A Reduced Data Dynamic Energy Model of the UK Houses

By

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To My Parents

“The answers we have found only serve to raise a whole set of new questions. In some ways we feel we are as confused as ever, but we believe we are confused on a higher level and about more important things…”

Earl C. Kelley

Abstract

This thesis describes the development of a Reduced Data Dynamic Energy Model (RdDEM) for simulating the energy performance of UK houses. The vast quantity of Energy Performance Certificate (EPC) data stored at the national scale provides an unprecedented data source for energy modelling.

The majority of domestic energy models developed for the UK houses in recent years, including the Standard Assessment Procedure (SAP) model used for generating EPCs, employ BREDEM (Building Research Establishment Domestic Energy Model) based steady-state calculation engines. These models fail to represent the transient behaviours that occur between building envelope and systems with external weather conditions and occupants. Consequently, there is an ongoing debate over the suitability of such models for policy making decisions; which has raised the interest in dynamic energy models to overcome these shortcomings.

The RdDEM eliminates the main drawback associated with dynamic energy modelling, namely the large amount of required input data compared to steady-state models, by enhancing a reduced set of data which was originally collected for EPCs. A number of new inferences and methodological enhancements were tested and implemented in the RdDEM using a sample of semi-detached houses. In this way, SAP equivalent input data could be converted automatically for use in dynamic energy modelling software, EnergyPlus.

Simulations of indoor air temperatures and space heating energy demand from the RdDEM were compared to those from SAP for 83 semi-detached houses. The comparison was also carried out with more detailed models, on a sub-set of the modelled dwellings. Finally, the predicted energy savings that resulted from energy efficiency improvements of the dwellings were compared and estimated potential for saving energy from the RdDEM was quantified.

The results show that it is technically feasible to develop dynamic energy models of these houses using equivalent inputs. In the majority of cases, the RdDEM predicted lower indoor air temperatures than SAP, and consequently the energy demands were lower. The RdDEM predicted annual space heating demand to be lower than SAP in 72% of the houses, however the difference was less than 10% in 94% of the houses. The RdDEM predicted slightly higher (< 2%) energy saving potentials compared to SAP when the same set of energy saving measures were implemented in both models.

The development of these new methods for automatically creating SAP equivalent inputs from reduced data but for use in a dynamic energy model offers new opportunities for inter-model comparisons as well as a dynamic alternative to the SAP when variations in energy demand and indoor air temperatures are required.

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Abbreviations

ACH	Air Changes per Hour
ADEPT	Annual Delivered Energy and Temperature
ASHRAE	American Society of Heating Refrigeration and Air-Conditioning
A&P	Allen and Pinney
BERG	Building Energy Research Group
BGT	Building Generation Tool
BRE	Building Research Establishment
BREDEM	Building Research Establishment Domestic Energy Model
BREHOMES	Building Research Establishment's Hosing Model for Energy Studies
CDA	Conditional Demand Analysis
CDEM	Community Domestic Energy Model
CF	Conversion Factor
CHM	Cambridge Housing Model
CHREM	Canadian Hybrid Residential End-use Energy and Emissions Model
CIBSE	Chartered Institution of Building Services Engineers
CREEM	Canadian Residential Energy End-use Model
CSDDRD	Canadian Single-Detached and Double/Row Housing Database
CSV	Comma Separated Value
DHW	Domestic Hot Water
DDM	Domestic Dwelling Model

DECC	Department of Energy and Climate Change
DEFACTO	Digital Energy Feedback and Control Technology Optimisation
DEN&T	Departments of the Environment and Transport
DOE	Department of Energy
DTI	Department of Trade and Industry
DETR	Department of the Environment Transport and the Regions
EDEM	ESRU Domestic Energy Model
EEP	Energy and Environment Prediction Model
EHCS	English House Condition Survey
EHS	English Housing Survey
EI	Environmental Impact
EPBD	Directive on Energy Performance of Buildings
EPC	Energy Performance Certificate
EPW	EnergyPlus Weather
ESRU	Energy Systems Research Unit
EU	European Union
EWY	Example Weather Year
gbXML	Green Building XML
GDP	Gross Domestic Product
HLP	Heat Loss Parameter
HPXML	Home Performance XML
HVAC	Heating, Ventilation and Air-Conditioning
IDF	Input Data File (EnergyPlus)

IEA	International Energy Agency
IPCC	Inter-Governmental Panel on Climate Change
IWEC	International Weather for Energy Calculations
LARA	Local Area Resource Analysis
NCM	National Calculation Methodology
NN	Neural Network
ONS	Office for National Statistics
RdSAP	Reduced Standard Assessment Procedure
RdDEM	Reduced Data Dynamic Energy Model
SAP	Standard Assessment Procedure
STEP	Seasonal Temperature Energy Price
TFA	Total Floor Area
TIDF	Template IDF
TMP	Thermal Mass Parameter
TRV	Thermostatic Radiator Valve
UKDCM	UK Carbon Domestic Model
XML	Extensible Mark-up Language

1. INTRODUCTION

1.1. Background

The scientific community has widespread agreement that changes to the global climate are taking place, primarily due to an increase in anthropogenic greenhouse gases, and human societies will be required to adapt to these changes (Hulme & Jenkins, 1998; Royal Commission on Environmental Pollution, 2000; IPCC, 2001; and McCarthy et al., 2001). The main greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Each of these gases adds to global warming to a varying extent. Carbon dioxide is the most important greenhouse gas, due to its vast concentration in the atmosphere and its long atmospheric lifetime (IPCC, 2001).

The scientific evidence in support of anthropogenic climate change is now overwhelming (IPCC, 2007). In the latest IPCC report (IPCC, 2017), the importance of preventing scenarios to be implemented by all governments is highlighted. The global community is warned that, failure to implement effective policies would result in significant changes. These changes including: a 2 to 3.5°C increase in average annual temperature by the 2080s; an increase in the frequency of high summer temperatures; an increase in winter rainfall; a rise in the relative sea level around most of the UK's shoreline; and an increase in the temperature of UK coastal waters (Hulme et al., 2002). All of these effects will have potentially significant socio-economic and political impact in the UK. If such disruption to the global climate system is to be minimised, significant reductions in CO_2 emissions will be required during this century (Johnston, 2003).

As a part of 2008 Climate Change Act, the UK government made a commitment to reduce the greenhouse gas emissions by at least 80% compared to 1990 levels by 2050 (Office of Public Sector Information, 2008). The Climate Change Act which was initially targeted to reduce emissions by

26% by 2020 was later tightened to 34% (Office of Public Sector Information, 2009). Figure 1.1 shows the contribution of each sector to the total UK carbon dioxide emissions.

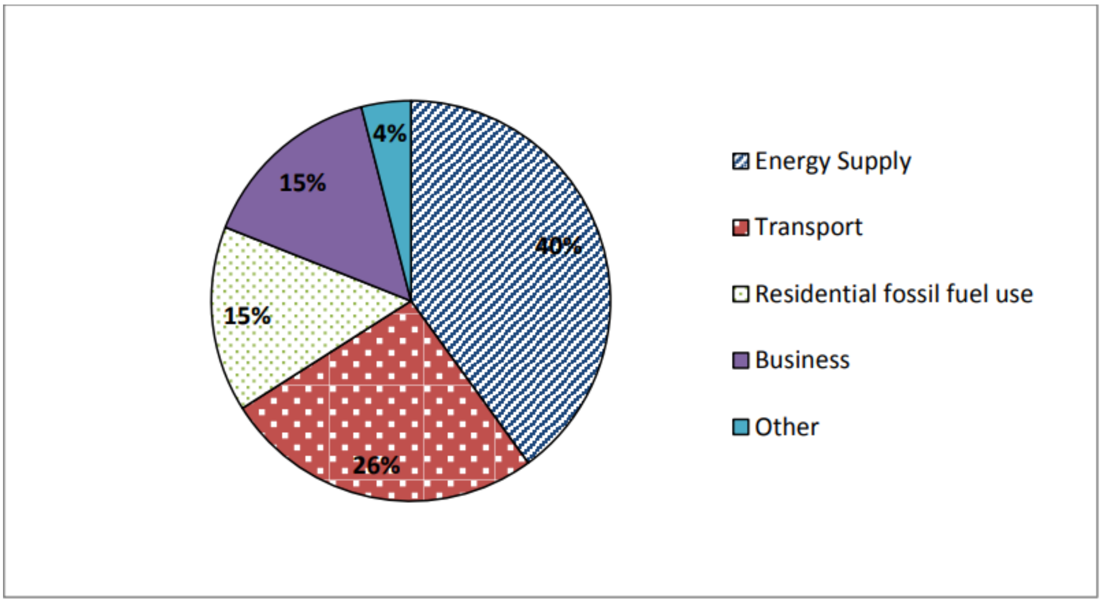


Figure 1.1 Contribution of different sectors to the UK's total carbon dioxide emissions of 2011 (DECC, 2012)

Achieving the Climate Change Act targets will require substantial reductions in energy consumption in different sectors; though reductions in the domestic sector are considered to be "relatively low cost" and "realistically achievable" (Committee on Climate Change, 2008). Since 1990, emissions from fossil fuel use in the residential sector have fluctuated but in 2010 they were 8% above the 1990 level (DECC, 2011c). In 2010, the UK residential sector emissions of carbon dioxide increased by 13.4% compared to the previous year (the highest rise for any single sector) due to a considerable rise in residential gas use for space heating as 2010 was on average the coldest year since 1986 (DECC, 2011c). In 2013, the emissions from this sector were estimated to be 3% below the 1990 level (DECC, 2014).

The energy consumption of UK residential buildings accounts for 31% of national energy consumption (Figure 1.2), which is the largest proportion in Europe (Saidur et al., 2007). The UK's housing stock is one of the oldest and least efficient in Europe (Boardman et al., 2005) and the majority of energy consumption in UK dwellings is due to space heating which in 2009 accounted for 61% of the total energy consumption in the domestic sector (DECC, 2011a).

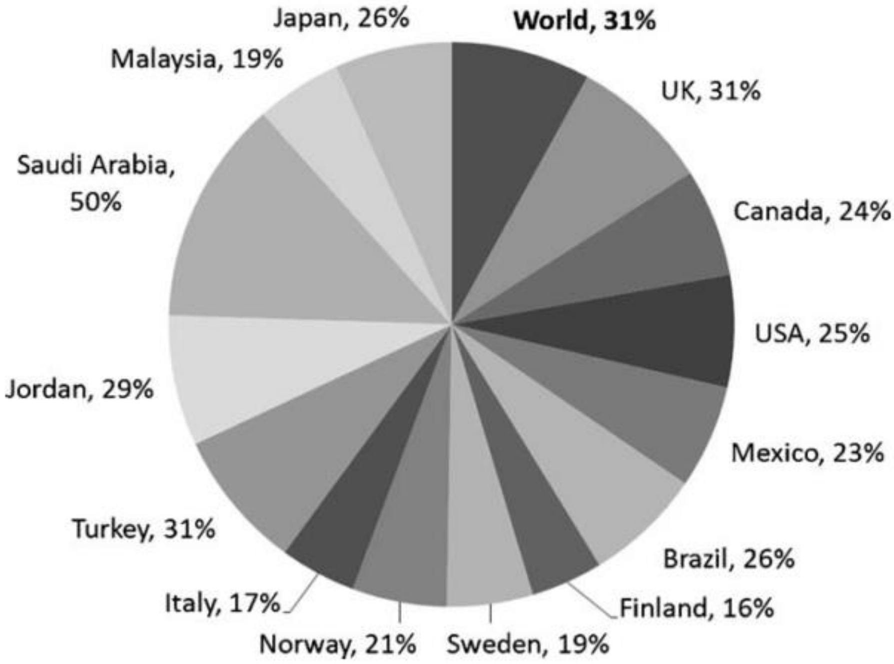


Figure 1.2 Residential energy consumption shown as a percentage of national energy consumption and in relative international form (Saidur et al., 2007)

The recognition of the domestic sector's significance in reducing greenhouse gas emissions has led to an ongoing development of technologies to reduce energy demand from the housing stock. In order to develop the policy required to meet the criteria set by the Climate Change Act, it is important to try to predict the potential impact that these technologies can have on energy consumption and the resultant CO_2 emissions. The reliable prediction of the impact of the energy saving technologies requires a detailed model of energy and emissions from the housing stock.

The increasing power of personal computers, their reasonable price and increasing need for computer-based analysis have resulted in a considerable increase in the number of building energy-analysis tools in recent years (Neymark et al. 2001). An on-line directory (BETD, 2014) supported by US Department of Energy (DOE) lists more than 200 building energy software tools developed worldwide that have thousands of users. The main reason for the increasing number of building energy software tools is regulations imposed by governments which require various government bodies and organisations to use computer-based analysis (Raslan & Davies 2012). A good example is the Directive on Energy Performance of Buildings (EPBD) which was introduced by the European Union (EU) to speed up the process of adopting performance based energy standards in buildings. The EPBD urges member states to adopt a National Calculation Methodology (NCM) in order to demonstrate that buildings comply with energy performance standards and to provide computer based tools to enable this (Raslan & Davies 2012).

1.2. Justification of the Research

The National Calculation Methodology (NCM) for dwellings in the UK is SAP 2012 (SAP, 2012), which is based on Building Research Establishment Domestic Energy Model (BREDEM) and uses monthly steady-state calculations to estimate energy consumption and carbon emissions. Many studies have investigated modelling tools and their capabilities (Crawley et al., 2008; Gale, 1990; Kenny and Lewis, 1995) and still there is debate over the suitability of steady-state models in policy making decisions (Schwartz and Raslan, 2013). The steady-state models are not capable of taking into consideration the complex, interdependencies, and dynamic nature of the energy consumption and carbon emission (Oladokun and Odesola, 2015). A recent study (Kane et al. 2015) criticised the use of simple steady-state models by stating that these kind of models were used traditionally to enable the equations to be solved manually. However, we no longer need to understand mathematics of model and it is time to adopt a more realistic approach to modelling housing stock.

Dynamic modelling of the UK dwellings, using well-established simulation software such as EnergyPlus (EnergyPlus, 2015) has the potential to overcome these shortcomings and provide insight into the transient energy-use and thermal behaviours, such as peak heating loads and indoor air temperature extremes. The main issue associated with use of dynamic modelling of dwellings is the increased amount of input data required, compared to simple steady-state models. There are currently no datasets of the UK housing stock that contain sufficient data for dynamic simulation, and considerable additional expense would be required to collect all of the additional detailed data required to achieve this.

There has been little research to investigate the possibility of developing robust dynamic energy models of UK dwellings using only the available reduced datasets. Therefore, this research was conducted to answer the following questions:

i. Is it technically feasible to develop robust dynamic energy models of UK dwellings using available (reduced) datasets?

ii. How close will the estimates of such dynamic energy models be to the results of equivalent steady-state models and to more detailed dynamic energy models?

1.3. Aim and Objectives

The overall aim of this research was to develop a Reduced-data Dynamic Energy Model (RdDEM) that is capable of simulating the transient energy and thermal behaviours of UK dwellings.

The following objectives were undertaken to meet this aim:

1) Identify and review literature on the modelling approaches that could be used to forecast energy use and CO_2 emissions in the UK dwellings, and perform a critical analysis of the work that has been undertaken to utilise available reduced data for energy modelling purposes.

2) Identify a suitable dataset of UK dwellings to be used as the source of modelling data.

3) Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation.

4) Develop and run a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models.

5) Compare the results of the reduced data dynamic energy model with those from equivalent steady-state models.

1.4. Contribution to Knowledge

This is, to the author's knowledge, the first dynamic energy modelling exercise to be undertaken using the EPC data for a set of UK dwellings. Automating the data enhancement and translation processes eliminates the additional time and cost associated with collecting further data and modelling each of the homes individually. The reduced data dynamic energy model introduces a set of new methods for enhancing reduced data in order to create equivalent detailed geometry and zoning information. These methods enable a unique inter-model comparison to be carried out across 83 buildings, demonstrating that similar results can be obtained from different models when the inputs are equivalent. Ultimately, the techniques developed here can be used to provide new insights into the transient aspects of energy use and indoor air temperatures in the UK housing stock and therefore, the model has value as both a policy and a research tool.

1.5. Outline of the Thesis

- **Chapter 2** presents the literature review which was conducted for this study. This covers the existing steady-state and dynamic energy models developed for the dwellings with focus on strength and weakness of each model, technical specifications, and the input data sources.

- **Chapter 3** provides an overview of the methodology to develop the reduced data dynamic energy model and describes the source of the input data.

- **Chapter 4** describes the zoning and geometry enhancements made to the reduced input data in order to develop detailed geometry and zoning information.

- **Chapter 5** describes the process of developing the equivalent construction materials and, inside and outside boundary conditions that were suitable for dynamic energy simulation.

- **Chapter 6** describes the translation process and how the modelling process was verified. The chapter also presents the results and compares them to equivalent steady-state models.

- **Chapter 7** discusses the achievements against the aim and objectives alongside the contributions to knowledge. The limitations of the work are quantified, and the application of the modelling framework developed in this thesis is expanded for academia, policy makers and industry.

- **Chapter 8** summarises the main conclusions from the studies and investigations undertaken as part of this thesis.

2. LITERATURE REVIEW

2.1. Introduction

This chapter presents the context for development of the Reduced Data Dynamic Energy Model (RdDEM) of the UK dwellings, in pursuit of Objective 1 (*Identify and review literature on the modelling approaches that could be used to forecast energy use and* CO_2 *emissions in the UK dwellings, and perform a critical analysis of the work that has been undertaken to utilize available reduced data for energy modelling purposes*). The chapter starts with a description of the Energy Performance Certificates (EPC) which provide a rich source of reduced-data for the UK housing stock. The chapter continues with a critical analysis of existing modelling techniques for dwellings and also other models that have used reduced-data datasets. The detailed description and critical analysis of eight prominent steady-state models developed for the UK dwellings as well as four dynamic energy models of the dwellings are also provided in this chapter. The chapter concludes with a description of data translators that have been created for the purpose of energy modelling of the housing stock.

2.2. Energy Performance Certificate (EPC)

2.2.1. Context

Following the oil crisis of 1972-1979, the first World Climate Conference took place in 1979, which was consequently resulted in the setting up of the Inter-Governmental Panel on Climate Change (IPCC) in 1988. The IPCC's first report assisted the formation of the United Nations' Framework Convention in 1992 in Rio. The IPCC's second report, which was published in 1995, highlighted the 'human influence' on global warming. It was this report that eventually resulted in the creation of the Kyoto Protocol of 1997 (which came into force in 2005). The initial form of Kyoto Protocol insisted on overall 5% reduction in greenhouse gas emissions (Watson, 2009).

The EU produced a European directive: ‘2002/91/EC Energy Performance of Buildings’ to assist in achieving the Kyoto protocol goals (European Union, 2002). This was followed in the United Kingdom by development of the White paper: ‘Our Energy Future – Creating a Low Carbon Economy’ in 2003, which insisted on reducing CO_2 emissions by 60% by 2050, compared to 1990 levels. The EU directive led to a series of legislation across Europe, as the main requirement, which was to produce Energy Performance Certificates (EPCs) for dwellings and residential buildings.

In the UK, the Housing Act (2004) for the first time made it compulsory to present EPC and improvement recommendations when an existing home was let or sold. In 2006 it was also made compulsory for new built dwellings to have EPC. The EPCs include both energy rating and Environmental Impact (EI) rating (Figure 2.1). A full example of an EPC is presented in APPENDIX A.

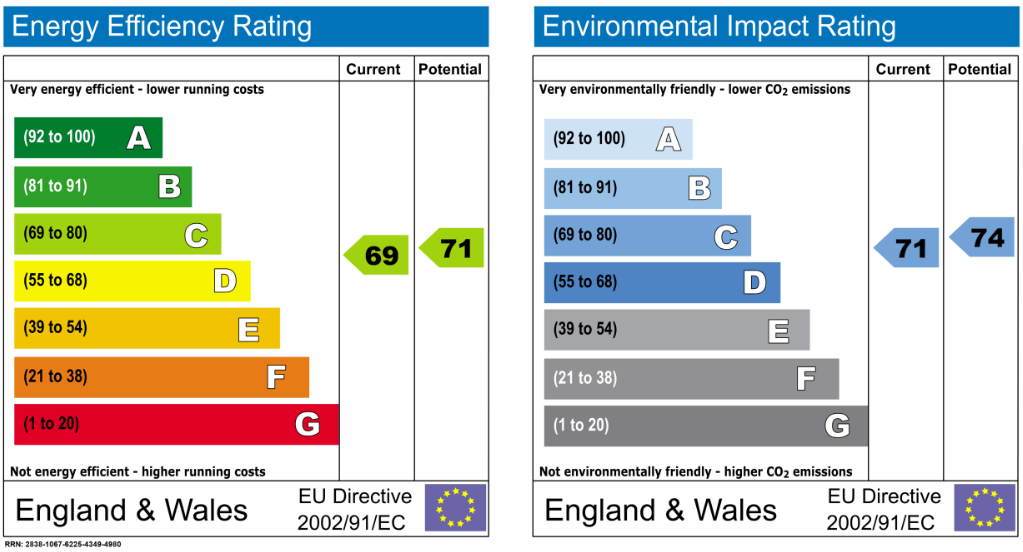


Figure 2.1 Example of EPC energy and EI ratings (RdSAP Manual, 2012)

The energy and EI ratings are based on the energy costs and the annual CO_2 emissions associated with space heating, water heating, ventilation and lighting, less cost savings from energy generation technologies. Both ratings are expressed on a scale of 1 to 100. The higher the energy rating the lower the running costs. In case of the EI rating, the higher the number the better the standard. The ratings are adjusted for floor area so that it is essentially independent of dwelling size for a given built form (SAP, 2012).

2.2.2. National Calculation Methodologies: SAP and RdSAP

In order to meet the requirements of the EU directive for providing EPCs on all buildings in England and Wales, a National Calculation Methodology was developed. This methodology contains two different approved calculation methods for dwellings: Standard Assessment Procedure (SAP) and Reduced Data SAP (RdSAP). SAP was introduced in the 1995 building regulations in order to represent the compliance with energy efficiency standards in UK domestic sector and in 2005 RdSAP was introduced as a lower cost method of assessing energy performance of existing UK dwellings.

i. Standard Assessment Procedure (SAP)

The Standard Assessment Procedure (SAP) underpins the Building Research Establishment Domestic Energy Model (BREDEM), and is the UK government's approved methodology for assessing the energy ratings of dwellings. Designs for new domestic buildings and those with major renovations are evaluated according to SAP for their estimated energy consumption and carbon emissions. SAP has been an important methodology in delivering a number of key energy and environmental policy initiatives including Energy Performance Certificates (EPCs).

As is the case for standard energy models in many countries, the calculations and assumptions contained in SAP are laid out in freely available documentation. However the implementation of SAP in approved software such as BREDEM is a ‘black box’, since it is impossible to inspect directly the implementation (Summerfield et al., 2011).

The SAP calculation is based on the energy balance taking into account a range of factors that contribute to energy efficiency (SAP, 2012) including:

- Materials used for construction of the dwelling.
- Thermal insulation of the building fabric.
- Air leakage ventilation characteristics of the dwelling, and ventilation equipment.
- Efficiency and control of the heating system(s).
- Solar gains through openings of the dwelling.
- The fuel used to provide space and water heating, ventilation and lighting.
- Energy for space cooling.
- Renewable energy technologies.

The SAP calculation is independent of factors related to the individual characteristics of the household occupying the dwelling like: household size and composition; ownership and efficiency of particular domestic electrical appliances, and individual heating patterns and temperatures (SAP, 2012).

ii. Reduced Data Standard Assessment Procedure (RdSAP)

SAP usually requires hundreds of input parameters and it is too complex and time consuming (and therefore expensive) to collect these data for assessment of existing dwellings. Hence, a Reduced Data SAP (RdSAP), which required considerably less input parameters, was developed for assessment of existing dwellings. RdSAP was developed in the form of a spreadsheet which can be accessed and used from www.bre.co.uk/SAP2012. The RdSAP spreadsheet is presented in APPENDIX B. The RdSAP employs extensive inference algorithms which automatically deduce the missing data (RdSAP manual, 2012).

The RdSAP is also a system of dwelling data collection, together with defaults and inference procedures that generates a complete set of input data for calculation. The calculation using the reduced data is done in two stages. First the reduced data set is expanded into a full data set, and then the SAP calculation is undertaken using the expanded data set. The actual SAP calculation is therefore identical, whether starting from a reduced data set or a full data set.

Since the EPCs were introduced and were made a mandatory requirement for all dwellings sold or rented in England and Wales, researchers have investigated different aspects of this initiative: from technical advantages and deficiencies to its effectiveness and impact on energy demand and carbon emissions reduction. Such research can be categorised into three main groups: research investigating the impact of EPCs on households, research investigating the impact of EPCs on energy demand and CO_2 emissions, and research investigating the technical aspects of EPCs.

