.76
	1945-1964	4.9	2.12	0.50	1.83	1.19	0.85
	1965-1982	4.2	1.88	0.51	1.31	0.77	0.62
	post 1982	3.9	1.04	0.31	0.61	0.57	0.41
Terraced $90m^2$	pre-1919	1.9	1.06	0.62	0.72	0.52	0.42
	1919-44	1.9	1.07	0.62	0.72	0.52	0.42
	1945-1964	6.2	2.90	0.52	1.97	1.44	1.16
	1965-1982	5.1	2.15	0.47	1.38	1.01	0.74
	post 1982	4.7	1.69	0.40	1.08	0.79	0.58
Tenement $60m^2$	pre-1919	8.3	3.07	0.62	2.00	1.55	1.20
	1919-44	1.9	0.71	0.62	0.46	0.36	0.28
	1945-1964	4	1.24	0.52	0.82	0.64	0.50
	1965-1982	3.6	0.93	0.43	0.61	0.47	0.37
	post 1982	3.3	0.73	0.37	0.48	0.37	0.29
4-in-block $68m^2$	pre-1919	1	0.59	0.87	0.36	0.25	0.19
	1919-44	3.7	2.19	0.87	1.34	0.94	0.71
	1945-1964	2.2	1.07	0.71	0.66	0.46	0.35
tower/slab $68m^2$	1945-1964	1.3	0.46	0.52	0.34	0.27	0.21
conversion $68m^2$	pre-1919	1.9	1.02	0.79	0.60	0.46	0.39
Total			**42.74**		**28.53**	**20.08**	**15.13**