The first group has mainly looked into social and psychological impacts of EPCs and the resultant changes made to occupants' behaviour and space heating habits. An example of such research is the work carried out by Watts et al. (2011) on 2000 households in Southampton on the South coast of England which presented the results of a questionnaire survey with response rate of 17%. The authors found out that EPCs had little impact on decision making or price negotiation. Where retrofitting measures have been undertaken, results were inconclusive as to whether retrofitting was done as a result of EPCs. Energy efficiency was not found to be a priority for home buyers. The authors conclude: "*Whilst there is an awareness of the scheme in general, there appears to be limited recognition of its potential*" (Watts et al., 2011).

The second group has mainly focused on the implications of EPCs in reducing future energy demand and carbon dioxide emissions from domestic and non-domestic buildings. The majority of such research highlighted the performance gap between real life data and EPC estimates. The magnitude of this gap is significant, with reports suggesting that the measured energy use can be as much as 2.5 times the predicted energy use (Menezes et al., 2012). Energy efficiency is only one of the various performance aspects of buildings; it is highly likely that similar performance gaps exist between predicted and measured indoor air quality, thermal comfort, acoustic performance, daylighting levels and others (De Wilde, 2014).

The last group of research provide insight to areas of EPCs needing improvement. Two of the main works in this group are the ones undertaken by Khayatian et al. (2016) and Koo and Hong (2015). The former employs a neural network evaluation technique to investigate accuracy of residential EPCs. The latter, on the other hand, employs a dynamic rating system to overcome shortcomings of conventional EPCs.

The methodology of employing Neural Networks for EPC prediction, suggested by Khayatian et al. (2016) offers an autonomous approach for detecting anomalies in building energy certificates. The developed model provides the opportunity to compare the predicted energy performance index with dynamic energy simulation tools. This process can define a correlation between steady-state and dynamic simulations with the intention of obtaining a more realistic overview on the energy consumption trend in the region. Furthermore, the provided methodology can be adopted to predict the actual energy performance of buildings.

This study by Koo and Hong (2015) analysed the potential problems of the conventional operational rating system for existing buildings by using the statistical and geostatistical approaches and developed the dynamic operational rating (DOR) system by using the data-mining technique and the probability approach. The developed DOR system can be used as a tool for building energy performance diagnostics. The developed DOR system can be applied for various purposes such as encouraging all the public to voluntarily participate in energy-saving campaigns, evaluating the historical trend in the energy performance of existing buildings, estimating the operational ratings of new buildings in the early design phase.

2.3. Energy Modelling in Domestic Buildings

In recent years, a variety of models have emerged that are capable of analysing energy and environmental performance of domestic buildings, and examining different strategies that are designed to reduce energy consumption and improve internal thermal comfort. These models are capable of modelling the complex interactions which occur between building envelope and systems with external weather conditions, investigate the influence of various energy demand reduction measures and policies, and suggest the resultant impact that these strategies and policies may have on future energy use. As a result, these models are needed in order to understand which strategies and policies are required, when such strategies and policies should be implemented, and estimate the potential impact of their implementation. The available models range from global, international and national energy models, to more detailed sectoral models. Such diversity has resulted in these models varying considerably in terms of their level of detail, their complexity, the data input required by the user, the time periods covered, their geographical coverage, and the methodological approach taken (Johnston, 2003). Since describing and critically analysing such wide variety of models is beyond scope of this theses, the remainder of this chapter investigates the main energy models which are considered to be of particular relevance to this study, namely: those that have been developed for domestic buildings in the UK using a limited set of data.

Energy models of the domestic building stock have been developed for a number of reasons which include: predicting energy demand in dwellings to adjust energy supply, identifying the subdivisions of society that consume more energy and enable policy makers to target high energy users better when designing demand reduction measures and assessing the potential of energy efficiency policy (Kane, 2013).

Techniques to model domestic energy consumption can be broadly divided into two main groups: “top-down” and “bottom-up”. The terminology is with reference to hierarchal position of input data as compared to the housing sector as whole. The top-down approach considers the residential sector as energy sink and is not concerned with the individual dwellings (Swan & Ugursal, 2009). It uses historical statistics of energy use and households on a national level and estimates the effect of changes in top level factors such as energy price, climate and macroeconomic indicators such as gross domestic product, unemployment and inflation on energy consumption of the whole housing stock (Swan & Ugursal, 2009). Bottom-up models are based on the principles of building physics and are able to quantify specific changes to the domestic building stock such as the impact of a national roof insulation programme.

The main difference between these two approaches is the adopted perspective (Figure 2.2).

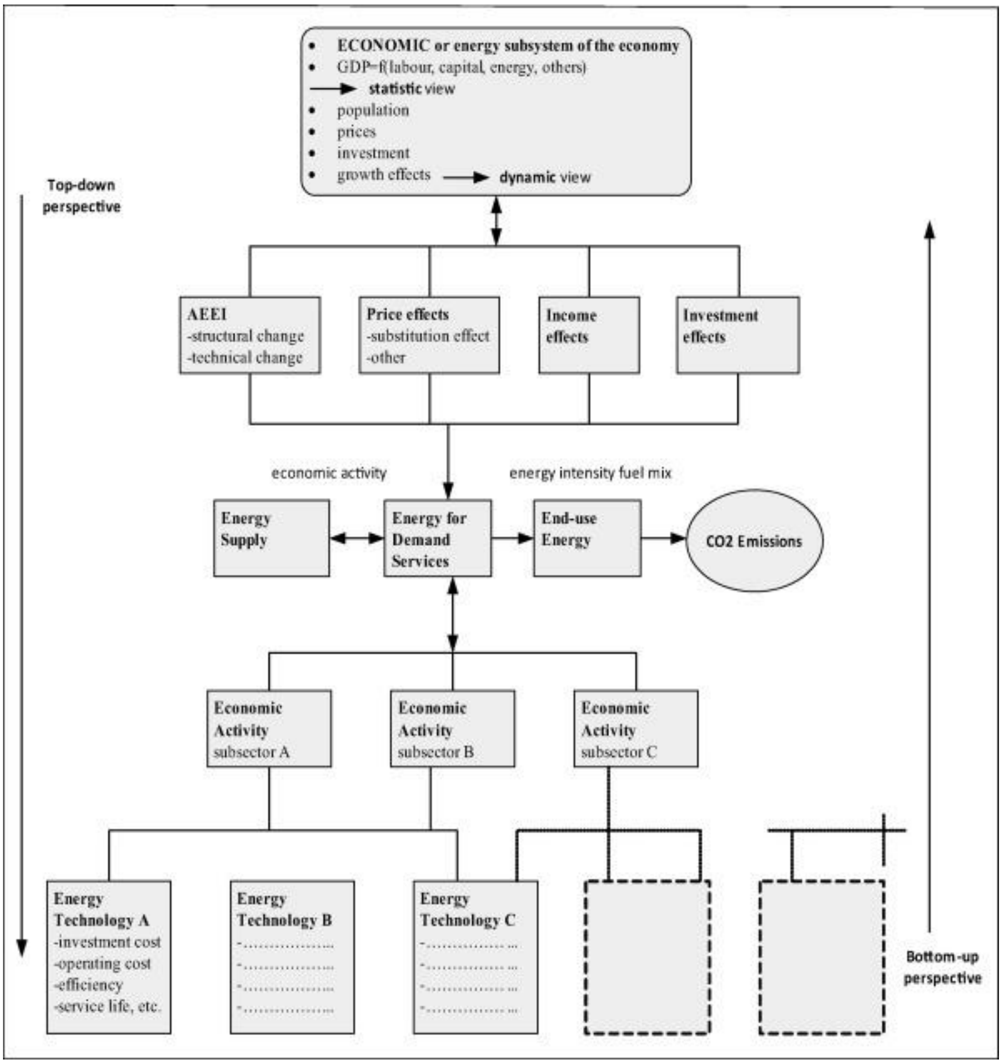


Figure 2.2 Top-down and bottom-up modelling approaches (IEA, 1998)

Top-down methods start with aggregate information and then disaggregate down as far as they can. Since they begin with aggregate data, top-down methods provide a comprehensive approach to modelling. Bottom-up methods, on the other hand, start with detailed disaggregated information and then aggregate this information as far as they possibly can. Since bottom-up approach only tends to model part of the whole picture, they lack the comprehensiveness of top-down methods.

Although top-down and bottom-up methods are two different approaches, they have some similarities. First of all, they are capable of operating at the same level of disaggregation, and secondly, they both make use of the same facts, but describe and use them in different ways (Johnston, 2003).

These two modelling approaches are introduced and examples of where they inform this work given in following sub-sections.

2.3.1. Top-down Modelling Approach

Top-down models take a macroeconomic approach to modelling energy supply and demand. They concentrate on the interaction between the energy sector and the economy at large, and use econometric equations to model the relationships that exist between the energy sector and economic output. They rely on aggregate economic factors to predict future changes in energy use and CO_2 emissions (IEA, 1998). Top-down models have been developed to inform policy makers regarding the social and economic drivers for energy consumption. They seek to improve understanding of how energy use relates to geographical areas, economic factors, and demographics; how this has changed historically and what impact policy instruments might have on future energy use in different segments of the population (O'Neill & Chen, 2001). Consequently, top-down models purposefully exclude detailed technology descriptions, as their focus is not on the individual physical factors that can influence energy demand, but rather on the macroeconomic trends and relationships (MIT, 1997). Therefore, the data input required for top-down models consist of econometrically based data, such as Gross Domestic Product (GDP), fuel prices, and income.

Top-down modelling techniques are mainly appropriate for modelling the societal cost-benefit impacts of different energy and emissions policies and scenarios (MIT, 1997). Therefore, they have been widely used in the UK by Government organisations to identify future trends in energy use and CO_2 emissions and to study the effects of macroeconomic policy decisions on the various factors that drive energy use. Such organisations include: the Department of Energy in Energy Papers 39 and 58 (DoE, 1979a, 1979b & 1990); the Departments of the Environment and Transport in Research Report 33 (DEn&T, 1981); the Department of Trade and Industry in Energy Papers 59, 65 and 68 (DTI, 1992, 1995 and 2000); and by the Department of the Environment Transport and the Regions (DETR, 1998). However, the models developed by these organisations generally do not identify energy demand at a technological or process specific level (DTI, 1995).

The most significant UK based top down model is MARKEL which is used as a core policy tool for the UK Government (Kannan et al., 2007) and has been used to establish pathways to the achieve CO_2 emissions reduction goal by 2050 (DECC, 2011b). Druckman and Jackson (2008) developed a socio-economic model of the UK Local Area Resource Analysis (LARA) which calculates CO_2 emissions at the national and regional levels. Summerfield et al. (2010) developed two regression models to predict future UK energy demand. The first model, Annual Delivered Energy and Temperature (ADEPT), used linear regression on data available from 1970 and the second model, Seasonal Temperature Energy Price (STEP), used a polynomial regression and was based on quarterly energy data from 1998.

The strength of top-down modelling approach is that they only require historical aggregate data which is largely available. The dependence on aggregate data is also a disadvantage for top-down approach as it doesn't allow modelling discontinues advances in technology. Besides, the lack of information on individual end-use energy consumption eliminates the ability to identify main areas for energy demand reduction (Swan & Ugursal, 2009).

2.3.2. Bottom-up Modelling Approach

The bottom-up approach includes all models that use input data from a hierarchal level less than that of the sector as a whole. Bottom-up modelling approach takes a disaggregated approach to modelling energy supply and energy demand. Models using bottom-up approach can account for the energy consumption of individual end-uses, individual houses, or groups of houses and are then extrapolated to represent the region or nation (Swan & Ugursal, 2009).

Based on the data inputs used by each model, the bottom-up approach can be divided into a number of sub-groups (Figure 2.3). The common data input for bottom-up models are dwelling properties such as: geometry, construction materials, appliances and systems, weather data, internal temperatures and occupancy patterns. This high level of details is both strength and weakness of the bottom-up approach. High level of details allows modelling new technologies and identifying the areas of improvements. However, the input data requirement of such high level of details is considerably greater than top-down models and simulation techniques are more complex.

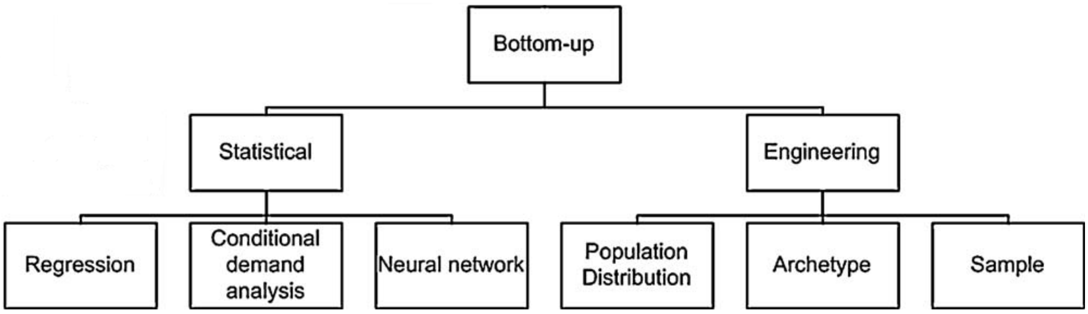


Figure 2.3 Bottom-up modelling approach and its sub-groups based on input data [re-created from (Swan & Ugursal, 2009)]

Statistical methods use historical data and regression analysis to assign dwellings energy consumption to individual end-uses. Once the relationships between end-uses and energy consumption have been established, the model can be used to predict the energy consumption of domestic building stock. Engineering method, on the other hand, explicitly takes the energy consumption of end-uses into account. In this method, consumption values are estimated based on use of equipment and systems, and heat transfer and thermodynamic relationships (Swan & Ugursal, 2009).

Since customer energy billing information is stored in vast quantity worldwide, researchers have applied different statistical methods to regress energy consumption as a function of dwellings characteristics. The main advantage of statistical method is the ability to separate the effect of occupant behaviour from model (Swan & Ugursal, 2009). This provides great benefits in domestic stock modelling as occupant behaviour has been found to vary widely and is poorly represented by simplified assumptions (Seryak and Kissock, 2003; Lutzenhiser, 1992; Emery and Kippenhan, 2006).

Three well-documented statistical method techniques as identified in Figure 2.3 are: Regression, Conditional Demand Analysis (CDA) and Neural Network (NN). Models employing the regression technique regress the aggregate dwelling energy consumption data onto parameters which are expected to affect energy consumption and the input data with negligible effect are removed from model for simplicity. The CDA technique regress total dwelling energy consumption onto the list of owned appliances. In order for the CDA technique to produce reliable results, data from hundreds or even thousands of dwellings are required based on number of variables used. The NN method uses a simplified mathematical model based on interconnected parallel structure of neural networks (Swan & Ugursal, 2009). Among the three statistical method techniques, regression is the least favoured due to widely varying input parameters in different models and limited comparison possibility. The CDA, however, is focused on simplified end-uses and its predictions a comparable among different studies.

The engineering method, in contrary to statistical method, can estimate the domestic energy consumption without any historical consumption data. The engineering method has high capability in modelling new technologies with no historical data. However, occupant behaviour must be included in this method. The main engineering method techniques (Figure 2.3) are: Distribution, Archetypes and Sample. The distribution technique calculates end-use energy consumption of appliances based on common appliances ratings and doesn’t account for interactions between appliances. The archetype technique broadly classifies the housing stock according to vintage, size, etc. and scales up the energy consumption estimates from each archetype to represent national housing stock. The sample technique uses the actual sample house data to model energy consumption (Swan & Ugursal, 2009). As the variety of houses vary in UK, this technique requires a large database of representative dwellings. However, if the aim is to study new technologies and their impact on energy consumption, the engineering methods are currently the only option. The main drawbacks of the engineering method are: 1) assumption of occupant behaviour; and, 2) the high level of expertise required in developing such models.

The data input required for all bottom-up models largely consists of quantitative data on physically measurable variables like the thermal performance of walls, the efficiency of a space heating systems, or the specific energy consumption of appliances. Economic variables, such as income and fuel prices, are not explicitly modelled within bottom-up methods. Instead, they are incorporated within the model in terms of their effect on physically measurable variables, such as mean internal temperatures, the ownership and usage of appliances and the different fuels that are used (Johnston, 2003).

The use of physically measurable data within bottom-up modelling techniques has resulted in these techniques being widely used to suggest the likely outcome of policies, or to identify a range of technological measures that are intended to improve end-use efficiencies (Shorrock, 1994). Consequently, over the last 30-40 years, bottom-up models have been extensively developed and used by a number of researchers in the UK: Leach et al. (1979); Barrett (1981); Olivier et al. (1983); Evans & Herring (1989); Shorrock & Henderson (1990); ETSU (1994); Shorrock (1994 & 1995); DECADE (1994, 1995 & 1997); Evans (1997); Shorrock & Dunster (1997); Hay et al. (1999); ECI (2000); Letherman & Samo (2001), Shorrock et al. (2001); and, Johnston (2003).

2.3.3. Top-down or Bottom-up Approaches?

The top-down and bottom-up approaches each have many commonalities, similarities and differences, as well as advantages and disadvantages. Although each approach views the domestic energy sector from a different perspective, they are in fact complementary to one another, and each method can give insights into a particular problem that the other may miss (Shorrock & Dunster, 1997). Consequently, no approach is clearly superior to the other. Two of the main characteristic differences between these two approaches are the required input data and range of energy saving scenarios that can be implemented in each approach. The main advantages and disadvantages of the three major residential energy modelling approaches (top-down, bottom-up statistical and bottom-up engineering) are summarised in Table 2.1.

Swan and Ugursal (2009) discussed all three modelling methods and concluded that the models are useful considering the current focus placed on efficient use of energy and technology implementation. When the supply side is the main point of consideration, top-down models provide great advantages compared to bottom-up methods. Bottom-up statistical method takes into account the occupants behaviour and individual appliances which helps to identify areas of improvement in energy consumption. Finally, bottom-up engineering models help identify the impact of new technologies and account for wide variety of housing stock.

Despite the comprehensiveness and macroeconomic coherence that this approach provides, there are important limitations that make top-down approach inappropriate for this study. Firstly, top-down models employ historical economically based input data which is contrary to aim of this PhD in using reduced data available on individual dwellings. Secondly, top-down models lack the level of technological detail that is contained within bottom-up methods. As a result, top-down methods tend to parameterise technological advance, rather than explaining it within the model (MIT, 1997); which makes them inappropriate for identifying energy saving potentials of various energy saving measures.

Table 2.1 Advantages and disadvantages of the three major residential modelling approaches [re-created from (Swan & Ugursal, 2009)]

Method	Advantage	Disadvantages
Top-down	• Long term forecasting in the absence of any discontinuity • Inclusion of macroeconomic and socioeconomic effects • Simple input information • Encompasses trends	• Reliance on historical consumption information • No explicit representation of end-uses • Coarse analysis
Bottom-up statistical	• Encompasses occupant behaviour • Determination of typical end-use energy contribution • Inclusion of macroeconomic and socioeconomic effects • Uses billing data and simple survey information	• Multicollinearity • Reliance on historical consumption information • Large survey sample to exploit variety
Bottom-up engineering	• Model new technologies • ‘‘Ground-up’’ energy estimation • Determination of each end-use energy consumption by type, rating, etc. • Determination of end-use qualities based on simulation	• Assumption of occupant behaviour and unspecified end-uses • Detailed input information • Computationally intensive • No economic factors

Bottom-up methods, on the other hand, provide a number of advantages which makes them more appropriate for this research. Firstly, they allow use of physically measurable input data, which is the main type of data in EPC datasets. Secondly, bottom-up methods explicitly calculate energy consumption of different end-uses based on detailed description of houses (Swan & Ugursal, 2009). Finally, and most importantly, bottom-up methods can explicitly evaluate and calculate the impact of different energy saving measures on delivered energy use (Johnston, 2003).

As with all modelling approaches, there are limitations associated with bottom-up methods. The bottom-up methods tend to increase the amount of input data that is required by the modelling system, due to the disaggregation of information, and the greater complexity associated with this (Johnston, 2003). The increased amount of required input data is reported as one of the main barriers to modelling domestic buildings by number of previous studies (Judkoff and Neymark, 1995; Karlsson et al., 2007; Kalema et al., 2008; Judkoff et al., 2008).

The vast majority of UK based domestic energy models have dealt with the issue of lacking required data by employing steady-state calculation engines which require relatively less amount of input data compared to dynamic energy models. However, a few studies have been identified outside UK which have employed dynamic energy modelling and have dealt with inadequate input data in different ways. Following section presents critical analysis of both steady-state and dynamic models developed within and outside the UK.

2.4. Reduced Data Building Energy Models

2.4.1. Steady-State Models

In the UK a number of energy models have been developed in past decades targeting to estimate domestic sector energy consumption as well as to predict future residential energy demand. Eight main energy models developed for the UK housing stock were identified. Critical analysis of these models provides a great opportunity to identify the weakness and strength of different modelling methodologies applied to same building stock. The identified models are described and analysed as bellow:

i. **The Building Research Establishment's Hosing Model for Energy Studies (BREHOMES)** developed by Shorrock and Dunster (1997a, 1997b, 2005)

The BREHOMES model disaggregate the UK housing stock into more than 400 categories which are separated by 4 age bands, 17 built forms and by whether or not central heating is present (Shorrock and Dunster, 1997). The categories into which the model disaggregates are mainly based on data source used. The large number of categories in BREHOMES is made possible through employing more than one data source which makes BREHOMES a database as well. The most important sources used in developing BREHOMES are: the Digest of UK Energy Statistics published annually by Department of Energy, the English House Condition Survey (EHCS) published every five years by Department of Environment, the Central Household Survey published annually by office of Population Census and Surveys, and the Family Expenditure Survey published annually by Department of Employment.

The main drawback associated with this model is using a single dwelling type to predict future trends in all the stock which results in simplified calculations at the cost of the thoroughness (Natarajan and Levermore, 2007). Figure 2.4 presents the overall structure and form of the BREHOMES model.

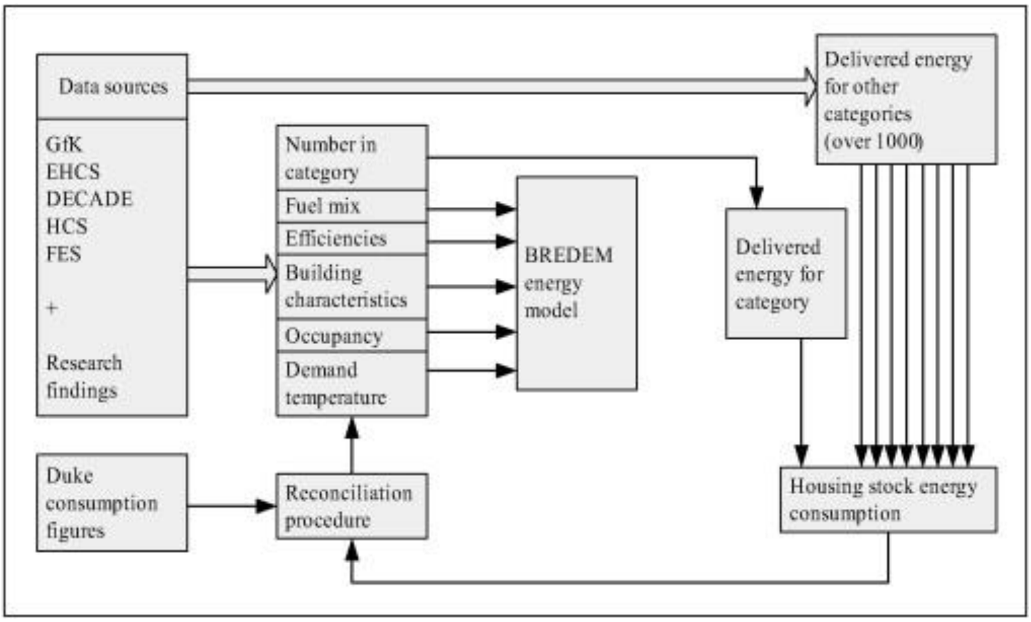


Figure 2.4 Structure and form of BREHOMES model (Shorrock and Dunster, 1997)

As shown in Figure 2.4, central to the BREHOMES model is the Building Research Establishment's Domestic Energy Model (BREDEM) (Dickson et al., 1996). BREDEM consists of a set of heat balance equations and empirical relationships to estimate annual (in case of BREDEM-12 (Anderson et al., 2002)) or monthly (in case of BREDEM-8 (Shorrock et al., 1991; Anderson and Chapman, 2002)) energy consumption of individual dwellings. An important modified version of BREDEM (BREDEM-9) forms the basis of the UK Government's Standard Assessment Procedure (SAP) (BRE, 2005) which is used for identifying energy rating of dwellings and creating Energy Performance Certificates (EPC).

BREHOMES examined two illustrative scenarios with 1996 as their base year and projected scenarios to 2050: 'Reference' scenario and 'Efficiency' scenario (the same, but the uptake of efficiency measures, such as loft insulation, is increased). These scenarios have been improved and used by Johnston (2003) to investigate demand- and supply-side of domestic energy sector with regards to the UK Government's plans to cut CO_2 emissions.

ii. **The Johnston model** developed by Johnston (2003)

The Johnston model explores the technological feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by 2050. This model investigates three illustrative scenarios of energy use and CO_2 emission: a 'Business-as-Usual' scenario, which represents a continuation of current trends in fabric, end-use efficiency and carbon intensity trends for electricity generation; a 'Demand Side' scenario, which represents the improvements to current rate of uptake of fabric and end-use efficiency measures; and an 'Integrated' scenario which shares the same demand side assumptions as the 'Demand Side' scenario, but represents what may happen if the carbon intensity of electricity generation were to fall even further (Johnston, 2003). The Johnston model employ BREDEM-9 calculation engine to estimate energy and CO_2 emission of the UK housing stock (Figure 2.5).

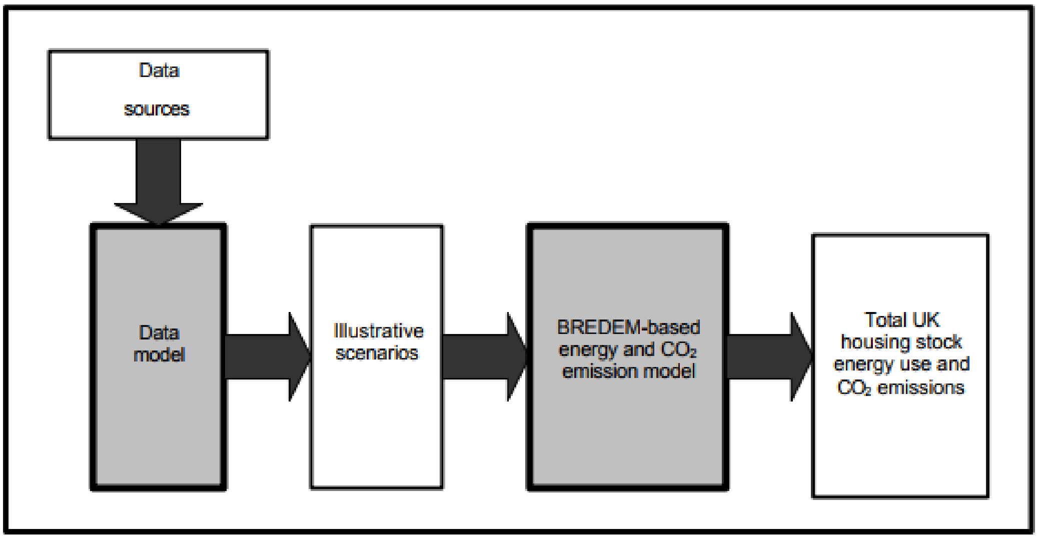


Figure 2.5 Structure and form of Johnston model (Johnston, 2003)

In contrary to BREHOMES, the Johnston model has a very low level of disaggregation and is constructed around only two notional dwelling types; namely: pre- and post-1996. The drawback caused by low level of disaggregation is that the model only provides broad results when comparing impact of different energy saving measures. Johnston (2003) discuss that two notional dwelling types makes it difficult "*to explore* *what reductions in energy consumption and CO_2 emission could be achieved if different age classes of the UK housing stock were selectively upgraded or demolished*". The main reason behind low level of disaggregation is usually the lack of sufficient data to support high level of disaggregation as acknowledged by Johnston (2003). The Johnston model has used a number of data sources including: population projections from the Office for National Statistics, mean household size data from the Department of Environment, Transport and the Regions (DETR) and, the English House Condition Survey (EHCS).

iii. **The UK Carbon Domestic Model** (UKDCM) developed by Boardman (2007)

The UKDCM is basically a numerical model of energy flows, which takes into account all the sources of heat gain and heat loss in a stock of dwellings whose characteristics change through time (Figure 2.6).

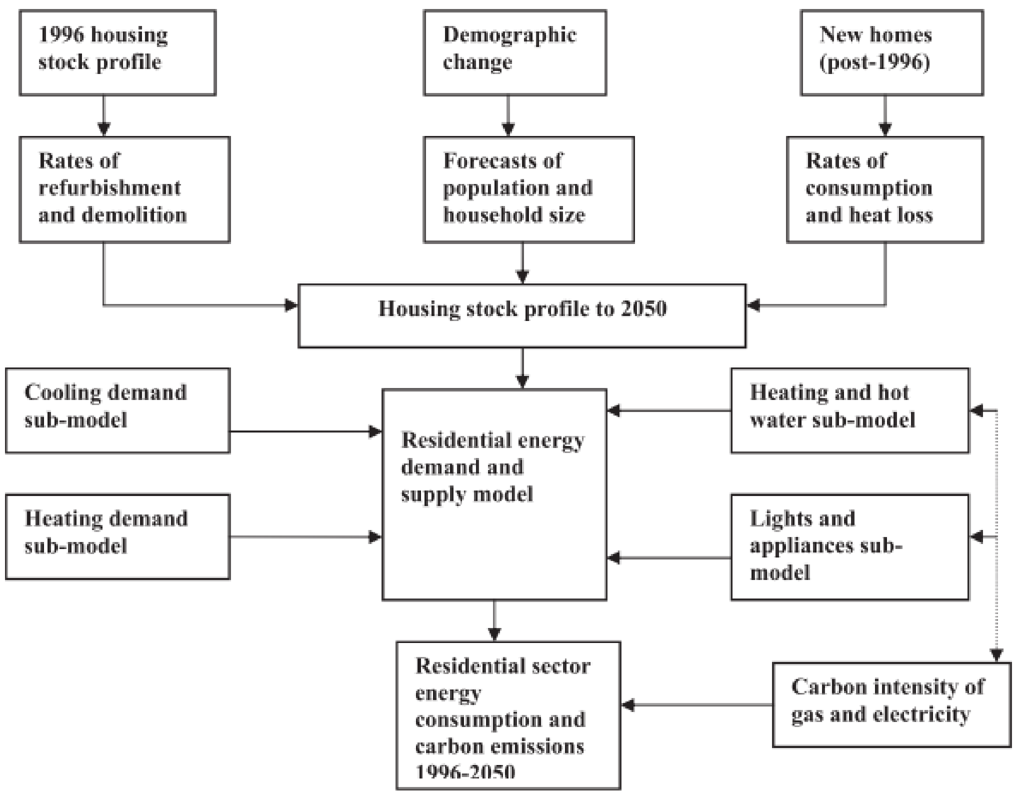


Figure 2.6 Structure and form of the UKCDM (Boardman, 2007)

Similar to the BREHOMES and the Johnston model, the UKCDM has 1996 as the base year and projected scenarios to 2050 and makes use of government statistics on energy and housing, as well as population. The UKCDM disaggregate the UK housing stock into 9 regions, 12 age bands, 10 dwelling types, 6 tenure types, 4 classes for number of floors, and 6 construction types. In addition to these classification parameters, double glazing, loft insulation and wall insulation have been included as defining characteristics of the energy performance of individual dwellings (Boardman, 2007).

iv. **The DECarb Model** developed by Natarajan and Levermore (2007)

The DECarb is another prominent model for the UK housing stock which is capable of implementing different energy saving and CO_2 reduction scenarios in order to predict future trends in consumption and emissions. The DECarb model is based on building physics approach. Figure 2.7 shows the structure and form of the model. The DECarb model is highly disaggregated and has unique 8064 combinations of six age bands of the UK housing stock. Similar to models discussed above, the DECarb model uses the BREDEM-8 procedure for calculating consumption and emissions of the dwellings, and has 1996 as the base year (Natarajan and Levermore, 2007).

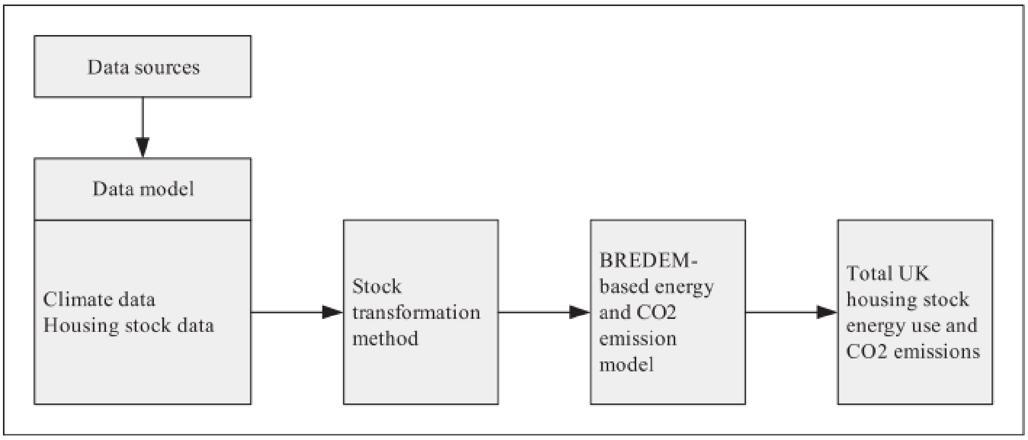


Figure 2.7 Structure and form of the DECarb model (Natarajan and Levermore, 2007)

The DECarb model has examined the scenarios developed by BREHOMES, Johnston, and UKDCM instead of adding further scenarios. The findings suggest that neither of the two low carbon scenarios tested with the Johnston model would reach the target of 50% reduction in carbon emissions by 2050. The results from the DECarb model, however, approve the UKDCM's 40% scenario of achieving the targeted 60% CO_2 emission reduction by 2050 (Natarajan and Levermore, 2007).

v. **The Energy and Environment Prediction Model (EEP)** developed by Jones, Patterson and Lannon (2007)

The EEP model is different to the previously introduced models in that it is based on Geographic Information System (GIS) techniques (not BREDEM) and employs a number of sub-models (Figure 2.8) to estimate current energy consumption and CO_2 emissions from domestic and non-domestic buildings, traffic and industrial processes for a city or region (Jones et al., 2007). Each sub-model uses UK Government's accepted procedures to predict energy use and emissions with the exception of the traffic sub-model that has been developed using Spatial Analysis procedures.

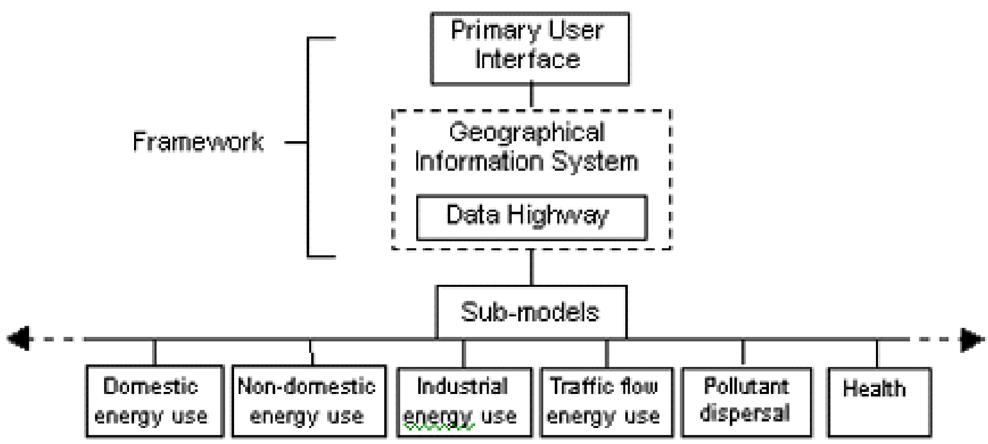


Figure 2.8 Structure and form of the EEP model (Jones et al., 2007)

The domestic energy use sub-model of EEP consists of 1300 dwellings. This sub-model employs the SAP rating as an indicator of the energy performance of dwellings. The SAP rating is calculated based on the UK Government's Standard Assessment Procedure which assesses the energy performance of dwellings (BRE, 2005). There is an important weakness in the SAP procedure regarding the way electrical appliances and cooking is handled. SAP takes into account the internal heat gain from electrical appliances and cooking but excludes their energy use in the calculation of total energy consumption. This issue was not explicitly addressed in the domestic sub-model of EEP. Although this sub-model has been evaluated against the SAP ratings, the validation of the actual energy consumption and CO_2 emission estimates was not clearly described (Oladokun and Odesola, 2015).

vi. **The Community Domestic Energy Model** (CDEM) developed by Firth, Lomas and Wright (2010)

The CDEM is another prominent model of energy consumption and carbon emissions of the UK housing stock that was developed by the staff in the Building Energy Research Group (BERG) of Department of Architecture, Civil and Building Engineering, Loughborough University in 2009 (Firth et al., 2010). This model is highly disaggregated, with 47 house archetypes derived from unique combinations of built form and dwelling age bands. For energy and emission calculations, the model requires input from many sources including English House Condition Survey (EHCS), Standard dwelling types (Allen and Pinney, 1990), BREDEM-8 (Shorrock et al., 1991; Anderson and Chapman, 2002) calculation engine, SAP rating (BRE, 2005), and etc. (Figure 2.9).

The main data requirement for the CDEM was provided from the BREDEM-8 calculation engine, monthly average external temperatures and monthly average solar radiation which is available from the Met Office. The model estimates monthly energy consumption and carbon emissions of the whole UK housing stock.

The main drawback associated with the CDEM is that instead of examining future scenarios, the model only estimated energy consumption and carbon emissions of the 2001 English housing stock (Firth et al., 2010).

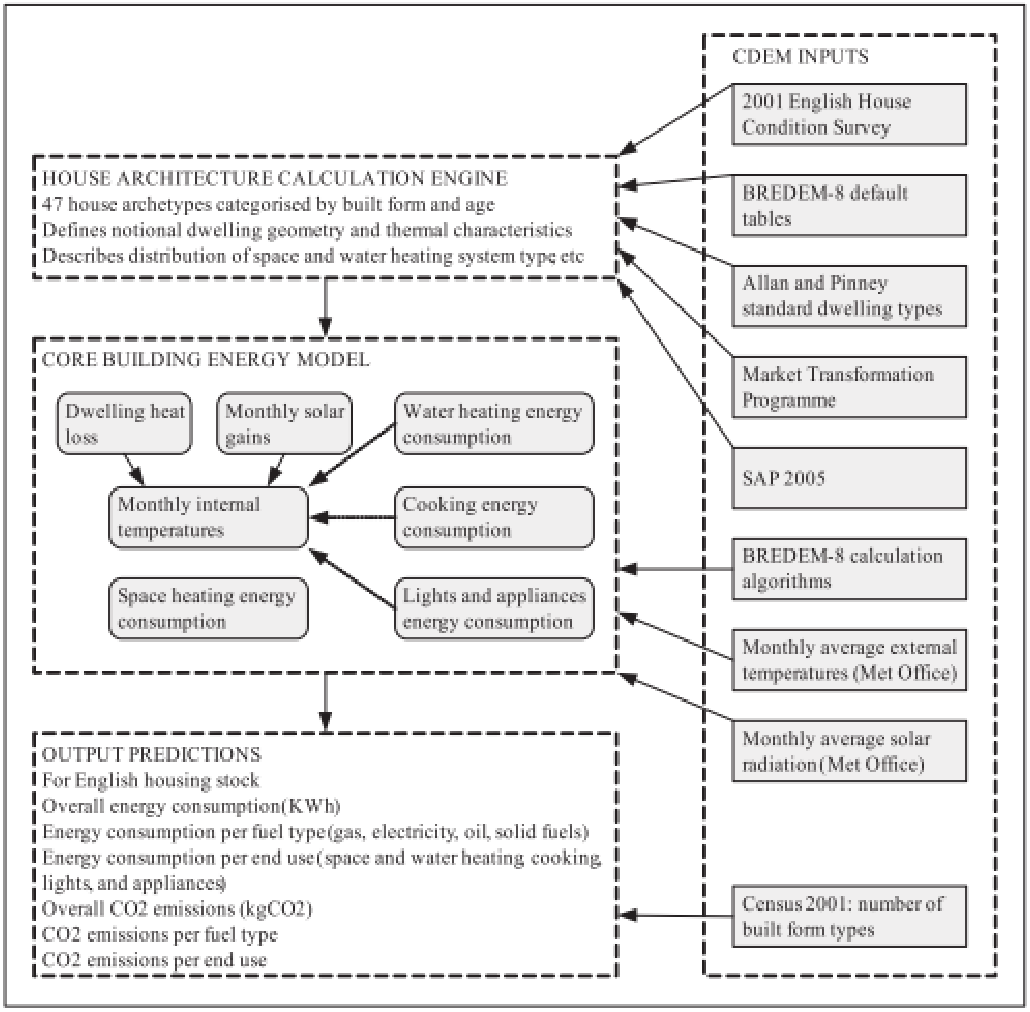


Figure 2.9 Structure and form of the CDEM (Firth et al., 2010)

Unlike, other UK models the CDEM investigated effect of the uncertainties on the results associated with the input variables. Frith et al. (2010) carried out an extensive local sensitivity analysis and assigned sensitivity coefficients to the primary input parameters of the model. They found that the various input parameters have widely varying effects on the prediction outputs. The characteristics and usage patterns of heating systems (such as the thermostat temperature and hours of heating use) and the heat losses of the dwellings were identified as highly determining factors of domestic space heating demand.

vii. **The Cambridge Housing Model (CHM)** developed by Hughes (2011); Hughes and Palmer (2012)

The CHM is another steady-state bottom-up model that uses the calculations formulated and established by SAP 2009 (BRE, 2011) and BREDEM engine (Shorrock and Dunster, 1997b) to run necessary calculations. The model has three basic data input components (Figure 2.10); namely: climate data, housing data, and building physics data. For climate data input, the model uses SAP's monthly solar declination and regional latitude data, BREDEM-8's monthly/regional solar radiation data, and monthly/regional year-specific wind speed and external temperature data from a number of different stations across the UK.

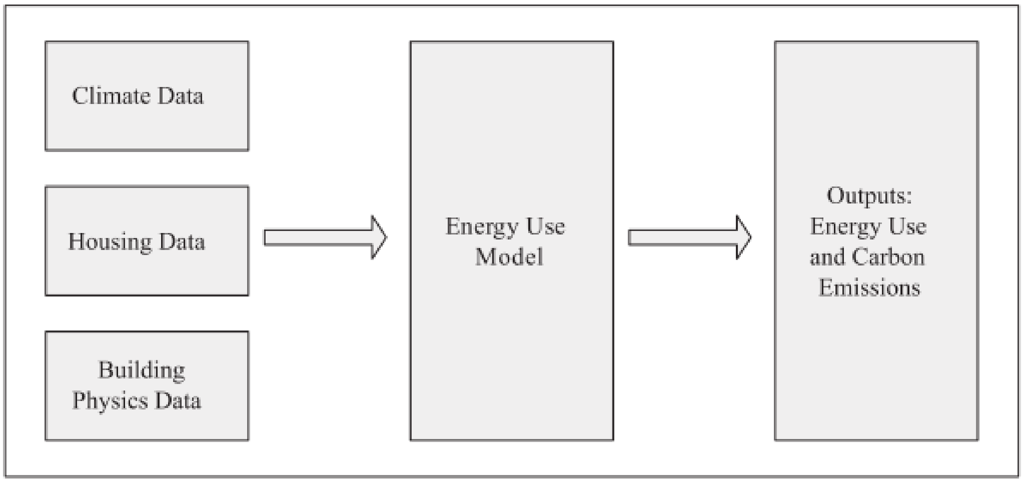


Figure 2.10 Structure and form of the CHM (Hughes, 2011)

The main source of housing data is based on 16,670 dwellings defined in English Housing Survey of 2010 (Palmer and Cooper, 2012) with an adjustment to reflect the UK housing stock. However, the building physics data inputs are the direct results of the calculations performed in SAP and BREDEM. The model then reads in data for individual representative dwelling in order to perform building physics calculations. The CHM is one of the most transparent models because the model is built and all its calculations performed in Microsoft Excel.

The output of CHM is one of the studies that made up the UK housing fact file in the Department of Energy and Climate Change (DECC) (Palmer and Cooper, 2012).

viii. **The Domestic Dwelling Model (DDM)** developed by Mhalas, Kassem, Crosbie, and Dawood (2013)

The DDM is a new approach which has very different characteristics to the previously described UK based steady-state model. The DDM models energy consumption and carbon emissions of dwellings and neighbourhood based on visualisation. The model is highly disaggregated as it estimates each dwelling independently within the neighbourhood. The model uses the SAP and BREDEM energy calculation engine. The DDM utilises information from aerial and terrestrial imagery, digital maps, household surveys, census, and ONS (Figure 2.11) (Mhalas et al., 2013).

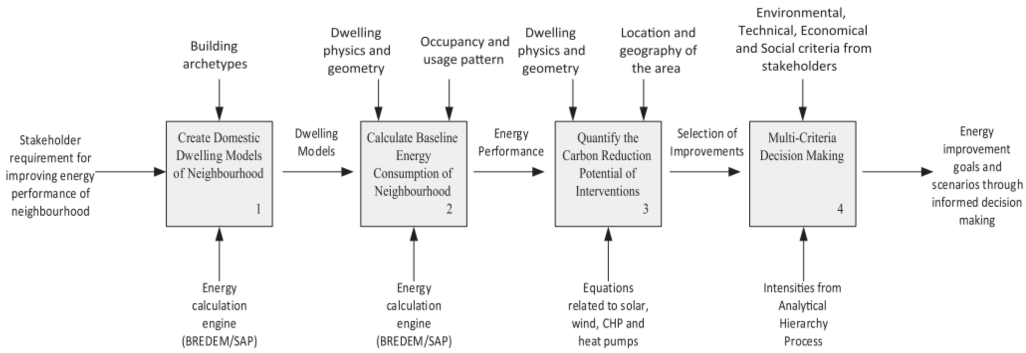


Figure 2.11 Structure and form of the DDM (Mhalas et al., 2013)

This model is implemented on a GIS platform which makes it possible to replicate data entry process for several dwellings that have similar characteristics. This is particularly useful in undertaking the energy assessment for terraced, semi-detached and detached houses built during similar time periods (Mhalas et al., 2013). The DDM currently include scenarios on fabric change, PV addition, condensing boiler improvement, etc. but not future scenarios or energy saving measures. Further work is planned to identify the impact of improvements and the development of a more accurate calculation of the rate of return of investment based on inflation indices.

2.4.2. Critical Analysis of the UK based Models

The models introduced all share the same calculation engine, BREDEM, modified to varying degrees based on the aims and needs of each model. They are capable of estimating baseline energy consumption of existing housing stock, predicting energy saving and carbon emission reductions from a variety of scenarios and except for EEP, they are all capable of predicting future energy demand and savings from proposed scenarios. Natarajan et al. (2011) has judged BREDEM as a well-established method which estimates UK dwelling energy consumption and predicts dwellings' energy consumption and carbon emissions at a highly disaggregated level based on building physics. However, one of the major drawbacks associated with BREDEM is the generalisation of occupant behaviour patterns, as in simplifying appliances consumption based on floor area and number of occupants (Cheng and Steemers, 2011).

All eight models are used as policy decision-making tools. However, the models are varied in terms of their output levels, extent of stock disaggregation, and the scenarios analysed, as shown in Table 2.2. These models have been developed since the early 1990s and each model was criticised by its successor and by more recent researchers due to a number of limitations. Firstly, all the models have been criticised for their low level of transparency. Kavgic et al. (2010) and Mhalas et al. (2013) discussed that the models' transparency, in terms of the architecture and data sources, is one of the main issues that needs to be addressed in future models. Cheng and Steemers (2011) state "*No model is perfect. Models become useful if their assumptions and limitations are known to the users so that the users can make informed decisions on the practical application of the results. This transparency is generally lacking in the existing UK domestic energy models and as a result significantly limits the viability of the existing models in assisting policy formation*".

Table 2.2 Comparative analysis of prominent UK based steady-state domestic energy and carbon models

Model	Year	Calculation	Output	Disaggregation	Analysed scenarios
BREHOMES	Early 1990s	BREDEM-12	Annual energy consumption	1000 dwelling types: based on age, tenure type, etc	Reference and efficiency until 2020
Johnston	2003	BREDEM-9	Annual energy consumption and carbon emission	Two dwelling types: pre and post-1996	Business-as-usual, demand, integrated until 2050
UKDCM	2006	BREDEM-8	Monthly energy consumption and carbon emission	20,000 dwelling types by 2050	Business-as-usual, 44% reduction, 25% emission reduction below 1990 levels by 2050
DECarb	2007	BREDEM-8	Monthly energy consumption	8064 combinations of dwellings from 6 age bands	Scenarios from: UKIPO2, BREHOMES, Johnston, UKDCM, Back-cast (1970–96)
EEP	2007	SAP	Annual energy consumption and carbon emission	1300 dwelling based on age band and built form	Fabric change, PV addition, condensing boiler improvement
CDEM	2009	BREDEM-8	Monthly energy consumption and carbon emission	47 archetypes based on age band and built form	A scenario to predict 2001 housing stock
CHM	2010	BREDEM-8 and SAP	Annual energy consumption and carbon emission	16,670 dwelling types	Conducted sensitivity analysis for the 15 most sensitive parameters in the model
DDM	2013	BREDEM-8 and SAP	Annual energy consumption and carbon emission	756 dwelling types	Fabric change, PV, I-CHP, Condensing boiler, ASHP (Under-floor and radiator)

Secondly, and more importantly, these models are not capable of taking into consideration the complex, interdependencies, and dynamic nature of the energy consumption and carbon emission (Oladokun and Odesola, 2015). This is because the modelling approaches of these models are based on steady-state calculations. These models therefore work with particular sets of data inputs trying to generate particular sets of outputs that have little or no room to accommodate uncertainty in input datasets. Kavgic et al. (2010) state that "*the new generation of bottom-up building stock models should include multidisciplinary and dynamic approaches, so that for instance they can improve the synergy in policy development on energy efficiency, comfort, and health*".