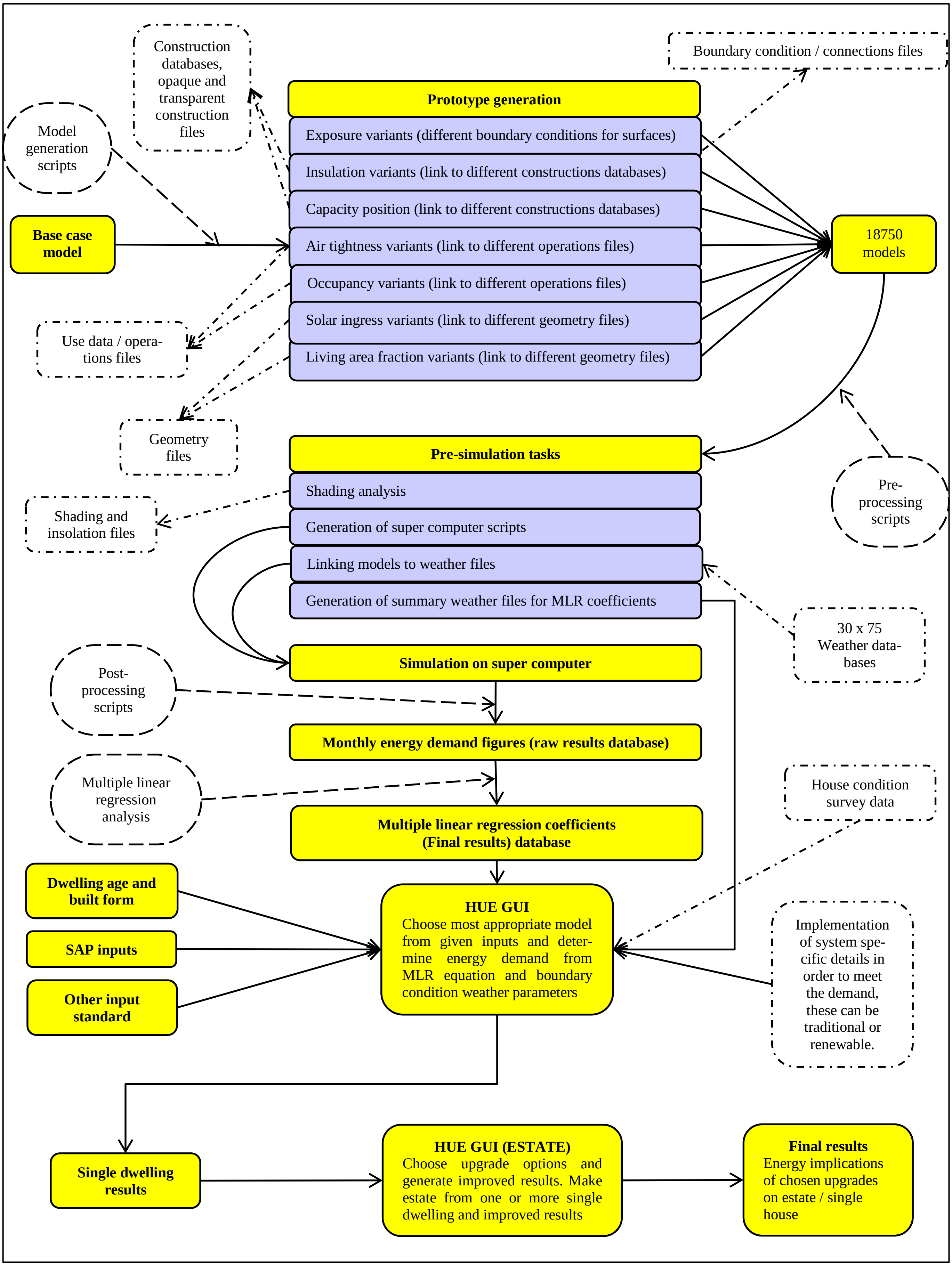

Figure 1 Process flow for HUE

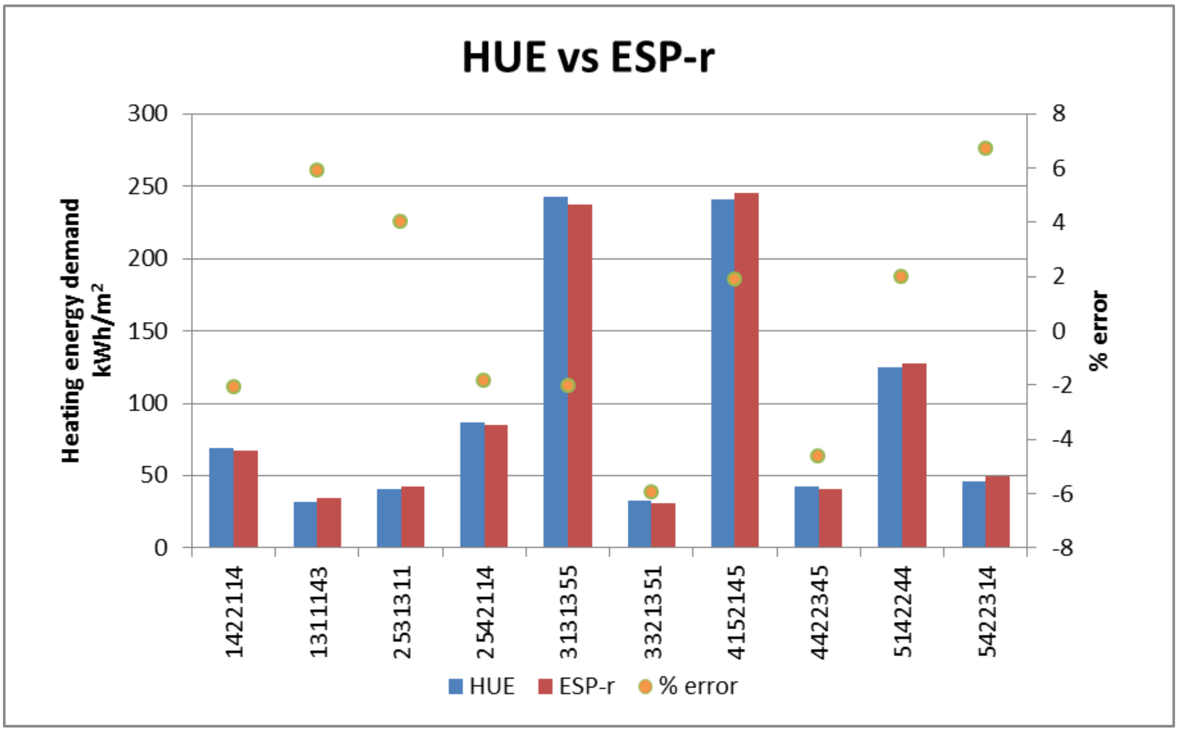

Figure 2 HUE compared with ESP-r (heating energy demand)

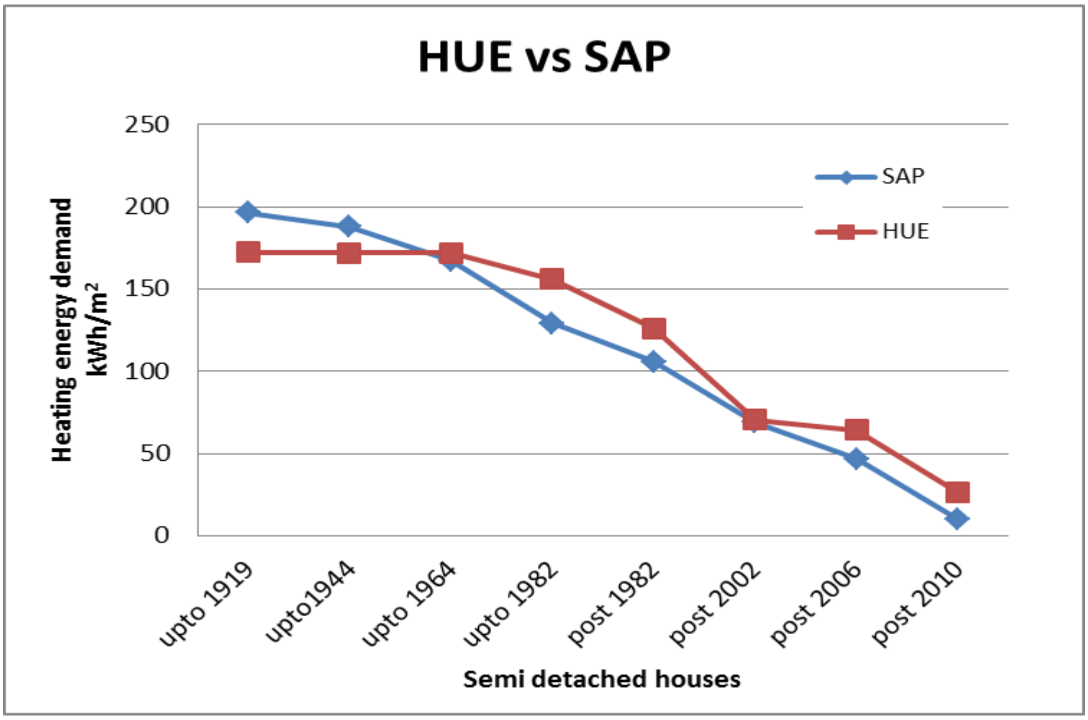

Figure 3 HUE compared with SAP