The critical analysis of UK-based domestic energy models suggests that there is the need to look for more detailed modelling approaches capable of dealing with the limitations discussed (Oladokun and Odesola, 2015). It is evident that the uniformity of the assumptions made by BREDEM will result in systematic errors that could have negative consequences for energy policy making, and the targeting of energy efficiency measures. A more recent study by Kane et al. (2015) discussed that much has changed in the 25 years since the BREDEM modelling framework was created, in the way we use our homes, the amount data made available to the research community, and the availability of more detailed energy models. They state: "*We no longer expect to be able to understand the mathematics behind models or be able to complete calculations by hand; arguments that have been used in support of simple BREDEM-like modelling*". Consequently, recent researches have modelled stocks using more detailed dynamic simulation programmes. Detailed analysis of such models, which are found to be of relevance to the model developed in this thesis, is presented in the following sub-sections.

2.4.3. Dynamic Energy Models

Only a few dynamic energy models of building stocks have been developed and the advantages or disadvantages of using such models have not been investigated in depth. This review identified four prominent dynamic energy models which were developed for Canadian, US, Scottish and English housing stock. Critical analysis of these models provides a great opportunity to identify the weakness and strength of current dynamic energy building stock models.

i. **The Canadian Residential Energy End-use Model (CREEM)** developed by Farahbakhsh, Ugursal and Fung (1998)

The Canadian residential stock includes five major types of dwellings: single-detached, single-attached, apartments, high-rise apartments, and mobile homes. Single- detached and single-attached houses account for 68% of the households in Canada and are responsible for the largest share of residential energy consumption. Hence, the CREEM only considers single-detached and single-attached dwellings (Farahbakhsh et al., 1998). The CREEM used the HOT2000 simulation programme to calculate the delivered energy use from Canadian residential stock. The CREEM included 8767 dwellings which were divided into 16 archetypes based on built year (pre-1941, 1941- 1960, 1961-1977, 1978 and later) and regional location (Western Canada, Prairies, Central Canada, Atlantic Canada).

Actual energy billing data from fuel suppliers and utility companies for a complete year were available for 2524 of the 8767 houses. Hence the data on these dwellings were compared to simulation results in order to verify the model. The refinements identified from the verification process were applied to the rest of the 8767 house files as necessary to improve the accuracy of the simulation results (Farahbakhsh et al., 1998). The CREEM was then used to assess the reductions in energy consumption and carbon dioxide emissions from the Canadian residential sector as a result of various energy efficiency measures.

The work carried out in developing the CREEM was evolved over time and with addition of new datasets on Canadian housing stock to develop a new hybrid model, namely: the Canadian Hybrid Residential End-use Energy and Emissions Model (CHREM). The CHREM relied on the 17,000 house details of a representative database called the Canadian Single-Detached and Double/Row Housing Database (CSDDRD) (Swan et al. 2009). This database accounted for the wide range of climate, construction types, and energy sources found throughout Canada's regions which could be used to develop dynamic energy models. The CSDDRD included detailed information on each dwelling's location, geometry and orientation, thermal zone presence, construction materials including windows and doors, air-tightness, and HVAC and DHW components.

The CHREM employed two energy modelling techniques: statistical and engineering (Figure 2.12).

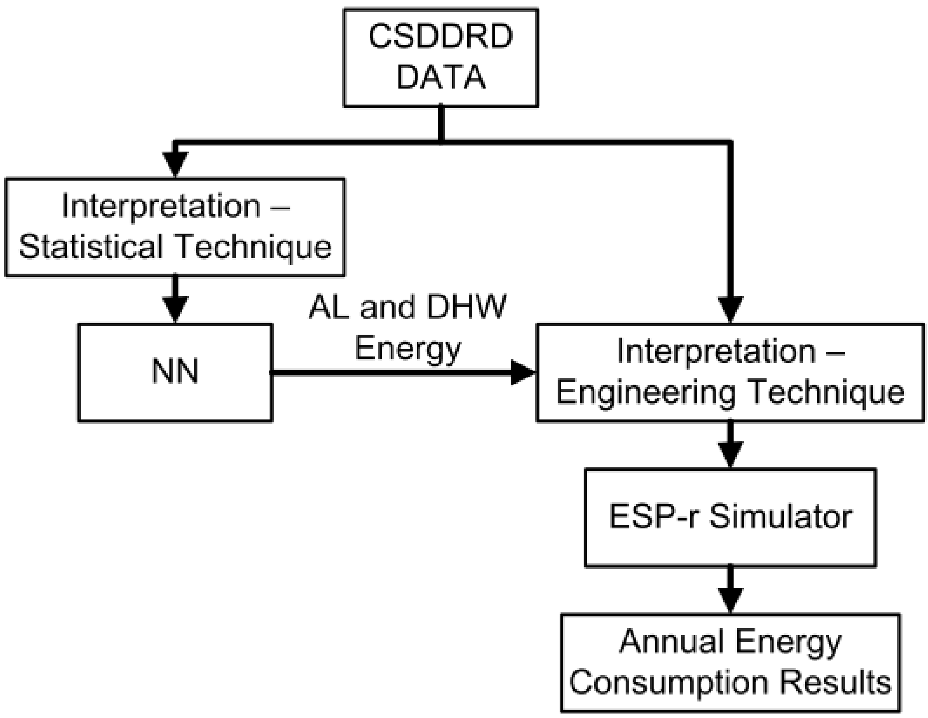


Figure 2.12 Structure and form of the CHREM (Swan et al. 2009)

These techniques were used to estimate the energy consumption of the two main end-use groups: domestic appliances and lighting (AL), domestic hot water (DHW), and space heating and cooling. The CHREM employs neural network (NN) technique as the statistical half of the model for use in estimating the annual energy consumption for AL and DHW loads; and uses the ESP-r dynamic simulation engine to calculate heating and cooling loads (Figure 2.12).

The CHREM assumed only one thermal zone for the main part of the dwellings and justified this zoning strategy by highlighting lack of data on thermal zones. The individual storeys of the main zone were not identified, but instead combined into one thermal zone with a modification to building height to account for each storey's floor area (Swan et al. 2009).

The CHREM also made a few simplifications to the geometry of the modelled dwellings. All houses were modelled as a rectangular block using a width to depth ratio (Swan et al. 2009). The authors identified that this method only partially accounted for the perimeter to area relationship that affects energy consumption due to exposed surface area and no sensitivity analysis was performed to investigate impact of such simplification on thr model estimates.

Another assumption made in the CHREM was regarding the conditions on the outside face of each zone surface. In case of Double/Row houses, adiabatic conditions are specified on one or both side walls with regard to opposing dwelling location and the thicknesses are halved to account for thermal mass attribution (Swan et al. 2009). Adiabatic party walls specified in ESP-r dynamic simulation programme, will assume that the neighbouring dwellings have exactly same thermal conditions and will neglect the heat transfer between the two dwellings.

Finally, the CHREM used an XML reporting technique to store simulation results in annual form to evaluate energy consumption and contributions due to a variety of housing components.

ii. The Huang and Brodick Model developed by Huang and Brodick (2000)

This model was developed for the US building stock (both residential and commercial) and is based on the aggregated cooling and heating loads attributable to different building envelope components in the stock, such as windows, roofs, walls, and space heating and cooling systems. The modelled building stock comprised of 112 single-family, 66 multi-family housing and 481 commercial buildings. The dataset used included information on age (pre-1940s, 1950-1959, etc.), dwelling type (single- family, small multi-family) (Huang and Brodick, 2000). The overall energy use of the US housing stock was calculated using the DOE-2.1E simulation tool.

DOE-2 is a widely used dynamic energy simulation tool that can estimate the energy consumption and cost for all types of buildings. DOE-2 uses a description of the building layout, constructions, operating schedules, and air conditioning systems, along with weather data, to perform an hourly simulation of the building and to estimate utility bills. DOE-2.1E is the “legacy” version of DOE-2 and provides for more detailed modelling of the thermal and optical properties of windows (DOE-2, 2016).

The authors of this model acknowledge that the totals for the non-space conditioning end-use such as water heating and lighting were modelled very simply. Only gas was included as the primary fuel source for space and water heating, even though electricity and other fuels are also used as a primary energy source (Huang and Brodick, 2000). The model provides information on potential improvements in certain building components, such as improving windows from single to double- glazing, but doesn't specify in which parts of the stock these gains would occur or would benefit most from the change. The inadequate description of model and lack of evidence on decisions made in development of model are the main weakness of the Huang and Brodick Model.

iii. **The Energy Systems Research Unit (ESRU) Domestic Energy Model (EDEM)** developed by Clarke et al. (2004); Clarke, Johnstone, Kim and Tuohy (2009)

The EDEM is a web based tool developed at the University of Strathclyde for Scotland housing stock. The EDEM is able to estimate energy consumption and carbon emissions both at individual and national scale. The EDEM was used to rate the energy and carbon performance of individual dwellings as required by the EU Directive on the Energy Performance of Buildings (European Union, 2002). The model used the 2002 Scottish House Condition Survey (Scottish Homes, 2003) as main source of data. The model categorise the dwellings in terms of Thermodynamic Classes (TC) so that different Architecture Classes (AC) may belong to the same TC (Clarke et al., 2009).

The EDEM employed the ESP-r dynamic energy simulation programme to determine dwelling performance by subjecting the dwelling models to long-term weather sequences. Clarke et al. (2004) justified use of dynamic energy simulation over BREDEM based steady-state models by stating "*Simplified methods cannot adequately represent the performance of the myriad upgrade options that may be applied individually or in combination. Also, as buildings have extended lifetimes, it is important to assess performance under likely future contexts*".

The EDEM results were verified using detailed models of 5 real houses. The house models were subjected to energy efficiency improvements and simulations were re-run. The predicted heating energy demands resulting from the detailed simulations were then compared to the value associated with the matched TC model. The results indicated discrepancies ranging from 3% to -13%, indicating that the TC approach is a reasonable proxy for the real situation (Clarke et al., 2009).

The EDEM was also used to investigate 6 case studies: national stock upgrade, regional housing upgrade, dwelling energy labelling, impact of grid electricity generation mix, financial appraisal of upgrade options, and financial appraisal of individual dwelling upgrade.

iv. The He et al. Model developed by He, Lee, Taylor, Firth and Lomas (2014); He, Brownleeb, Lee, Wright and Taylor (2015)

The He et al. model (2014) is a dynamic energy model which uses English Housing Survey (EHS) database as main source of input data and employs EnergyPlus as simulation engine. 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. The model simulates the housing stock in the North East region of England to examine the possible CO_2 reductions corresponding to different scenarios.

The model used 2008-9 EHS database which contains 935 sample dwellings in the North East England. These sample dwellings are representative of about 1.2 million homes in that region. The 935 sample dwellings were distributed among 6 dwelling types, 10 age bands, 8 types of wall construction, and 12 loft insulations. Only 759 houses, including 90 detached houses, 329 semi-detached housed, 221 mid-terrace houses and 119 end-terrace houses were considered in the model. All the dwellings were assumed to have East/West orientation (He et al., 2014).

The dwellings were modelled with two separate zones: the living area and the rest of the dwelling. The authors justify using such zoning configuration by referencing the study performed by Taylor et. al. (2013) where it was found that the two zone models separating living area from the rest of house can predict annual energy demand within about 10% of the best estimate using individual room zones. The results of the model were verified through inter-model comparison with CHM results (see section 2.4 [vii] for CHM description). Since both models take inputs from the EHS database and simulate each dwelling individually, the results from both models were comparable (He et al., 2014). The dynamic model developed by He et. al. (2015) predicted lower demand values compared to the steady-state CHM result which were consistent with findings of other studies (Shorrock et. al., 1996; Yilmaz et. al., 2014).

2.5. Model Validation

Although building simulation has been widely used during the past three decades to investigate the effect of retrofit measures on energy savings and comfort, without validation of the base case model, results produced are not reliable (Westphal & Lamberts, 2005). A large number of studies have shown discrepancies (which were often significant) between the model predictions and measured building energy use (Coakley, Raftery & Keane, 2014). The purpose for validation is to ensure that the model could reasonably represent the thermal and energy behaviour of the real building and thus achieve confidence in model predictions (Westphal & Lamberts, 2005).

Judkoff (1988) identifies a number of ways to validate the whole-building energy models: comparative testing (Inter-model comparison), analytic verification and Empirical validation. The three validation techniques are shown schematically in Figure 2.13 Analytic, Comparative and Empirical techniques (re-created from (Judkoff et al., 2008))Figure 2.13. Table 2.3 compares these techniques by highlighting their advantages and disadvantages.

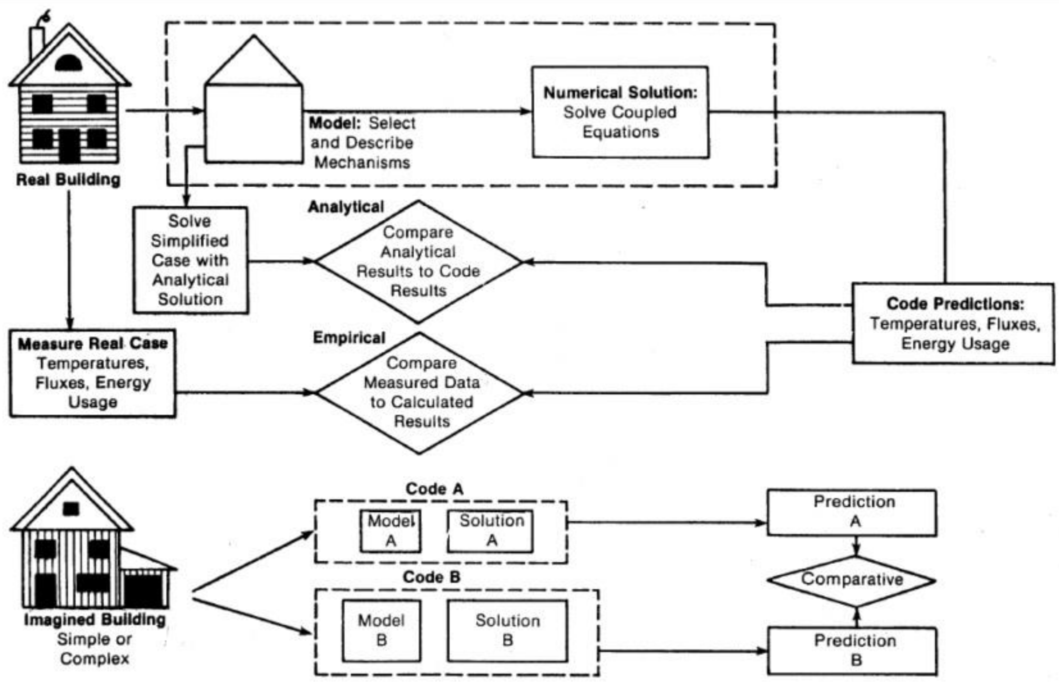


Figure 2.13 Analytic, Comparative and Empirical techniques (re-created from (Judkoff et al., 2008))

Table 2.3 Comparison of validation techniques (Judkoff 1988)

Validation Method	Advantages	Disadvantages
Comparative (Inter-model comparison)	• No input uncertainty • Any level of complexity • Many diagnostic comparisons possible • Inexpensive and quick	• No absolute truth standard (only statistically based acceptance ranges are possible)
Analytical	• No input uncertainty • Exact mathematical truth standard for the given model • Inexpensive	• No test of model validity • Limited to highly constrained cases for which analytical solutions can be derived
Empirical	• Approximate truth standard within experimental accuracy • Any level of complexity	• Experimental uncertainties: − Instrument calibration, spatial/ temporal discretization − Imperfect knowledge/ specification of experimental object (building) being simulated • High quality detailed measurements are expensive and time consuming • Only a limited number of test conditions are practical

Comparative testing is an inexpensive and quick technique which involves no input uncertainty. A comparative test directly compares results of two or more building energy simulation tools which have used similar inputs. In this type of validation, a piece of code can be compared to itself by changing a specific parameter and determine sensitivity of simulations to that parameter. One main advantage of comparative testing is that it doesn't require any data from a real building. Comparative testing enables the investigator to control accuracy of input data and eliminate any external error. Furthermore, input parameters can be modified to test the sensitivity of simulations to change in input data.

In Analytical verification simulation results are compared with the results of a solved analytical solution (ASHRAE, 2009). The same as comparative testing, analytical verification is inexpensive and has no input uncertainty. In analytical verification the investigator can test some specific heat transfer mechanisms in the building. In this technique output of modelling tools, which is based on numerical solution used in the code of programme, is compared to a unique analytical solution of heat transfer problem. An example of work using analytical verification (and comparative testing) is Building Energy Simulation Test, BESTEST (Judkoff & Neymark 1995). BESTEST is a method for systematically testing building energy simulation programmes, diagnosing sources of disagreement, and validating the capabilities of building energy simulation programs.

In empirical validation results from building simulation are compared with the data measured in real buildings (ASHRAE, 2009). In other words, empirical validation is the comparison of the estimates of the model with physical measurements (Bowman & Lomas 1985). There are various published literature on validation mainly for residential buildings rather than large commercial buildings; where conducting detailed measurements require considerable efforts and costs (ASHRAE, 2009). A number of empirical validation studies are summarized by Neymark and Judkoff (2002).

One of the main challenges researchers have been faced with to calibrate building energy models using empirical validation is the lack of detailed empirical data particularly for residential buildings which is necessary to understand the operational complexities and develop better models (Buswell et al., 2013). In majority of the cases, even when the measured data is available, it has not been measured by end use and for example the gas use measured include the use for space heating, hot water and cooking which makes the calibration difficult. In addition, the measured data has also an uncertainty and the differences observed between the models and measurements will be due to errors in either set of data (ASHRAE, 2009).

2.6. Data Translators for Dynamic Simulation

The four dynamic energy models described in previous section, all use some sort of translator to develop Input Data Files (IDFs) which are suitable for the employed calculation engines. The CREEM (Farahbakhsh et al., 1998), the Huang and Brodick (2000) Model, and the EDEM (Clarke et al., 2004) didn't provide any documented detail on technical aspects of the translators they developed. He et. al. (2014; 2015), on the other hand, identified that available tools to create IDFs were not suitable to simulate a relatively large number of real houses with different characteristics. Consequently, He et al. (2015) developed an in-house programme called the Building Generation Tool (BGT) to automatically create the IDFs of the modelled dwellings. The BGT implemented all the assumptions which were required to developed dynamic energy models based on EHS data.

2.5.1. The gbXML Translator

A study by Dimitriou et al. (2016) was identified where a translator was developed to convert data from gbXML format into EnergyPlus IDFs. This translator was developed as part of the Design4Energy retrofit scenario which uses Building Information Modelling (BIM) of existing domestic buildings to assess their energy performance using a Building Energy Modelling (BEM) technique (Dimitriou et al., 2016). The XML based gbXML format enables easy incorporation of additional information that might be required for energy analysis. The conversion process extracts as much information as possible the gbXML file and introduce additional parameters to create the IDF files that can be used by EnergyPlus to perform the analysis (Figure 2.14).

As seen in Figure 2.14, the selected BIM software was Autocad's REVIT. The process begins by developing REVIT models based on the data collected from building surveys. Then the gbXML files were used to fill in for lacking data and create EnergyPlus IDFs. The simulations were run and results were exported in csv file formats for further analysis and to proceed with the model calibration. Multiple iterations of the calibration process was required to achieve good agreement between the modelled and the actual building energy performance (Dimitriou et al., 2016).

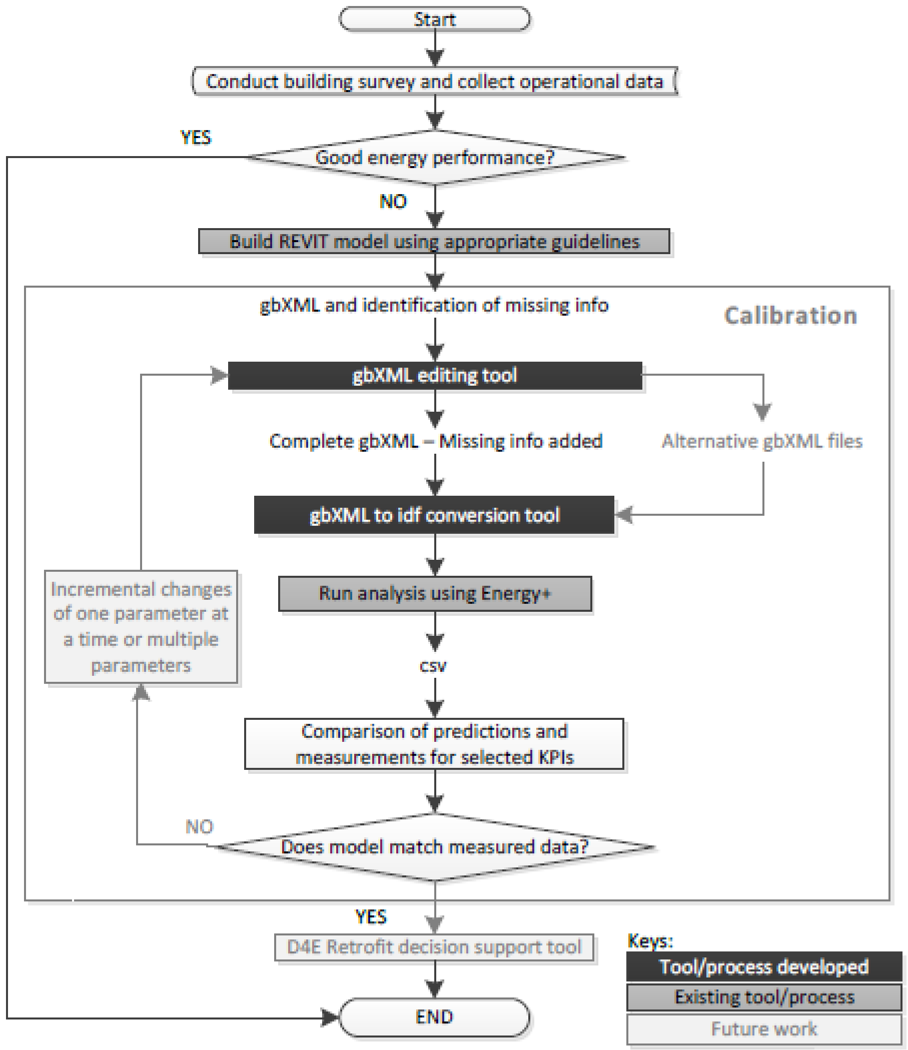


Figure 2.14 Structure and form of the BIM to BEM translator (Dimitriou et al., 2016)

The translator developed by Dimitriou et al. (2016) is the best documented one identified within UK building energy modelling context. The translator converts gbXML files into IDFs in two steps (Figure 2.15). The first step in the conversion process is the conversion of the gbXML file to a XML file that contains all the information required for EnergyPlus simulation. All the nodes required by EnergyPlus were included in a 'idfXML' file and default values were stored prior to converting gbXML files. Then the idfXML file was populated with the available information from the gbXML file. Having developed the representative idfXML files, the EnergyPlus IDFs were created based on these files in the second stage of the translation process (Dimitriou et al., 2016).

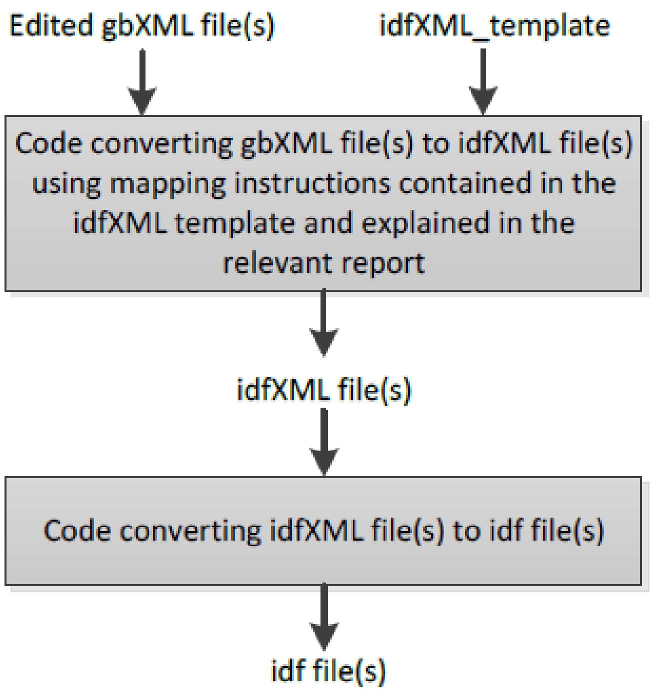


Figure 2.15 The translation process to convert gbXML files into EnergyPlus IDFs (Dimitriou et al., 2016)

The translation process described above can handle multiple files at the same time. The Translator was tested on a single house located in Loughborough, UK. The most significant assumption made in developing the BIM to BEM translator was that the heating system can be represented by an ideal loads system where calibration of the model to the measured data was not performed. Despite such assumption, the model presented relatively good agreement to the measured data. Dimitriou et al. (2016) concluded "*The deviations observed between the modelled and measured temperatures highlight the importance of transparent data exchange and default setting when forming the energy model*". Further work to validate the translator using other BIM tools was found necessary before using the translator for retrofit decision-making purposes.

2.5.2. The HPXML Translator

An ongoing work was also identified which is being carried out by National Renewable Energy Laboratory (NREL) and Building Performance Institute (BPI) in the USA. The first part of this initiative works on developing a new data storage national standard, called Home Performance XML (HPXML), to support the needs of home performance programs, quality assurance agents, and financial institutions. HPXML can also aggregate data across programs and remove redundancies in incentive compliance to support these additional consumers (Andrulis and Thomas, 2012). The second part of this work develops translators to convert HPXML data into different input data files which could be accessed and executed with various building energy modelling tools (Neymark and Roberts, 2013). Figure 2.16Figure 2.16 shows the overall structure of the work being carried out to use HPXML data for developing dynamic energy models of the US housing stock.

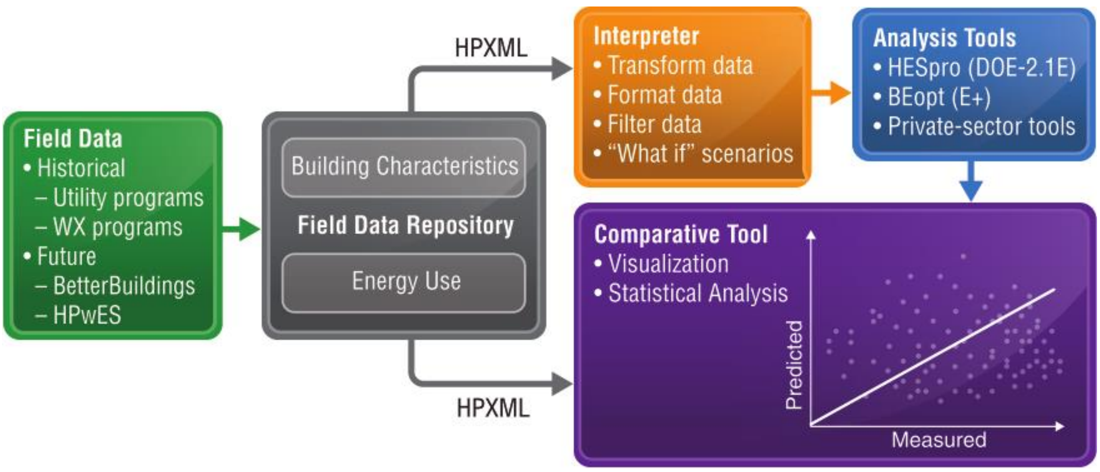


Figure 2.16 The translation process to convert HPXML files into various IDF formats (Polly et al., 2012)

The capacity of HPXML to store utility billing and building description details also provided an opportunity for developing standardised accuracy test for residential energy analysis tools (Neymark and Roberts, 2013). The authors identified the development of HPXML can enable software developers to create translators suitable for their input data scheme for efficient access to data. Such translators can facilitate the possibility of modelling whole building stock using dynamic energy simulation software and implement the standardised software accuracy test to translated data.

The work on developing translators for different software was ongoing at the time of writing this thesis. The work is being carried out within a working group which includes modelling expert from different organisations and software developers. The work presented in this thesis is the only contributor to this working group which is based outside US and provides an international insight into possibility of developing a worldwide building performance data repository which could be used for simulation purposes.

2.7. Summary

This chapter presented a review of the literature and completes objective 1 (*Identify and review literature on the modelling approaches that could be used to forecast energy use and* CO_2 *emissions in the UK dwellings, and perform a critical analysis of the work that has been undertaken to utilize available reduced data for energy modelling purposes*). The chapter presented a critical analysis of UK based domestic energy and emission models. The main application of all models is common as they are all used as policy decision making tools. However, the models are varied in terms of their output levels, extent of stock disaggregation, and scenarios analysed. These models have been developed since early 1990s and each model was criticized by its successor and by more recent researchers due to a number of limitations:

- All the models have been criticised for their low level of transparency. The model transparency, in terms of the architecture and data sources, is one of the main issues that need to be addressed in future models. The RdDEM model described in this thesis is an effort to remove all the ambiguities observed in the previous modelling practices by clearly describing the employed dataset, modelling methodologies including zoning and geometrical details, and model outputs.

- These models are not capable of taking into consideration the complex, interdependencies, and dynamic nature of the energy consumption and carbon emission. The RdDEM model described in this thesis employs a dynamic energy simulation engine, instead of steady-state BREDEM engine used by previous modelling exercises, enabling the model to capture transient and dynamic behaviours in the dwellings.

- The uniformity of the assumptions made by the models result in systematic errors that could have negative consequences for energy policy making, and the targeting of energy efficiency measures. The RdDEM model described in this thesis introduces evidence-based decision-making procedures to handle zoning and geometry aspects of the dwellings. These procedures reduced the uniformity of assumptions considerably compared to previous modelling exercises.

Dynamic energy models developed for Canadian, US, Scottish and English housing stock were also described providing details on positive and negative attributes of each model:

- The Canadian model only considered single-detached and single-attached dwellings, and employed two energy modelling techniques: statistical and engineering. The model assumed only one thermal zone for main building parts, and the storeys of the main zone were combined into one thermal zone. The party wall was modelled as adiabatic wall neglecting the heat transfer between the two dwellings. The RdDEM model described in this thesis improves the Canadian model by introducing more detailed zoning configuration and also through modelling a non-adiabatic party wall which is capable of representing heat transfer effects through the wall.

- The US model was based on the aggregated cooling and heating loads with very simple water heating and lighting details. Only gas was included as the primary fuel source for space and water heating, even though electricity and other fuels are also used as a primary energy source.

- The Scottish model categorised the dwellings in terms of Thermodynamic Classes (TC) and Architecture Classes (AC). The model results were verified using detailed models of 5 real houses. A similar verification process was applied to the RdDEM model developed in this study.

- The English model used EnergyPlus and custom weather files from North East region of the UK. All the dwellings were assumed to have East/West orientation. The dwellings were modelled with SAP zoning. The RdDEM model described in this thesis also uses EnergyPlus as calculation engine but applies a floor zoning configuration to the dwellings model instead of SAP zoning.

The chapter concluded with identifying and describing the available data translators developed for the purpose of domestic dynamic energy modelling. The focus was on the translators which convert XML based data into various input data files for dynamic energy simulation software: gbXML and HPXML translators. Based on this analysis of the literature, and to address the shortcomings of other models, a new model (the RdDEM) is proposed as outlined in the next chapter.

3. OVERVIEW OF METHODS

3.1. Introduction

This chapter presents an overview of the methods used to develop the Reduced Data Dynamic Energy Model (RdDEM) of the UK dwellings, based on the findings from the literature review (Chapter 2) and in pursuit of Objectives 2 (*Identify a suitable dataset of UK dwellings to be used as the source of modelling data*), 3 (*Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation*) and 4 (*Develop and run a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*). The new modelling framework that was developed is shown in Figure 3.1. It takes existing data from Energy Performance Certificate datasets and converts them into files suitable for use in EnergyPlus dynamic energy simulation software. EnergyPlus was chosen because of its technical capability, ease of use (text input file), cost (free), and validated code (US Department of Energy, 2013).

Data preparation process and translation are described below, with extended details in Chapter 4 (Zoning and enhanced geometry), Chapter 5 (Equivalent construction materials and boundary conditions), and Chapter 6 (Translation, simulation and results).

The reduced data used to test this approach was from the DEFACTO (Digital Energy Feedback and Control Technology Optimisation) project (Mallaband et al., 2014) which is being carried out by Loughborough University from 2012 to 2018. The dataset included 165 semi-detached dwellings located in the Midlands region of the UK. The format of the reduced data was individual XML files for each dwelling, as is described in detail in section 3.2. This modelling dataset was run through a data preparation process in which modifications and enhancements were made to increase the level of detail to meet the requirements of dynamic energy simulation.

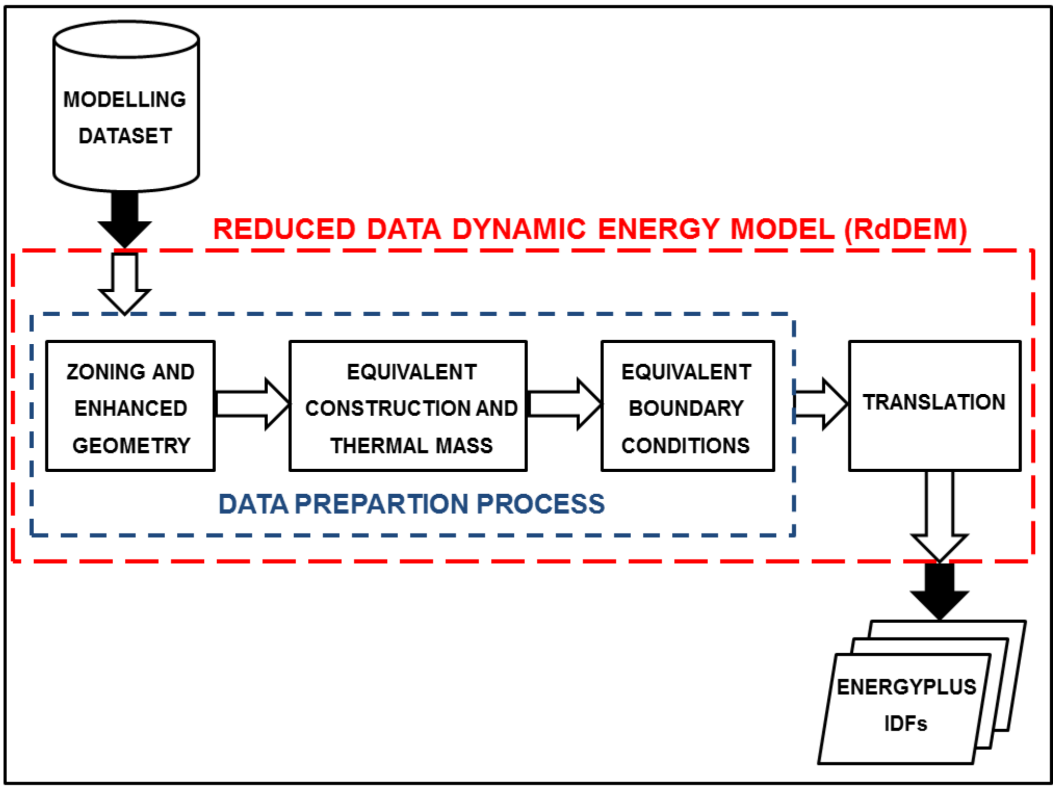


Figure 3.1 Overall structure and the modelling framework

The prepared data was called the 'Equivalent Data' as the nature of reduced data was kept intact, and only controlled modifications were made to facilitate dynamic energy simulation. The data preparation process was carried out in three steps:

i. Defining zoning and enhanced geometry,
ii. Defining equivalent construction and thermal mass, and
iii. Defining equivalent boundary conditions.

These three steps of developing equivalent data are described in section 3.3. The equivalent data was then run through a translation process which converted the equivalent data into the format required for the dynamic energy simulation. The translation process created individual IDFs for each dwelling in the dataset. The IDFs were then fed into the EnergyPlus engine and simulations were run. Description of the translation process and IDFs is presented in section 3.4. The translation process together with three steps of the data preparation process (as shown in Figure 3.1) formed the Reduced Data Dynamic Energy Model (RdDEM).

3.2. Modelling Dataset

The DEFACTO project investigates how the use of digital control and feedback technologies to enable reduction and management of energy use (Mallaband et al., 2014). The DEFACTO dataset describes semi-detached dwellings which are owner occupied and are located in the Midlands region of the UK. The reduced data were collected by professional home energy assessors for the purpose of creating Energy Performance Certificates (EPCs). EPCs are calculated using steady-state BREDEM (Dickson et al., 1996) based calculations as used in the Government's Reduced Data Standard Assessment Procedure (RdSAP). These reduced data are stored in individual XML files for each dwelling, as in the national EPC database (Watson, 2009).

The reduced data was stored under 'SAP Data' heading of the XML files (see APPENDIX C for example EPC XML File). The data described each dwelling with just enough details to enable RdSAP calculations (for more details see Section 2.2.2). The data had three main categories: geometrical dimensions of the dwellings, construction details and, heating and hot water systems.

The geometrical details available in the modelling dataset included: floor area, floor height, heat loss perimeter and party wall length for each floor of the dwellings and, roof area. The construction details included: construction age band, wall, roof and floor construction types, wall thickness, multiple and single glazing proportion and, number of extensions and conservatories. Where extensions existed, all construction and geometrical details were provided separately from the main dwelling. Details of heating and hot water systems, boiler type, heat emitter type, control type and fuel type were also included in the dataset.

In this research, 83 of the 165 dwellings described in the DEFACTO dataset were chosen to test the RdDEM approach. It was assumed that if the method was found to be appropriate for these dwellings, further work could be carried out to expand it to other dwellings. All the DEFACTO dwellings were semi-detached and located in the same geographical region but had very diverse characteristics, being constructed from before 1900 to 2012. This resulted in dwellings having very different layouts, construction types, materials, insulation levels and systems. Since such diversity of characteristics added further complexity to the modelling process, a subset of dwellings in the dataset was selected for this study. This subset will be referred to as ‘Modelling Dataset’ for the rest of this thesis. The modelling dataset was selected such that while reducing complications and obstacles in the dynamic simulation process, it would still be representative of common UK semi-detached dwellings.

The modelling dataset included most common age band and construction types in the dataset. In the DEFACTO dataset, 155 of the dwellings had one of ‘B’, ‘C’, ‘D’ or ‘E’ age bands and only 10 dwellings had other age bands (‘A’, ‘F’, ‘J’ or ’L’). These 10 dwellings were excluded from the modelling dataset.

The modelling dataset also excluded a number of dwellings based on their external wall construction type. 148 of the dwellings had either cavity or solid brick external walls. Only 7 dwellings had other external wall construction types (Timber frame, Sandstone or system built). These 7 dwellings were excluded from the modelling dataset and only dwellings with cavity and solid brick external walls were included. This round of shortlisting left the modelling dataset with 148 dwellings.

The majority of the dwellings in DEFACTO dataset had a pitched roof and the remaining had a ‘room in roof’. The dwellings with room in roofs were excluded from the modelling dataset which left 134 dwellings.

In the DEFACTO dataset, 92 dwellings had solid floor, 4 of which were insulated. Of remaining 42 dwellings, 41 had non-insulated suspended floor and only one had insulated suspended ground floor. The 5 dwellings with insulated ground floors were excluded leaving 129 dwellings in the modelling dataset.

Most of the remaining dwellings (122) had 100% double glazing, 4 had more than 90% double glazing, 2 had more than 70% double glazing and only one dwelling had 10% double glazing proportion. The dwellings with less than

100% double glazing proportion were excluded from the modelling dataset to allow a single fenestration type in all models.

The majority of houses in the dataset were two-storey and there were only 3, three-storey dwellings. The three-storey dwellings were excluded from the modelling dataset. The DEFACTO dataset also specified the number of extensions and conservatories for each dwelling. From the remaining 119 two storey dwellings in the dataset, 51 had no extensions, 54 had only one extension, 10 had two extensions, 3 had three extensions and one had 4 extensions. The dwellings with more than one extension were excluded from the modelling dataset. Dwellings with conservatories were also excluded from the modelling dataset to leave 85 dwellings.

All of these dwellings had a gas central heating boiler and radiators as the main heating and hot water system. The main heating control for dwellings in the modelling dataset was a boiler programmer with room thermostat. Only two dwellings had ‘TRVs and bypass’ as the main heating control and these were removed to leave the modelling dataset with 83 dwellings.

Having completed the shortlisting process, the modelling dataset included a simpler set of houses with which to test the RdDEM process. The modelling dataset was representative of many UK semi-detached dwellings with common age bands, construction types and systems. In the modelling dataset (Figure 3.2), 22 (27%) of dwellings had age band ‘B’, 20 (24%) had age band ‘C’, 17 (20%) had age band ‘D’ and 24 (29%) had age band ‘E’.

As Identified in the shortlisting process, only the dwellings with cavity and solid external wall constructions were included in the modelling dataset: 9 (11%) dwellings had cavity walls with no insulation, 50 (60%) had cavity walls with filled cavities and 24 (29) dwellings had solid walls with no insulation. Figure 3.3 shows the distribution of each external wall construction type in the modelling dataset.

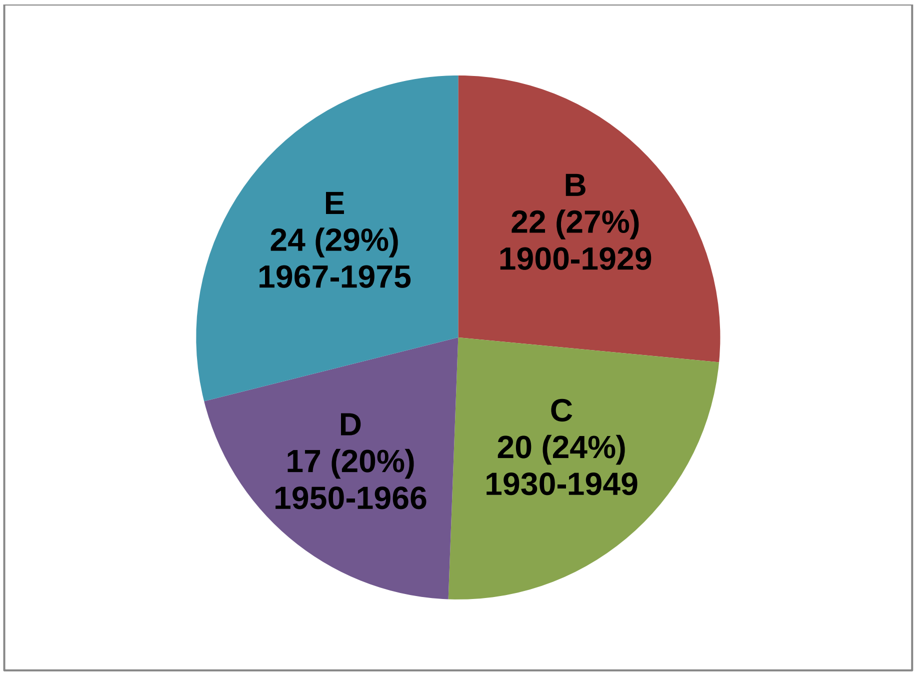


Figure 3.2 Dwellings distribution in the modelling dataset based on construction age band and the corresponding construction years

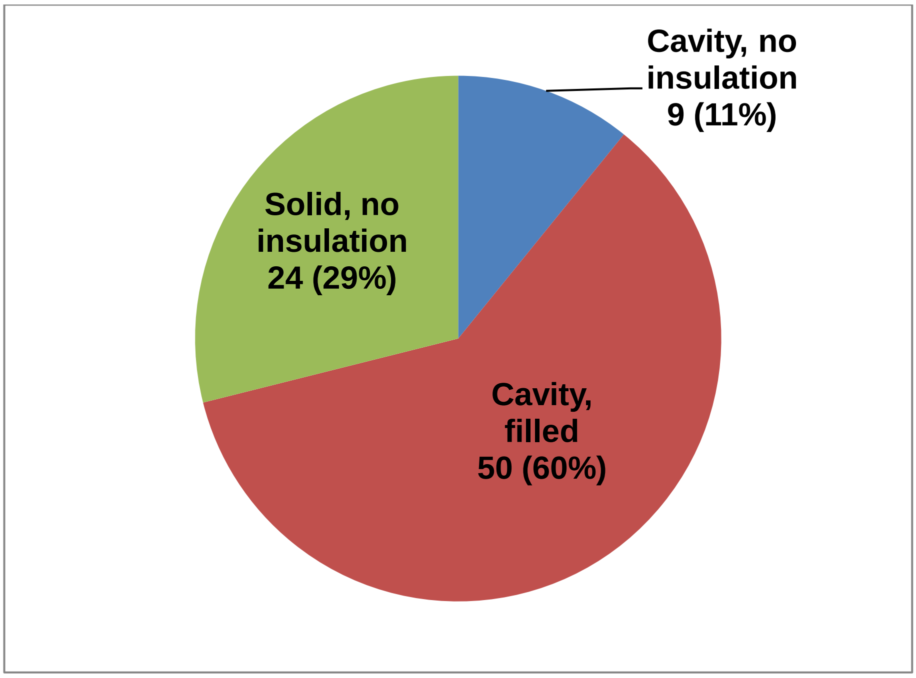


Figure 3.3 Dwellings distribution in the modelling dataset based on external wall construction

In the case of roof construction, only the dwellings with pitched roof were included in the modelling dataset: 62 dwellings had pitched roofs with known insulation, 16 had pitched roof with no insulation, 2 had pitched roofs with insulation at rafters and 3 dwellings had pitched roofs with unknown insulation level i.e. the assessor couldn't measure the loft insulation thickness. The dwellings with known level of roof insulation, had loft insulation thickness ranging from 50 mm to 300 mm (Figure 3.4): 2 (3%) had 50 mm loft insulation, 4 (6%) had 75 mm, 15 (25%) had 100 mm, 8 (13%) had 150 mm, 16 (26%) had 200 mm, 10 (16%) had 250 mm, 4 (6%) had 270 mm and 3 (5%) dwellings had 300 mm.

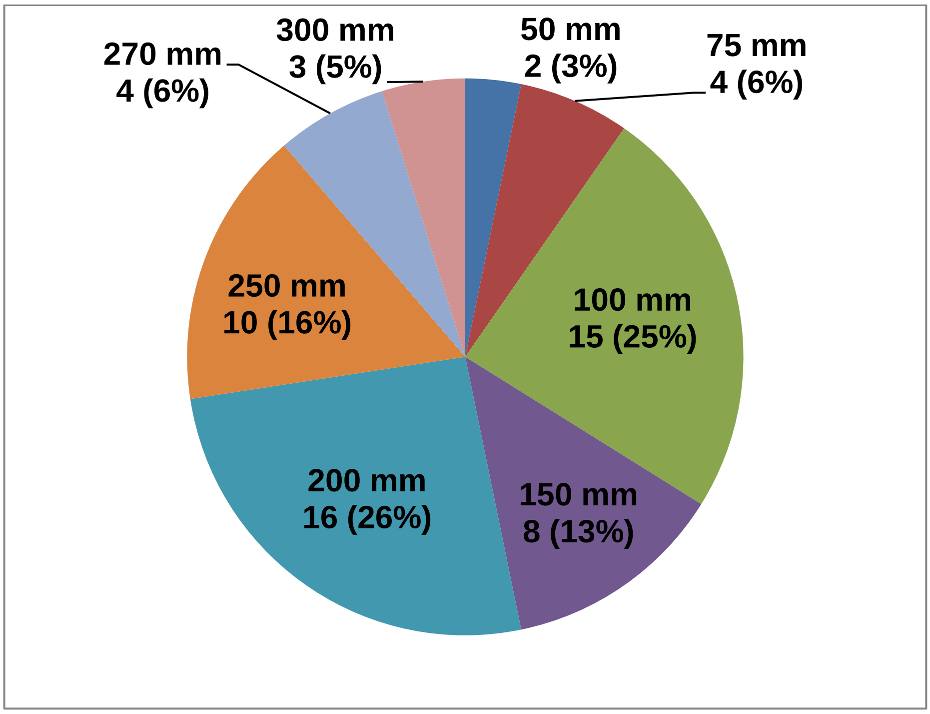


Figure 3.4 Dwellings distribution in the modelling dataset based on loft insulation thickness

Dwellings in the modelling dataset had two main ground floor constructions: 57 (69%) had solid ground floor and 26 (31%) had suspended ground floor. The dwellings in the modelling dataset had total floor area ranging from 62 m^2 to 191 m^2 (Figure 3.5): 54 (65%) dwellings had total floor area of 50-100 m^2, 21 (25%) had total floor area of 100-150 m^2 and 8 (10%) had total floor area of 150-200 m^2.

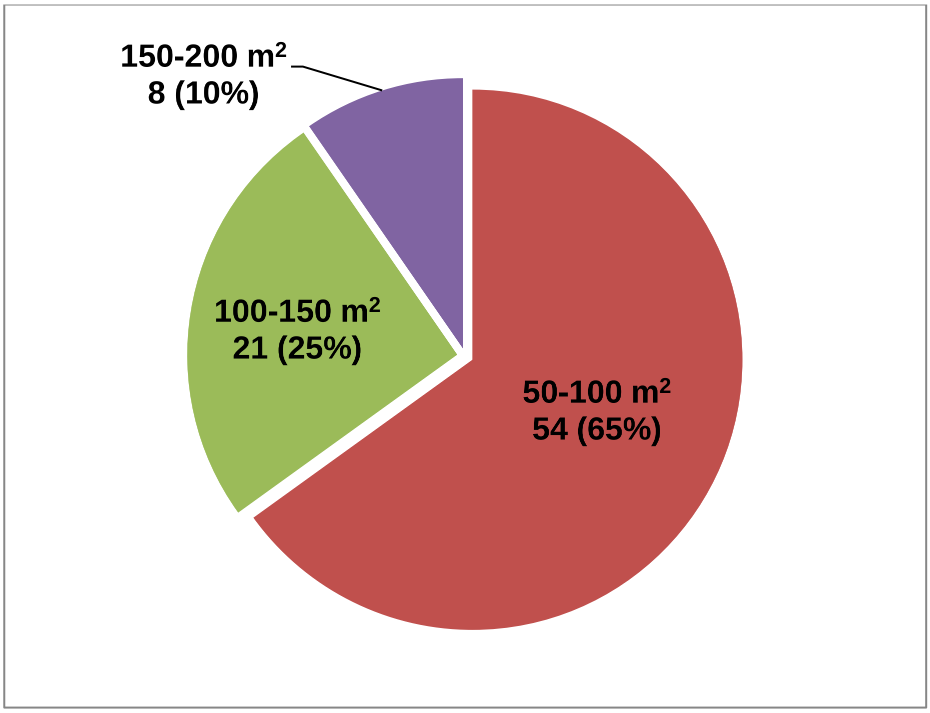


Figure 3.5 Dwellings distribution in the modelling dataset based on total floor area

3.3. Data Preparation Process

This section describes how the modelling dataset was modified and improved in order to prepare it for dynamic simulation as part of the RdDEM. The main areas of improvements in the modelling dataset were identified and each improvement was identified and tested:

- Zoning,
- Geometry,
- Construction materials and thermal mass,
- Internal boundary conditions,
- External boundary conditions (weather data and orientation).

These areas had a lack of required data to run dynamic simulations because they were not required for the SAP model, or were assumed to have a fixed value in SAP.

The enhancements to zoning and geometry required a coherent and detailed investigation of options which led to evolutions of the model. Whereas, the enhancements for internal boundary conditions, internal thermal mass, construction materials and weather data were simply based on SAP guidelines in order to achieve a set of equivalent input data for the dynamic energy simulation.

3.3.1. Zoning

In designing for heating ventilation and air conditioning systems (HVAC), a ‘zone’ is an area of a building in which temperature is controlled by one thermostat. The number of zones is based on the thermal demand of various building spaces. In dwellings, rooms with different heating set-point temperatures could be individual thermal zones. When modelling dwellings, the thermal requirements of different spaces should be considered, and thermal zones should be assigned accordingly.

SAP allows two zones to be implemented in the model: living area and the rest of the house. EnergyPlus has the capacity to implement as many thermal zones as required. Previous studies developing dynamic energy simulation of dwellings have justified their zoning strategy by highlighting the limitations of the dataset that was used.

In the Canadian Residential Energy End-use Model (CREEM) developed by Farahbakhsh, Ugursal and Fung (1998), which used dynamic energy simulation to investigate the impact of various carbon reduction strategies (see Section 2.4.3); all the habitable rooms in dwellings were assigned to a single thermal zone. The He et al. Model developed by He, Lee, Taylor, Firth and Lomas (2014), on the other hand, followed the SAP approach and considered two zones, separating the living area from the rest of the house (see Section 2.4.3). These authors justified using their preferred zoning strategy by highlighting the lack of geometry information in the original dataset but without presenting any detail on the impact of such a zoning strategy on the predictions of the model.

To determine the optimum number of zones to be modelled, three possible zoning strategies, with varying number and configuration of zones, were identified and a zoning study was carried out to investigate each strategy.

In the zoning study, a single semi-detached dwelling was modelled three times with exactly the same physical and thermal characteristics but varying the zoning strategy in each model:

i. Single zone strategy: where a single zone was assigned to the whole dwelling,

ii. Floor zoning: where two zones were considered - ground floor and first floor, and

iii. SAP zoning: where two zones were considered - living area and the rest of the dwelling.

The predictions of each model were compared to a reference model, where every habitable room in the dwelling was modelled as an individual thermal zone, giving a total number of nine zones to the model. The 'Reference Model' is described in detail in Section 4.2. The energy demand and internal temperature predictions of each model were compared to the predictions of the reference model and the most suitable zoning strategy was identified and then used in the RdDEM. The detailed description of zoning strategy models, their results and outcomes of the study is provided in Section 4.3.

3.3.2. Geometry

Building geometry is an important aspect of energy models: heat loss through fabric and ventilation is highly dependent on building geometry information. The energy balance between heat loss from the building and the heat gains into the building identifies the amount of required space heating energy for maintaining desired thermal conditions. As a result, a very important step in modelling energy performance of buildings is to understand geometry details and to implement those details in the model. The modelled geometry should be capable of representing the actual heat loss through building fabric.

The (reduced data) modelling dataset provided a limited amount of information on building geometry:

- floor area (m^2),
- floor height (m),
- exposed (heat loss) perimeter (m), and
- length of the party wall (m)

Floor area was measured from inner surface of external walls, floor height was measured from the floor surface to the ceiling surface, exposed perimeter was the total length of the external wall dividing the dwelling floor from the external environment or from an unheated adjoining space and, party wall length identified length of the wall separating two adjacent semi-detached dwellings.

These details were provided for each floor of the buildings in the modelling dataset and were intended for use by SAP to calculate the heat loss from the building fabric. However, a dynamic energy model of the dwellings requires full three-dimensional geometry. Hence, a methodology was needed to develop this geometry while retaining the heat loss areas using the limited details in the modelling dataset.

For the RdDEM, the available data was used to create a 3-dimensional rectangular geometry which maintained the limited details given in the modelling dataset. The methodology that was developed used the floor areas, heights, exposed perimeters and party wall lengths of each dwelling to create three-dimensional geometry for a rectangular building. The methodology was further developed to include extensions. The resultant geometry was still rectangular one, with correct party wall length, extension and main building exposed perimeter and correct floor area.

The RdDEM methodology was tested on a reduced data version of the 'Reference Model' and predictions were compared to the model which used all of the information in the 'Reference Model'. Ultimately, it was possible to successfully recreate representative three-dimensional geometry from the reduced data. All details and results are presented in Section 4.4.

3.3.3. Equivalent Construction Materials

The modelling dataset only included the construction type of the external wall, roof and ground floor. There was no further information on construction materials or corresponding U-values. Hence, an equivalent set of construction materials were developed for the RdDEM.

The equivalent construction materials for external walls were created such that the overall U-value of the walls matched the given values in Table S6 of SAP (SAP, 2012). Table S6 provides the external wall U-values based on wall type and dwellings' age band for houses located in England and Wales. The dwellings in the modelling dataset had three external wall types and belong to four age bands. Table 3.1 shows the relevant part of Table S6 for the dwellings in modelling dataset.

Table 3.1 Corresponding U-values (W/m^{2}K) of the wall types specified in the dataset based on dwellings' age band (re-created from Table S6 SAP 2012 (SAP, 2012))

Wall type	**Age band**			
	B	**C**	**D**	**E**
Solid brick as built	2.1	2.1	2.1	1.7
Cavity as built	1.6	1.6	1.6	1.6
Filled cavity	0.5	0.5	0.5	0.5

As seen in Table 3.1 there are four different U-values for the external walls of the dwellings in the modelling dataset. Hence, four sets of construction materials were required:

i. Solid brick wall with U-value of 2.1 W/m^{2}K for dwellings with age bands ‘B’, ‘C’ and ‘D’,

ii. Solid brick wall with U-value of 1.7 W/m^{2}K for dwellings with age band ‘E’,

iii. Cavity wall with U-value of 1.6 W/m^{2}K for dwellings with age bands ‘B’, ‘C’, ‘D’ and ‘E’; and

iv. Filled cavity wall with U-value of 0.5 W/m^{2}K for dwellings with age bands ‘B’, ‘C’, ‘D’ and ‘E’.

All of the dwellings in the modelling dataset had pitched roof with no or some insulation. A single construction type was used for all dwellings but with varying insulation levels. For the dwellings with known insulation thickness, the roofs were modelled such that they achieved the suggested U-values in Table S9 SAP 2012 (SAP, 2012): 2.3 W/m^{2}K for roofs with no roof insulation and U-values between 0.68 W/m^{2}K and 0.14 W/m^{2}K for roof insulation thickness of 50 mm to 300 mm. For the dwellings with unknown roof insulation, Table S10 SAP 2012 (SAP, 2012) was used to provide the roof insulation thickness based on the dwelling’s age band.

All of the ground floors were modelled as solid ground floor such that the correct U-values were retained. To do so, the guidelines in Section S5.5 SAP 2012 (SAP, 2012) were followed to calculate U-values of suspended ground floors based on ground floor area and exposed perimeter. The corresponding U-value was then used to calculate the thickness of necessary insulation for an equivalent solid ground floor. Knowing the insulation thickness, an individual solid ground floor reflecting the U-value of each suspended ground floor in the dataset was modelled.

All dwellings in the modelling dataset had 100% double glazed windows. Hence, based on Table 6E SAP 2012 (SAP, 2012) a double glazed, air filled window with 6 mm gap and U-value of 3.1 W/m^{2}K was modelled for all the dwellings.

RdDEM modelled all of the semi-detached houses as stand-alone buildings, without the adjoining building. Hence, the models would look like a rectangular block with three external walls and one party wall (Figure 3.6). Therefore, a party wall construction was developed in order to capture the heat loss from this element.

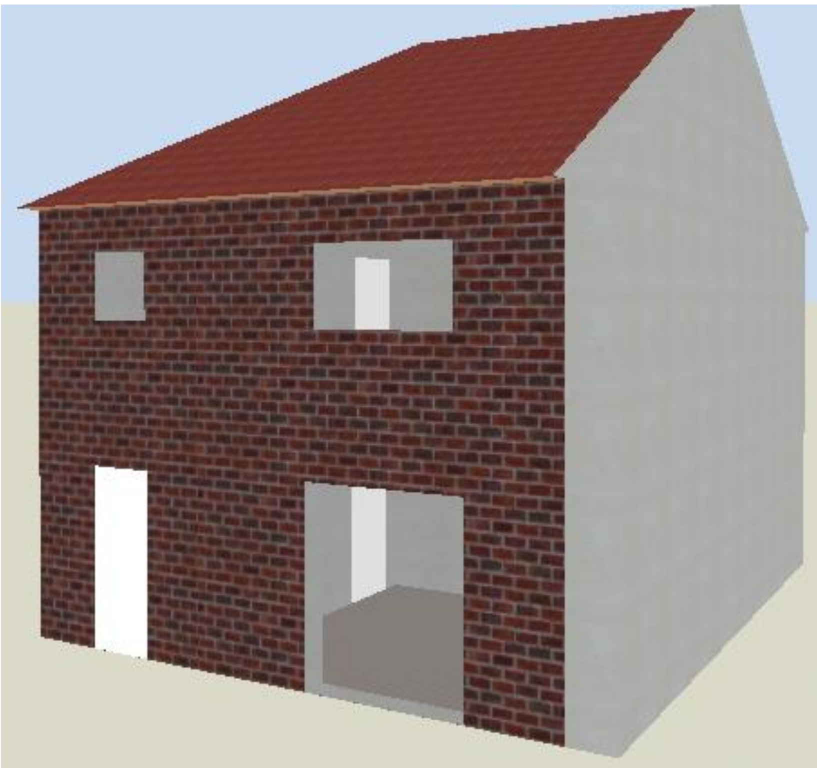


Figure 3.6 Party wall in semi-detached dwellings as modelled in DesignBuilder

In case of cavity wall construction, the party wall can provide a mechanism for heat loss via air movement within the cavity between lower floors and the loft space and between the cavity and outside. Hence, SAP 2012 suggests a U-value of 0.5 W/m^{2}K to account for this party wall bypass. In the case of solid wall construction, it is assumed that no heat transfer occurs across the party wall.

Where dwellings in the modelling dataset were of cavity construction, a single solid party wall with a U-value of 0.5 W/m^{2}K was modelled by the RdDEM. In the case of dwellings with solid wall construction, the party wall was set to be adiabatic and a component block (shown in grey in Figure 3.6) was added to shade it from incident solar radiation.

In creating the equivalent construction materials for the RdDEM, thermal bridging was included following the guidelines in SAP 2012 by increasing the U-value of individual building elements by 0.15W/m^{2}K.

Detailed descriptions of the equivalent construction materials used in the RdDEM, and the related calculations, are provided in Section 5.2.

3.3.4. Thermal Mass

Thermal mass is the ability of building element to store and release heat. SAP defines a Thermal Mass Parameter as the sum of (area times heat capacity) over all construction elements divided by the total floor area (SAP, 2012). So, to calculate the thermal mass of dwellings it is necessary to know the area of each of the building element (walls, roofs, floors, etc) and their corresponding thermal heat capacity. In RdSAP, the overall thermal mass parameter of all existing dwellings is assumed to be 250 kJ/m^{2}K. This same convention was used in the RdDEM. A process to derive the thermal mass of the external elements of the building, from their equivalent constructions, was developed. This thermal mass value was then deducted from the overall value of 250 kJ/m^{2}K to find the additional thermal mass required to represent the internal walls. This is described fully in Section 5.2.5.

3.3.5. Internal Boundary Conditions

The internal boundary conditions in the RdDEM were designed to exactly match those in SAP to enable direct inter-model comparison. Internal heat gains from occupants, appliances, lighting and cooking were the same as defined in SAP 2012 Table 5 (SAP, 2012) for the typical gains. Where required, these gains were calculated based on the number of occupants using the SAP guidelines to calculate number of occupants from the dwellings' total floor area (see APPENDIX D for details).

For the heating system, the heating periods and set-point temperatures, for living room and rest of the dwellings, were as described in SAP 2012 Table 9 (SAP, 2012). Detailed descriptions of the calculations used to achieve internal gains, heating periods and heating temperatures are presented in APPENDIX D.

3.3.6. External Boundary Conditions: Weather Data and Orientation

To make the predictions from the RdDEM comparable to those from SAP, equivalent weather files were created. SAP uses monthly average values of the local regional weather for EPC calculations (SAP, 2012): monthly external temperatures are given in SAP 2012 Table U1, monthly wind speeds are given in SAP 2012 Table U2 and, monthly solar radiations on horizontal surfaces are given in SAP 2012 Table U3 (SAP, 2012).

An equivalent hourly weather file was created for the RdDEM that was based on the average values given in SAP 2012. To achieve this, "typical weather year" data from the International Weather for Energy Calculations (IWEC) (IWEC, 2001) were used. The IWEC data was available for different regions of UK. Since all dwellings in the dataset were located in Midlands region of the UK, the IWEC weather data for Birmingham was used as the basis for creating the equivalent SAP Midlands weather data.

The hourly data for external temperature, wind speed and solar radiation in IWEC Birmingham weather data was averaged for each month. Using the SAP average values for Midlands, a conversion factor for converting monthly averaged Birmingham weather data to SAP data was calculated for each of external temperature, wind speed and solar radiation monthly values. Then, all the hourly values in IWEC Birmingham weather file were multiplied by the corresponding conversion factor. In this way, an equivalent weather file which had the matching monthly average values to SAP Midlands weather data was created.

Due to unknown orientation of dwellings in the dataset, SAP orientation of East-West was used in modelling dataset dwellings. As a result, the main windows are located on East and West facing walls of the dwellings.

Detailed description of the calculations used to achieve monthly averages of external temperature, wind speed and solar radiation, and the resultant values in the equivalent weather file are presented in Section 5.3.

3.4. Translation of Data: The RdDEM Translator

A translator is a code script that converts a programme written in one programming language into functionally equivalent programme in a different programming language without losing the logical structure of the original programme. In this study, the translator was a piece of code script that converted the reduced data into input data file format required for EnergyPlus, without changing the characteristic nature of data. The RdDEM translator script was written in MATLAB R2015a software package to convert XML files in the dataset into EnergyPlus version 8.3.0 Input Data File (IDF). Both XML and EnergyPlus IDF are text based formats used to store data and could be accessed, read and modified by most of available text editors. MATLAB is an object-oriented programming software which has advantage over simple text editors in handling text based formats. MATLAB allowed storing XML files in form of MATLAB Structures while converting the data in XML format into EnergyPlus IDF. Use of MATLAB Structures provides flexibility in handling large datasets and speeds up the translation process.

In the translation process, there were two types of data which needed to be handled differently. The first set of data were exactly the same for all of the dwellings in the modelling dataset and therefore could be translated into the IDFs only once. This fixed set of data included: zoning details, a scalable rectangular geometrical layout, a full set of construction materials, heating systems and heating periods, simulation details, and weather data. The second set of data varied from dwelling to dwelling and needed to be translated individually for each dwelling. This varying set of data included: internal mass, geometry and internal boundary condition details.

The fixed data were identified and written to a template IDF (TIDF) that the translator then filled with the varying data for each dwelling. A detailed description of the TIDF, the RdDEM translator and the checks performed to ensure effective and robust function of translation process is provided in Section 6.2 and 6.3. The translation process was tested using the reference model with different levels of detail and different modelling strategies:

i. A detailed dynamic model created by hand in DesignBuilder.

ii. A manually reduced dynamic model created by hand in EnergyPlus.

iii. An automated reduced dynamic model in EnergyPlus, created using the RdDEM translator.

iv. A steady-state model, created by hand in SAP.

Results from four variants of the reference model were compared and presented in Section 6.3.

Having tested and verified the performance of RdDEM translator, a further study was carried out to verify the code script for the data preparation process. To do so, the RdDEM predictions of three of the dwellings from the modelling dataset were compared to more detailed DesignBuilder models' predictions of the same three dwellings. All of the results of the RdDEM translator and data preparation verification together with the RdDEM predictions are presented in Chapter 6.

3.5. Summary

This chapter provided an overview of the methods for developing the RdDEM. A suitable modelling dataset was identified from DEFACTO project, which completes objective 2 (*Identify a suitable dataset of UK dwellings to be used as the source of modelling data*). The modelling dataset is formed of EPC XML files which contain reduced data on 83 semi-detached dwellings located in the Midlands region of the UK. A new data preparation process was developed for defining zoning and enhanced geometry, defining equivalent construction and thermal mass and, defining equivalent boundary conditions. This data preparation process will be tested in Chapter 4 (Zoning and enhanced geometry) and Chapter 5 (Equivalent construction materials and boundary conditions) to complete objective 3 (*Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation*). Finally, the RdDEM was completed by defining a translation process in order to create EnergyPlus IDFs as detailed in Chapter 6, which completes objective 4 (*Develop and run a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*).

4. ZONING AND ENHANCED GEOMETRY

4.1. Introduction

The first step in the data preparation process of the RdDEM is to define the zoning and enhanced geometry of the building from its reduced data (see Section 3.1). This chapter describes the processes that were used to identify the most suitable zoning strategy and the best way to enhance the geometry in pursuit of Objectives 3 (*Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation*) and 4 (*Develop and run a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*). The chapter starts with describing the 'Reference Model' (Section 4.2). The reference model uses a fully detailed input dataset and provides a comparator for investigating the impact of different zoning strategies and geometry enhancement techniques on the model predictions. The various strategies were developed based on the reduced data available in the modelling dataset and the suitability of each strategy was investigated through comparison with the detailed reference model.

The process for choosing the most suitable zoning strategy is described in Section 4.3 and the process of developing the most suitable technique to enhance the geometry is explained in Section 4.4. An enhanced geometry modelling technique is developed based on the reduced geometry details available in the modelling dataset. The DesignBuilder software package version 4.6.0.015 (DesignBuilder, 2015) was used to create the reference models and all subsequent models required to test the strategies and techniques. This version of Design Builder uses EnergyPlus version 8.3.0. EnergyPlus (US Department of Energy, 2012) is a well-known and powerful multizone building simulation tool which has more international recognition to its competitors (including IES VE which is used mainly in the UK for developing EPCs for commercial buildings). Besides, EnergyPlus is an open source code which provides more flexibility in automating the data translation.

4.2. Reference Model

The reference model was a two storey, semi-detached house, as described by Allen and Pinney (1990) - hereafter referred to as A&P. This house was chosen as the reference model because it represented a built form similar to the houses in the dataset (i.e. semi-detached); and possessed sufficient details so that no major assumptions were required.

4.2.1. Building Geometry

Building geometry details are provided as floor plans and building elevations by A&P, and re-created in Figure 4.1. Ground floor has floor-to-ceiling height of 2.40 m while floor-to-ceiling height of the first floor is 2.30 m. Internal and external walls have thickness of 0.14 m and 0.29 m, respectively. House geometry was modelled in using the exact dimensions from A&P. As suggested by A&P, double height was applied to the stair cases by creating a hole on the ceiling of ground floor hall (floor of first floor landing). Size of the hole is not specified explicitly by A&P but based on floor plans it was derived to be 2.3 m long and 0.95 m wide.

Figure 4.1 Floor plans of the semi-detached A&P house (left: ground floor, right: first floor) and floor area (m^2) of each room (re-created from (Allen and Pinney, 1990))

Both of the houses in the semi-detached pair were modelled, with the attached house being a mirror image about the party wall. Figure 4.2 presents the front and back view of the semi-detached A&P house model in DesignBuilder. External walls and internal floors were created by extruding wall and floor thickness towards the inside of the building (DesignBuilder, 2015). Hence, in creating the house model, internal floor thickness (0.255m) was added to the first floor height and external walls' thickness (0.29 m) was added to each side of floor plans. The roof and ground floor were treated as separate building elements and their thickness was not included in the floor heights.

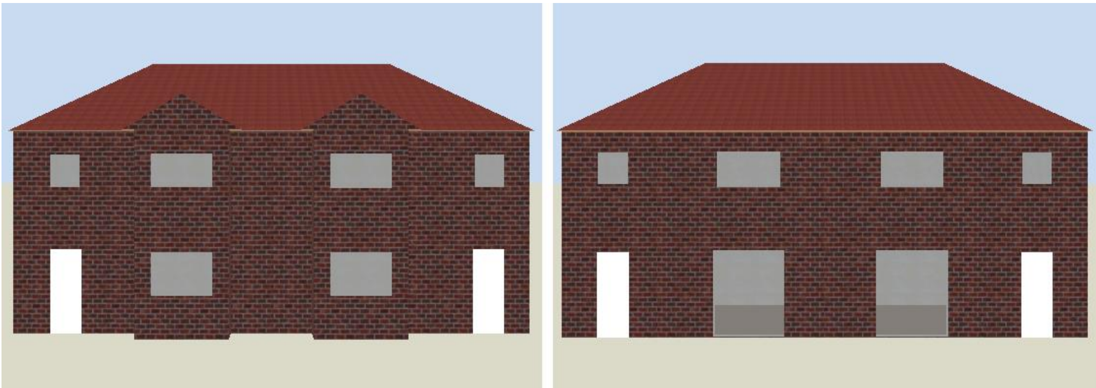


Figure 4.2 Front (left) and back (right) view of the semi-detached A&P house model in DesignBuilder

The width and height of each window was entered separately, including the frame according to the window corner definition in DesignBuilder (Figure 4.3). No information was given about window dividers in A&P; hence, no window dividers were modelled in the reference model.

Internal and external doors were modelled explicitly. The dwelling has two external doors, one in each of ground floor hall and kitchen and the front door has a window occupying one third of the door area. This window increases the door U-value from 2.5 W/m^2K to 3 W/m^2K. To simplify for DesignBuilder, the door was modelled as solid wood having a U-value of 3 W/m^2K to represent presence the same rate of heat transfer.

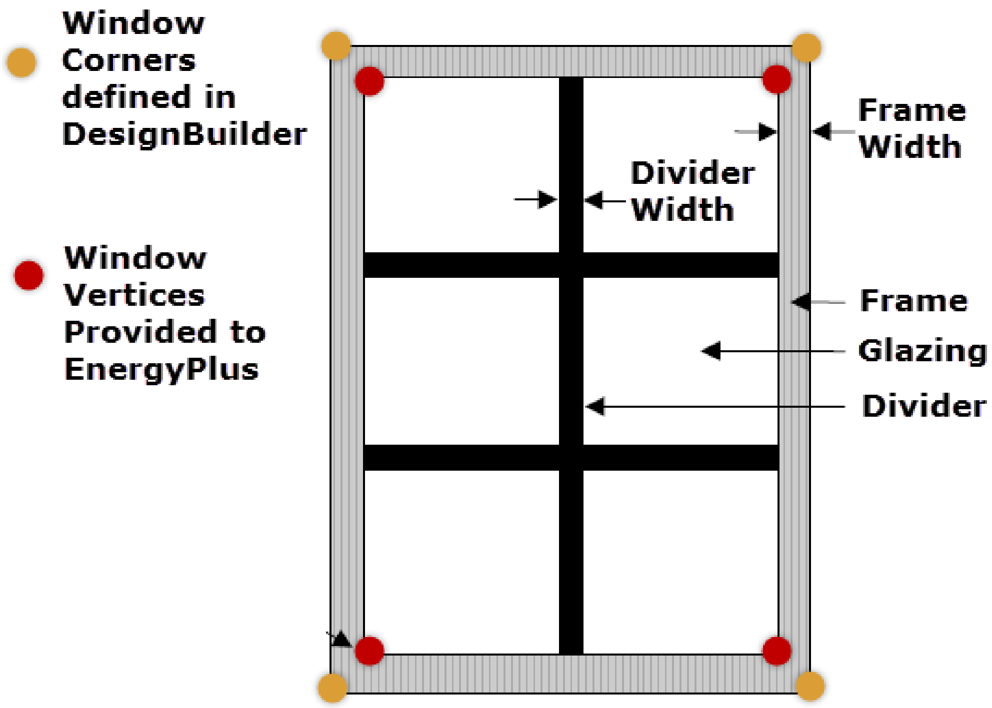


Figure 4.3 Window frame definition in DesignBuilder (DesignBuilder, 2015).

Note that dividers were not present in the reference model.

A&P do not provide any information on the dimensions of the roof: e.g. height, pitch and overhang. The roof of the reference model was modelled with 35° pitch, 0.3 m overhang and 2.5 m height to match the roof of the semi-detached house model in a similar study by Yilmaz et al. (2014). The roof was set to be a semi-exterior, unconditioned zone which was included in thermal calculations in the DesignBuilder.

4.2.2. Construction Materials

Construction details for the reference model, describing the materials used in each layer of the building elements and providing physical properties for these materials, were all taken from the A&P house description (Table 4.1).

The external wall type was a cavity wall with bricks on both sides (outer leaf brick has higher conductivity compared to inner leaf) and plaster on the inner side. Internal and party walls were constructed of only the inner leaf brick and plastered faces. Internal ceilings/floors were air cavity enclosed with timber and plasterboard layers. Roof was composed of roof tiles on outside with glass fibre quilt insulation and plasterboard.

A new glazing type with 6 mm clear float glass was created in DesignBuilder, using the simple glazing definition. All windows were single glazed with timber frame covering 30% of overall window area. The glazing had an overall U-value of 4.3 W/m^{2}K. Window frames and doors were composed of softwood with 0.03 m and 0.07 m thickness, respectively. The glazing has total solar transmission of 0.78 and light transmission of 0.88.

The building ground floor was modelled as a 100 mm concrete slab which matched the U-value of 0.74 W/m^{2}K given by A&P.

In EnergyPlus dynamic energy simulations, the average monthly ground surface temperatures under the building is used as the outside surface temperature for all surfaces adjacent to the ground. According to EnergyPlus documentation, the undisturbed ground temperatures calculated by EnergyPlus's weather converter program are often not appropriate for building heat loss calculations as these values are too extreme for the soil under a conditioned building (US Department of Energy, 2013). EnergyPlus documentation suggests using ground temperatures of 2°C below mean internal temperatures for large commercial buildings in the US. However, it does not suggest any method for calculating or estimating ground surface temperature for small residential buildings. Lstiburek (2008) suggests that a reasonable rule of thumb to estimate the ground surface temperature is to use the average annual ambient air temperature of that location. In absence of any other reference, the average annual ambient air temperature of 10°C was calculated from the weather file (Table 4.4) and used for all months of the year. Detailed description of the weather file is presented in section 4.2.6.

Table 4.1 Construction materials, each layer's thickness, physical properties of building elements (density, thermal conductivity and specific heat capacity

Building Element	Construction Materials as Described by A&P				
	Material	**Thickness (m)**	**Density (kg/m^3)**	**Thermal Conductivity (W/mK)**	**Specific Heat Capacity (J/kgK)**
External Walls	Plaster (medium density)	0.016	800	0.26	1000
	Brick (inner leaf)	0.105	1700	0.62	800
	cavity	0.065	N/A	N/A	N/A
	Brick (outer leaf)	0.105	1700	0.84	800
Internal and party Walls	Plaster (medium density)	0.016	800	0.26	1000
	Brick (inner leaf)	0.105	1700	0.62	800
	Plaster (medium density)	0.016	800	0.26	1000
Internal floors	Carpet	0.005	160	0.06	1000
	Timber	0.020	650	0.14	1200
	Cavity	0.200	N/A	N/A	N/A
	Plasterboard	0.010	950	0.16	840
Internal Ceiling	Timber	0.020	650	0.14	1200
	Cavity	0.200	N/A	N/A	N/A
	Plasterboard	0.010	950	0.16	840
Roof	Plasterboard	0.010	950	0.16	840
	Glass fibre quilt	0.105	250	0.04	840
	Roofing tiles	0.010	1900	0.84	800
Window	Glazing	0.006	2500	1.05	750
	Softwood (Frame)	0.03	230	0.12	2760
Doors	Softwood	0.07	230	0.12	2760
Ground Floor	Concrete slab	0.100	2400	0.16	880

4.2.3. Internal Gains

A&P gives the rates and timings of internal heat gains from occupants, cooking, lighting, refrigerator, television and hot water for each room (Table 4.2). Separate profiles were created in DesignBuilder for each of occupancy, appliances and lighting gains in each room in order to model the identical heat gains. Figure 4.4 shows occupancy heat gain profiles for each room. It can be seen that the living room is occupied for 6 hours in the evening, while the dining room and the kitchen are occupied for one hour in the morning for breakfast and two hours in the evening for dinner. Bedrooms 1 and 3 (children’s bedroom) are occupied for 12 hours and the main (parent’s) bedroom is occupied for 9 hours during night. The latent (40%) and sensible (60%) split of heat gains, given by A&P, were used for the metabolic and hot water gains.

Lighting gain profiles were created in DesignBuilder for individual rooms (Figure 4.5). No lighting gains are given for bedrooms as A&P consider that these rooms are occupied only for sleeping purpose. As seen in Figure 4.4 and Figure 4.5, lighting profiles coincide with occupancy gain profiles which show that rooms are lit only when they are occupied.

Table 4.2 A&P rates and times of occurrence of internal heat gains from occupants, cooking, lighting, refrigerator, television and hot water (re-created from (Allen and Pinney, 1990))

Room Type	**Internal Gains (W)**					
	Occupants	**Light**	**TV**	**Cooker**	**Fridge**	**Hot water**
Living room	17.0-23.0 (144)	17.0-23.0 (212)	17.0-18.0 (135) 20.0-22.0 (158)			
Dining room	08.0-09.0 (140) 18.0-20.0 (115)	08.0-09.0 (126) 18.0-20.0 (171)				
Kitchen	07.0-08.0 (84) 18.0-21.0 (84)	07.0-08.0 (56) 18.0-21.0 (56)		07.0-08.0 (1190) 18.0-21.0 (1700)	00.0-24.0 (60)	00.0-24.0 (77)
Bedroom 1	00.0-09.0 (38) 21.0-24.0 (38)					
Bedroom 2	00.0-08.0 (148) 23.0-24.0 (148)					
Bedroom 3	00.0-09.0 (38) 21.0-24.0 (38)					
Bathroom	07.0-08.0 (100) 17.0-18.0 (40) 21.0-23.0 (35)	07.0-08.0 (100) 17.0-18.0 (40) 21.0-23.0 (35)				00.0-24.0 (77)

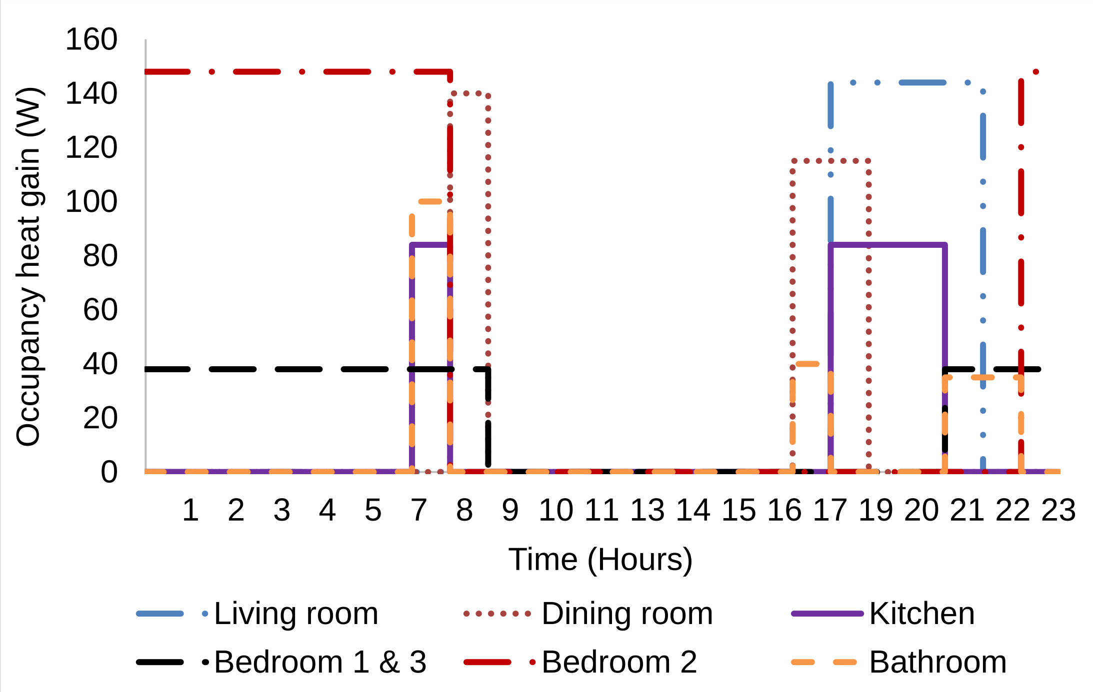


Figure 4.4 Occupancy gain profiles for individual rooms of A&P semi-detached house model

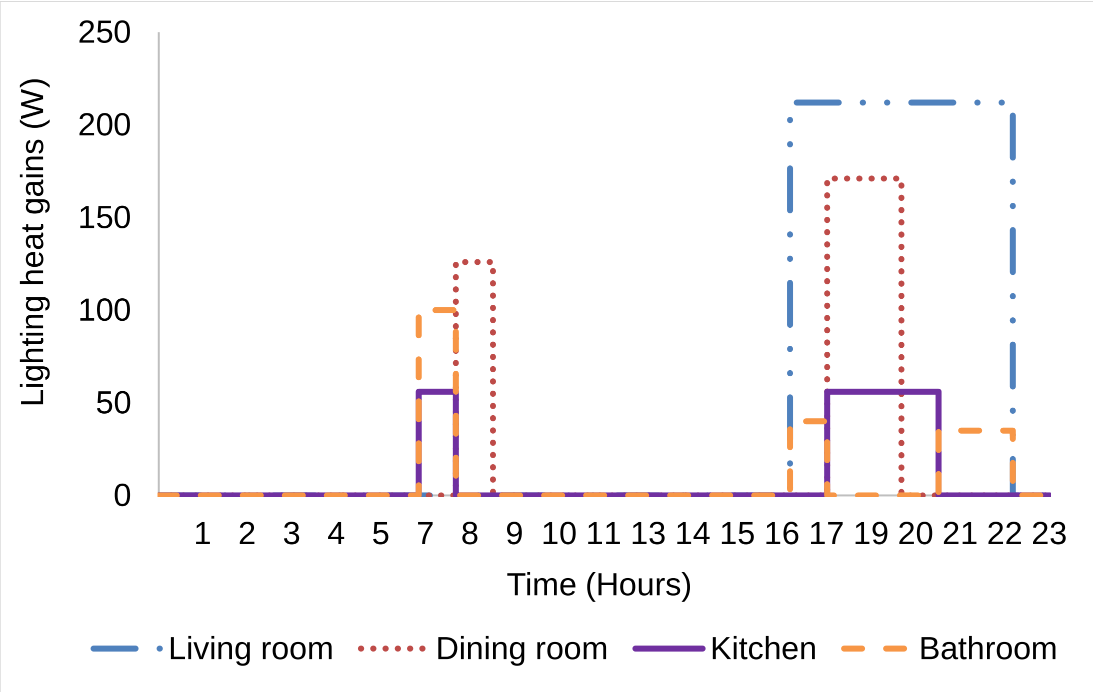


Figure 4.5 Lighting gain profiles for individual rooms of A&P semi-detached house model

4.2.4. Heating System

The heating system for the reference model comprised a central heating and radiators. A&P give no details on boiler type and so a regular natural gas boiler with 85% efficiency was used. These were modelled using DesignBuilder's detailed HVAC option (DesignBuilder, 2015).

The daily heating periods given by A&P are 07:00 to 09:00 and 16:00 to 23:00 for the heating season: 1st October to 31st May. This was modelled using the boiler operation availability schedule of DesignBuilder's circulating hot water loop data (DesignBuilder, 2015). The radiators availability schedules were set to be always 'ON'. There was no information available regarding the pipe run in A&P; and, all the pipes in the system were therefore assumed to be adiabatic in the reference model.

A&P provides heating set point temperatures for each room (Table 4.3) and so each room of the dwelling was modelled as a separate thermal zone which resulted in 9 different thermal zones. The zone type of the roof was set to a semi-exterior unconditioned, unoccupied and there was no heating or cooling assigned.

Table 4.3 Heating set-point temperature for individual rooms semi-detached dwelling (re-created from (Allen and Pinney, 1990))

Room type	**Heating set-point temperature**	**Room Type**	**Heating set-point temperature**
Living room	21°C	**Bedroom 1**	18°C
Dining room	21°C	**Bedroom 2**	18°C
Kitchen	18°C	**Bedroom 3**	18°C
Hall and Landings	16°C	**Bathroom**	22°C

4.2.5. Ventilation and Infiltration

A&P provide mean infiltration rates for each room and also a constant infiltration rate for the whole house as derived from whole house and single room measurements. These measurements were conducted in an unoccupied house with closed windows and A&P suggest that occupants will open and close windows in response to prevailing conditions and higher overall infiltration rates would be closer to reality; however, for the purpose of inter-model comparison and model verification they suggest a single infiltration rate of 0.7 ACH (Allen and Pinney, 1990). Hence, ventilation window opening was excluded from the reference model and fabric infiltration of 0.7 ACH was assigned to each room.

There was no information on the ventilation rate of the loft space in the A&P house description. The ventilation rates of loft spaces have been measured in a number of other studies. Dietz et al. (1986) conducted detail multi-zone PFT gas measurements in a number of homes in the US and reported 3 ACH as “typical” for ventilation rate of loft spaces. I’anson et al. (1982) measured loft space ventilation rate of 4.3 ACH in a middle terraced three-bedroom house using three tracer gases. Allinson (2007) modelled ventilated pitched roofs during low wind speed conditions in the UK and chose a ventilation rate of 2 ACH according to assumptions by Burch (1980). For the reference model, the same Burch assumption was employed and an infiltration rate of 2 ACH was assigned to the roof zone.

4.2.6. Orientation and Weather Data

A&P doesn’t specify any building orientation or external weather. The reduced form of SAP (RdSAP) assumes an East-West orientation for all dwellings (RdSAP, 2012) but Yilmaz et al. (2014) modelled the same A&P building and used South-North orientation. In order to compare the results of the reference model with the work of Yilmaz et al (2014) the same South-North orientation was used here with the front of building facing South.

The weather file was also the same as used by Yilmaz et al. (2014). It was CIBSE 'Kew67' and has been widely used in other modelling studies (Shorrock et al., 1996). This weather file is in (.csv) format and an EnergyPlus weather file format (.epw) version was created using the EnergyPlus custom weather data translation tool (EnergyPlus Weather Convertor, 2015). The Kew67 weather file is summarised in Table 4.4.

Table 4.4 Mean monthly temperature, wind speed and horizontal global radiation of Kew67 Example Weather Year (EWY) weather file

Month	EWY monthly mean Temperature (°C)	EWY monthly mean Wind speed (m/s)	EWY monthly mean horizontal global radiation (W/m^2)
Jan	4.4	4.9	27.5
Feb	4.1	3.9	39.2
Mar	6.4	4.2	99.6
Apr	9.1	3.8	142.5
May	12.9	3.9	194.2
Jun	15.5	3.5	205.4
Jul	15.5	3.7	159.2
Aug	15.5	3.1	162.5
Sep	13.1	3.1	112.5
Oct	9.4	2.7	75
Nov	8.7	3.5	29.2
Dec	4.9	4.8	19.6

4.2.7. Results of the Reference Model

The reference model was verified by comparing the space heating energy consumption to the result of 8,491 kWh/year reported by Yilmaz et al. (2014). The reference model predictions showed space heating energy consumption of 8,451kWh/year, which is only 1.5% lower. The small difference between the two predictions may be due to slightly different assumptions:

- Yilmaz et al. (2014) treated internal doors as internal walls while in this study internal doors were modelled explicitly. This affects the modelled thermal mass in as internal doors have a lower heat capacity.

- Yilmaz et al. (2014) modelled the party wall as an adiabatic wall, while in this study the neighbouring dwellings and party wall were modelled explicitly (see Section 4 and Figure 4.2).

- Yilmaz et al. (2014) did not provide details on infiltration rate of the roof space so it is not known if the same assumption of 2 ACH was used.

4.3. Zoning

This section describes the process of determining the most suitable zoning strategy for creating a model from reduced data in which room layout and dimensions are not given. Three simplifications of the thermal zoning were trialled to determine which simplification best reproduced the predictions of the reference model (where each room was modelled as an individual thermal zone).

4.3.1. Zoning Strategies

The first zoning strategy, 'SAP' zoning, employed the two zones defined by SAP (2012): the living area and the rest of the house. According to SAP (2012), living area is the room marked on a plan as the lounge or living room, or the largest public room, irrespective of usage by particular occupants. Hence, a thermal zone was assigned to the living room of the reference model (Figure 4.1) and all the remaining thermal zones were combined to create the second thermal zone in the model.

The second zoning strategy, 'Floor' zoning, was developed such that each floor of the house was a separate thermal zone. The third zoning strategy, 'Single' zoning, was developed by combining all the thermal zones in the reference model to create a single zone model

The three zoning strategies are illustrated by complexity in Figure 4.6. Although the 'Floor' and 'SAP' strategies have the same number of zones, 'SAP' zoning is geometrically more complex than 'Floor' zoning as the ground floor must be divided and the location of living room is not known in the modelling dataset. This also adds extra complexity in modelling internal gains and set-point temperatures.

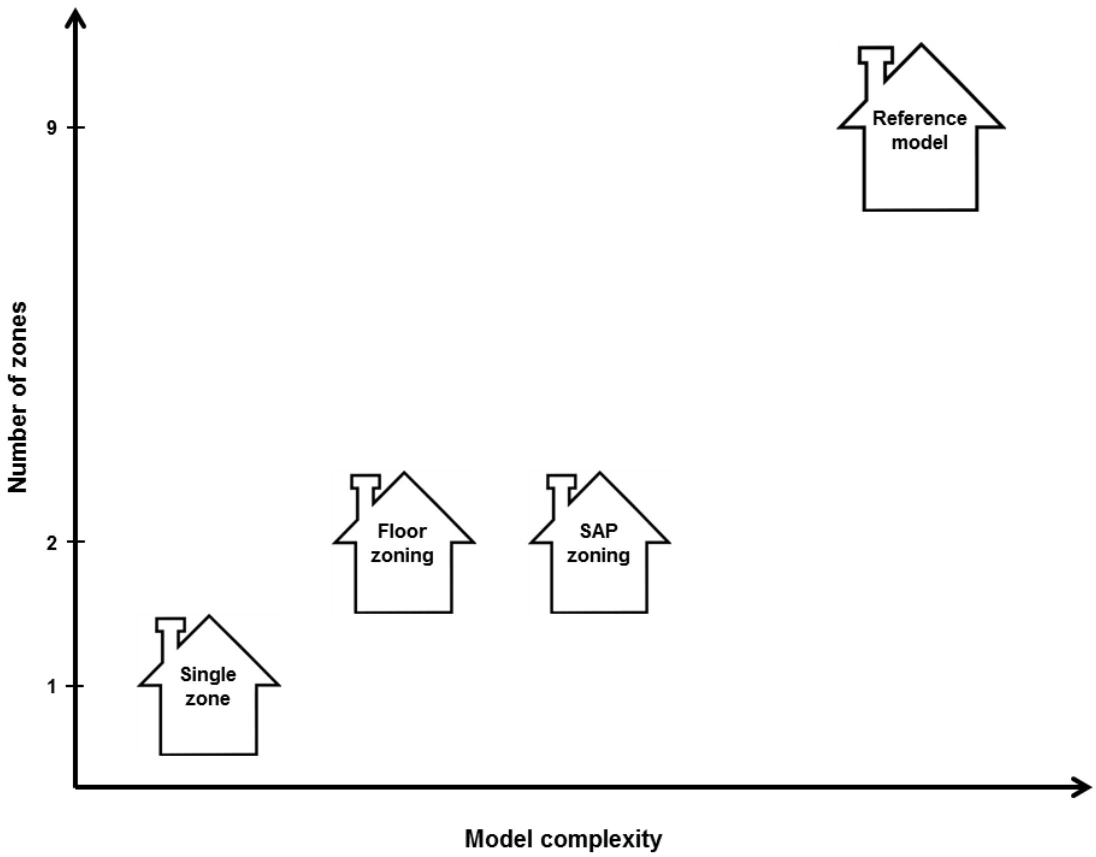


Figure 4.6 Zoning strategies, their level of complexity and number of zones

In applying each of the zoning strategies to the reference model, the internal gains assigned to each room (section 4.2.3) were combined and averaged for each zone by floor area. Heating set-point temperatures in each of the simplified zones were also averaged by floor area as summarised in Table 4.5. All other properties of the models, such as building geometry, construction materials, heating system, ventilation, infiltration, and orientation were independent of zoning strategy and were kept the same as the reference model.

Table 4.5 Heating set-points averaged over zone area in each zoning strategy

<table>
<tr><th>Room type</th><th>Reference</th><th colspan="2">SAP zoning</th><th colspan="2">Floor zoning</th><th>Single zone</th></tr>
<tr><td>Bedrooms</td><td>18°C</td><td rowspan="3">Living room</td><td rowspan="3">21°C</td><td rowspan="3">Ground floor</td><td rowspan="3">19.5°C</td><td rowspan="6">18.9°C</td></tr>
<tr><td>Living room</td><td>21°C</td></tr>
<tr><td>Dining room</td><td>21°C</td></tr>
<tr><td>Kitchen</td><td>18°C</td><td rowspan="3">Rest of the house</td><td rowspan="3">18.4°C</td><td rowspan="3">First floor</td><td rowspan="3">18.3°C</td></tr>
<tr><td>Bathroom</td><td>22°C</td></tr>
<tr><td>Hall/Landing</td><td>16°C</td></tr>
</table>

4.3.2. Simulation Results

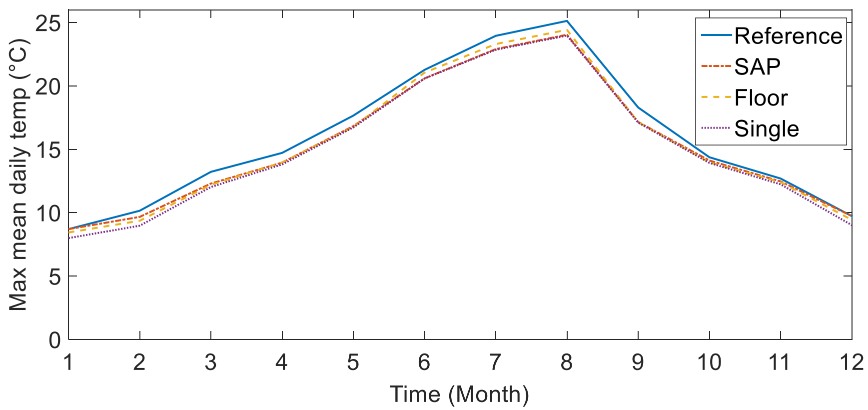
Two different simulations were run for the reference model and the models with each zoning strategy. This was so that the performance of the models could be compared in different conditions: summertime (May to September) with no internal gains, and wintertime (October to April), with heating and internal gains. This tested different aspects of the assumptions used for the zoning strategies.

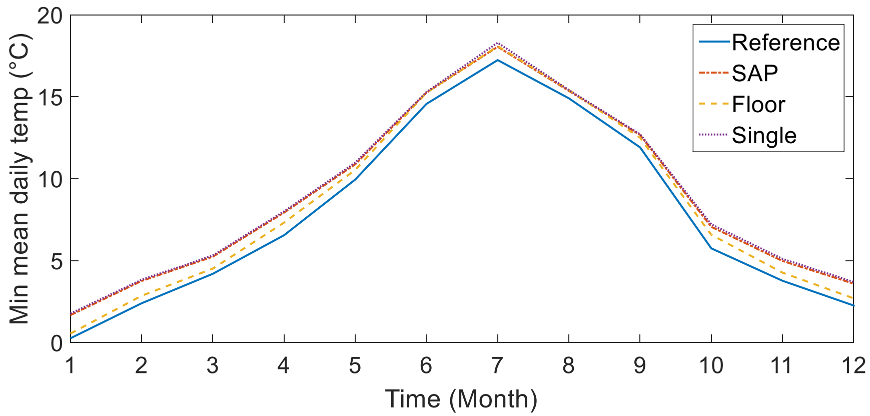
Internal temperature predictions from the three zoning strategies were compared to those from the reference model for summertime as seen in Figure 4.7. All three zoning strategies under-predicted maximum mean daily internal temperature by about 1°C in comparison with the reference model (Figure 4.7 (a)). Minimum mean daily internal temperature (Figure 4.7 (b)), is over-predicted by all three zoning strategies with ‘Floor’ zoning showing results slightly closer to the reference model.

Monthly mean internal temperature graphs (Figure 4.7 (c) and (d)) show a similar trend to the daily graphs and all zoning strategies predicting higher maximum monthly temperatures and lower minimum temperatures compared to the reference model. Figure 4.7 (c) shows ‘Floor’ zoning predicts maximum mean monthly internal temperatures better than the other zoning strategies. In all graphs presented in Figure 4.7 the ‘Single’ zoning strategy gives the poorest predictions. These results suggest that in hot summer weather conditions, all zoning strategies have the potential to underestimate the number of overheating hours compared to the reference model. However, ‘Floor’ zoning is marginally better for overheating risk assessment.

The simulation results for winter conditions (Figure 4.8) show a larger difference between predictions. All three zoning strategies predict lower maximum mean daily temperatures in the winter (Figure 4.8 (a)) with ‘SAP’ zoning giving closer predictions to the reference model. During the entire winter period, ‘SAP’ zoning predicts maximum mean daily temperatures within about 0.5°C of the reference model. All three zoning strategies predict warmer minimum mean daily temperatures compared to the reference model (Figure 4.8 (b)). The maximum and minimum mean monthly temperatures have similar trend to mean daily maximum and minimum values (Figure 4.8 (c) and (d)). ‘SAP’ zoning predicts maximum mean monthly temperatures that are closer to the reference model during heating season and, similarly to the summer results, ‘Single’ zoning gave the worst predictions compared to the reference model.

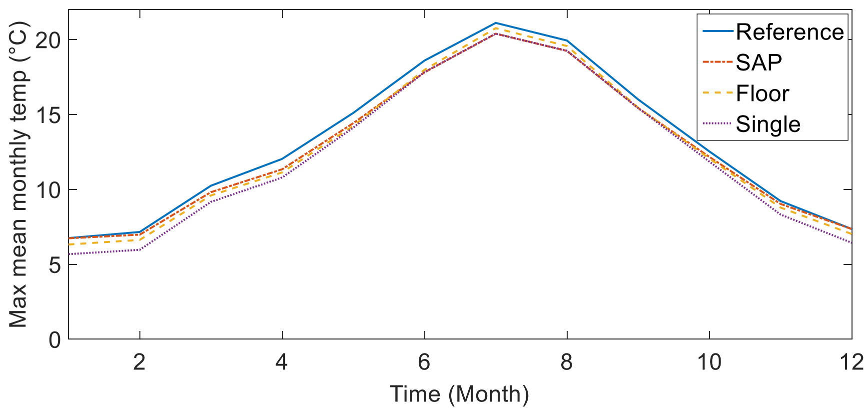
Overall, the ‘Single’ zone strategy was not suitable, ‘Floor’ zoning gave better predictions of internal temperatures in summer condition and ‘SAP’ zoning was better under winter conditions. In order to decide on which of these zoning strategies is more suitable, space heating demand predictions from each zoning strategy were also analysed.





Upper graph: (a), Lower graph: (c)

Upper graph: (b), Lower graph: (d)



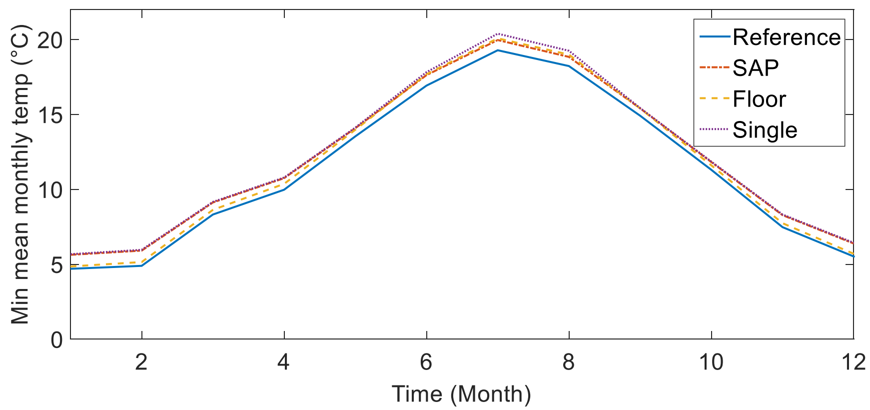


Figure 4.7 Internal temperatures of the three zoning strategies and the reference model under summer conditions. a) Maximum mean daily temperatures, b) minimum mean daily temperatures c) maximum mean monthly temperatures, d) minimum mean monthly temperatures

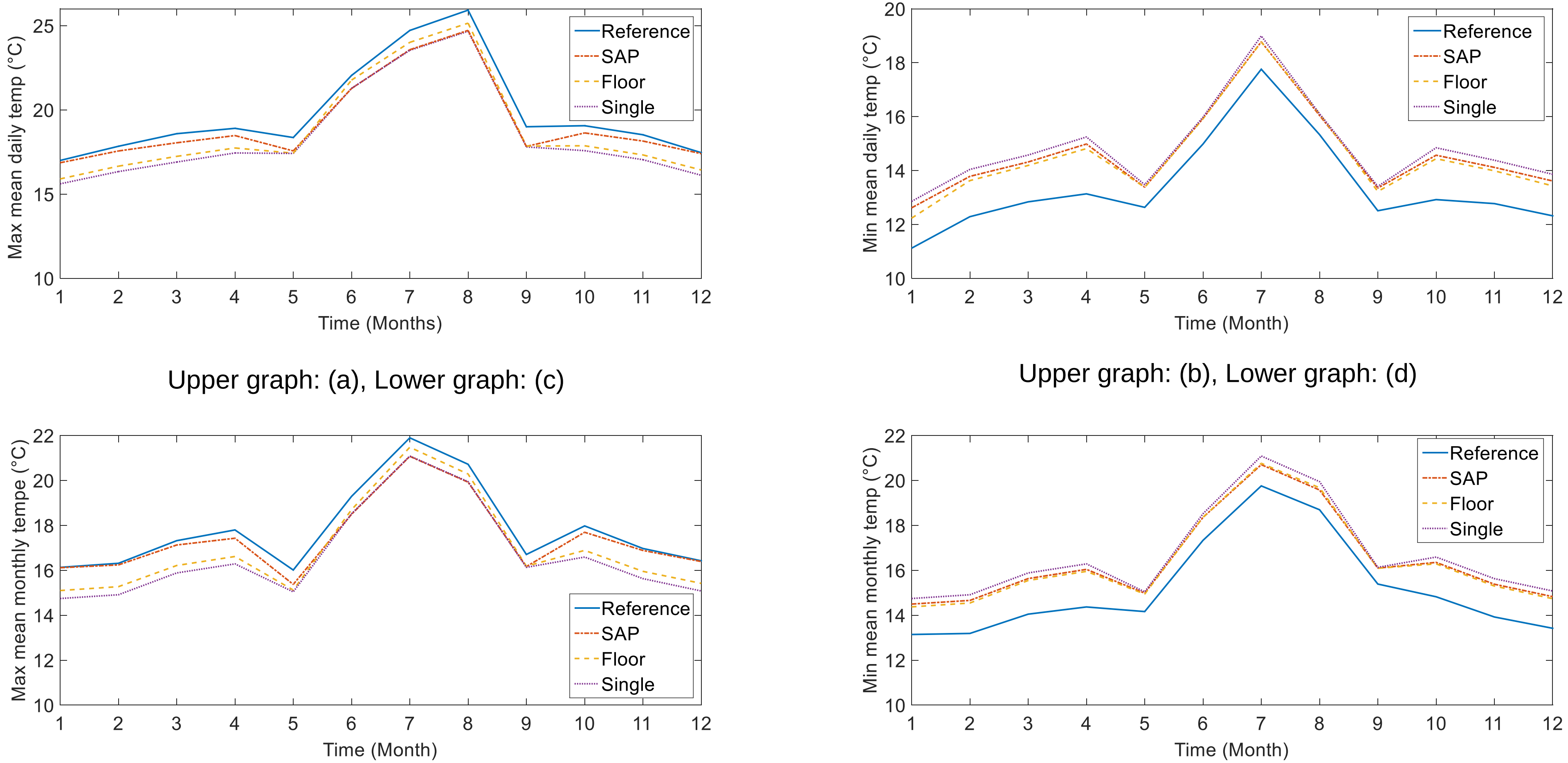


Figure 4.8 Internal temperatures of the three zoning strategies and the reference model under winter conditions. a) Maximum mean daily temperatures, b) minimum mean daily temperatures c) maximum mean monthly temperatures, d) minimum mean monthly temperatures

As seen in Figure 4.9, throughout the heating season 'SAP' zoning predicted the highest space heating demand each month while the results for 'Floor' zoning were closer to the reference model. A similar trend is observed in the annual space heating demand predictions shown in Table 4.6. Therefore, 'Floor' zoning was chosen as the most suitable strategy for implementation in the RdDEM.

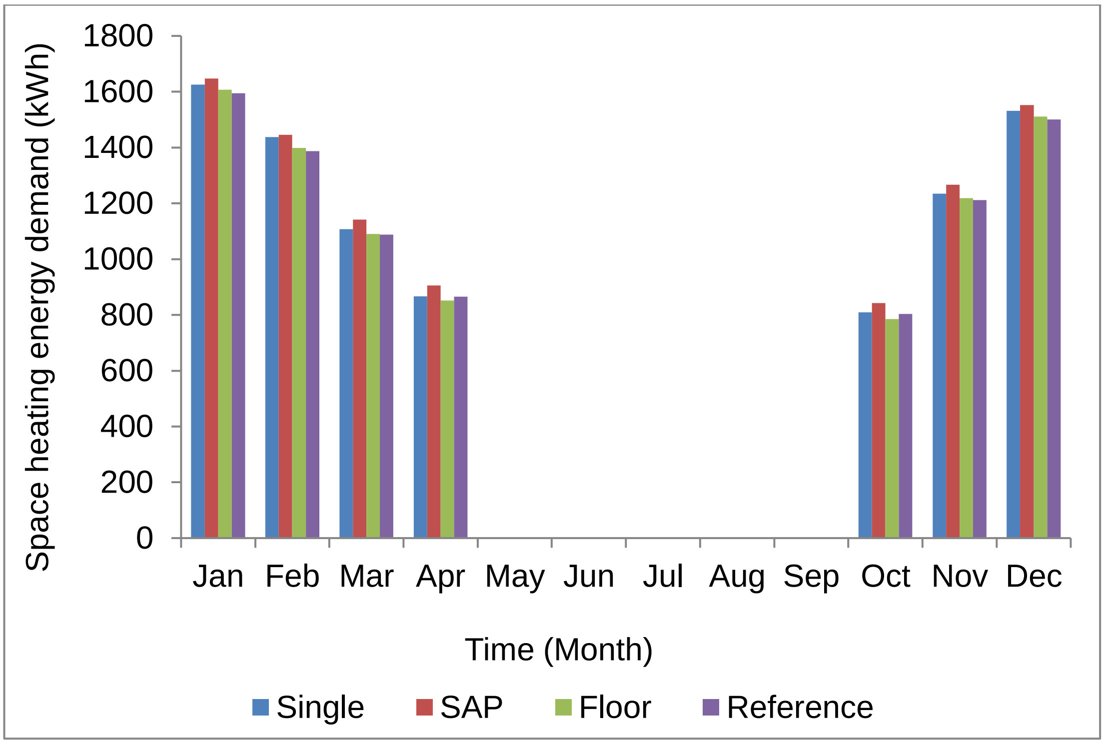


Figure 4.9 Monthly space heating energy demand of the three zoning strategies

Table 4.6 Space heating energy demand of the three zoning strategies compared to the reference model

Zoning strategy	**Space heating demand (kWh/year)**	**Difference to the reference model**
Single zone	8612	1.9%
SAP zoning	8802	4.0%
Floor zoning	8463	0.1%
Reference	8451	-

4.4. Enhanced Geometry

This section describes the process of choosing the best method to enhance the reduced geometry data available in the modelling dataset. The predictions were compared to those from the reference model and a method for including extensions was added.

4.4.1. Modelling Geometry

The modelling dataset includes numerical values for floor area, floor height, party wall length, and heat loss perimeter but there are no details of the three-dimensional geometry of the dwellings. The aim in enhancing the geometry was to preserve the values given, while creating the full three-dimensional geometry. Three possible potential layouts were considered for a hypothetical dwelling in the dataset (Figure 4.10). It can be seen that ratio of floor area to party wall length to heat loss perimeter differs in each of the layouts. There is not one simple geometry that will work in all cases.

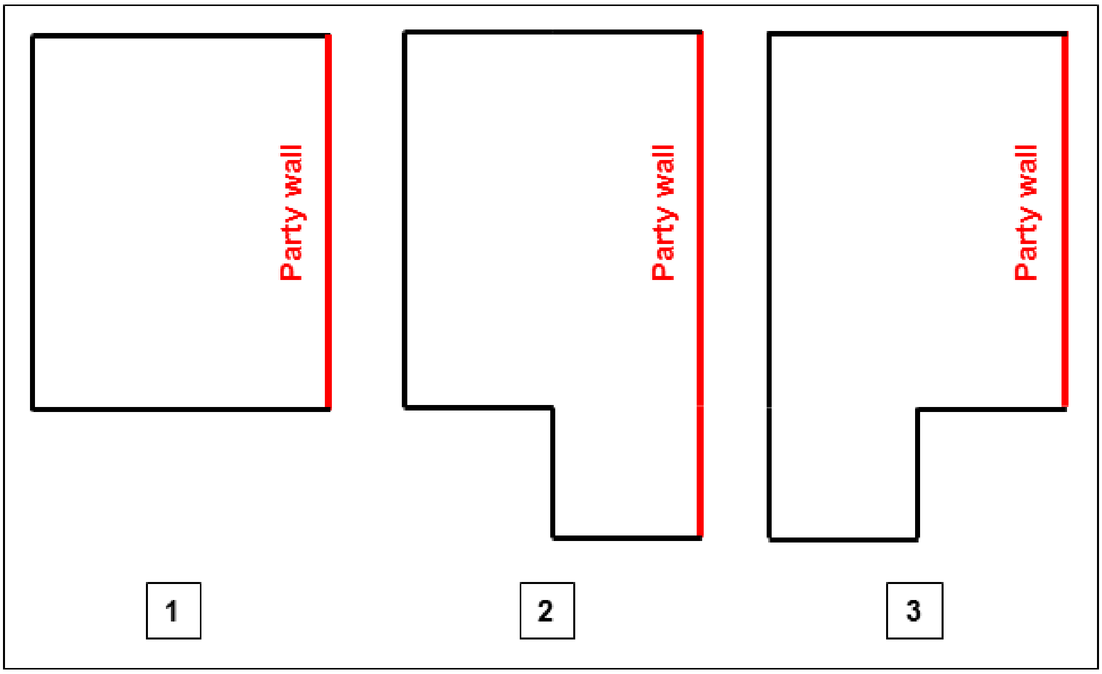


Figure 4.10 Possible geometry layouts and party wall location for the dwellings in the dataset

Figure 4.11 shows the methodology that was developed to enhance the geometry, which maintains the heat loss areas and preserves the reduced geometry details available in the dataset: party wall length, heat loss perimeter and floor height. The length of the created building is equal to the party wall length and its width is derived from the heat loss perimeter and party wall length (Equation 4.1).

$$W = \frac{P_{HL} - L_{PW}}{2} \tag{4.1}$$

Where 'W' is the width, 'P_{HL}' is the heat loss perimeter and 'L_{PW}' is the party wall length. Hence, the footprint area of the modelled building (A_{Model}) becomes (Equation 4.2):

$$A_{Model} = L_{PW} \times W \tag{4.2}$$

In this way heat loss perimeter, party wall length and floor height given in the dataset are all preserved. The resulting floor area was then checked against dwellings' actual floor area. If the actual building layout was rectangular (layout '1' in Figure 4.10), then the modelled building's floor area would be the same as the dwelling and no further processing would be necessary. However, if the actual building had non-rectangular layout (layouts '2' and '3' in Figure 4.10); two cases would be possible.

The first case is where the floor area of the actual dwelling is larger than that of the model (left branch of the graph in Figure 4.11). In this case the width (W) in the model was replaced with a dummy width (W_{dummy}) which was derived from the actual dwelling's area (A) and party wall length (L_{PW}) in Equation 4.3.

$$W_{dummy} = \frac{A}{L_{PW}} \tag{4.3}$$

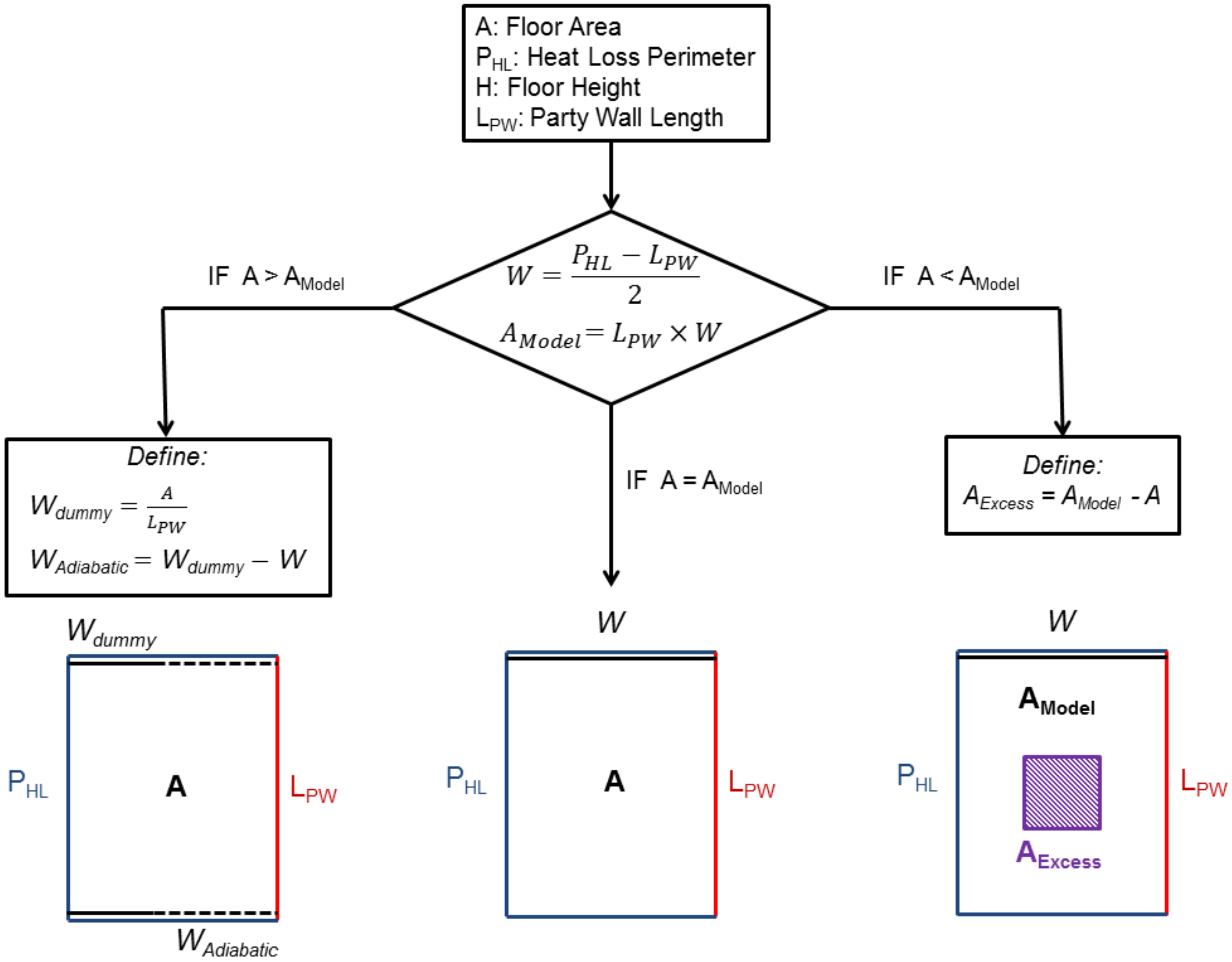


Figure 4.11 The methodology developed to model dwellings' geometry using the reduced data available in the modelling dataset

This preserves the floor area and party wall length but increase the heat loss perimeter. To preserve the heat loss perimeter, an adiabatic wall was added to the model with length (Equation 4.4):

$$W_{Adiabatic} = W_{dummy} - W \qquad 4.4$$

The second case is where the floor area of the model is larger than that of the actual dwelling (right branch of the graph in Figure 4.11). In this case a block with zero heat capacity was added to the middle of the modelled building to remove the excess floor area (A_{Excess}) and the additional volume of room air.

In applying this geometry enhancement methodology to the houses in the modelling dataset, it was found that the model always had a floor area larger or equal to the actual dwellings' floor area. Hence, the first case, where modelled area was smaller than the actual floor area, never happened in any of the modelling dataset houses.

A modified version of the reference model described in Section 4.2 was used to test the impact of modelling an L-shaped layout as a rectangular block. The reference model was extended to create an L-shaped layout. The width of the building was unchanged and an additional 25% was added to the floor area as an extension using DesignBuilder. As a result, individual window areas and internal wall areas were also increased by 25%. This 'geometry reference model' was created as a two zone model, separating ground and first floor following the findings of the zoning study in Section 4.3. The same total heat gains were used which resulted lower heat gains per square meter (due to the increased floor area). The lumped heat gain values were decreased to 1.6 W/m^2 and 0.9 W/m^2 for ground and first floors, respectively. The ground floor had heating set-point of 19.5°C and first floor had a heating set-point of 18.3°C. All other details were kept the same as the reference model.

To test the geometry enhancement method, the L-shaped layout of the geometry reference model was converted into a rectangular layout, following

Figure 4.11, and modelled in DesignBuilder as the ‘design geometry model’. Figure 4.12 shows the reference model, the geometry reference model and, the design geometry model. The geometry reference model had floor area of 110.5 m^2 and party wall length of 15.4 m. The design geometry model's length was kept as 15.4 m and its width was derived from Equation 4.1 as 8.6 m. The rectangular design geometry model had floor area of 132.4 m^2.

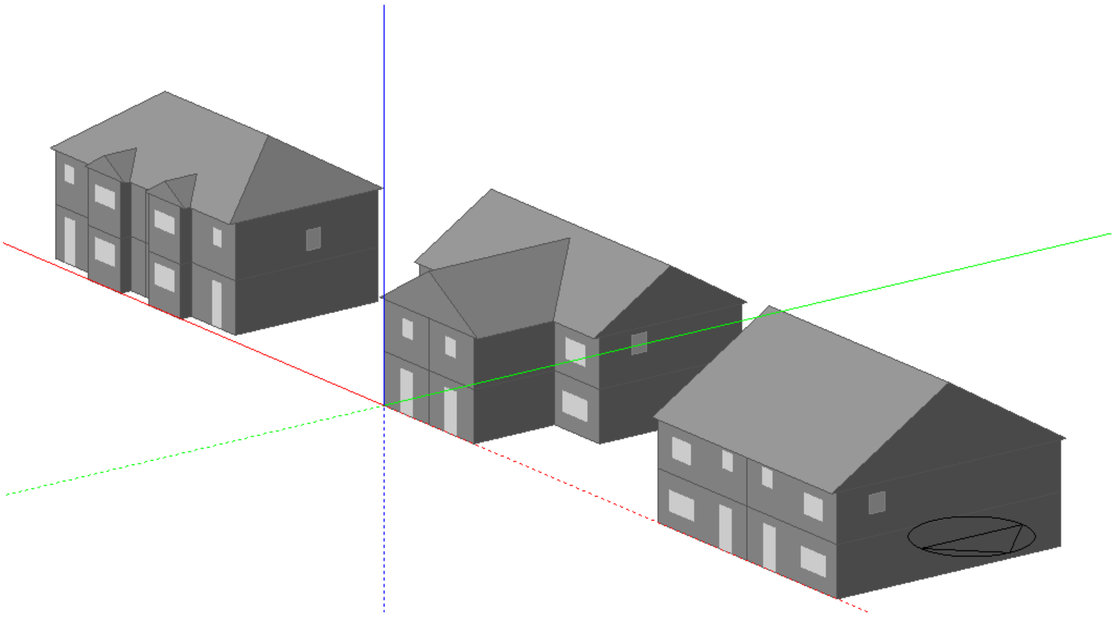


Figure 4.12 Left to right: The reference model, the reference geometry model and the design geometry model as created in DesigBuilder software package

Figure 4.13 shows the process of transforming the reference geometry model to design geometry model created in DesignBuilder. A block with zero heat capacity was added to the middle of rectangular model to remove the excess floor area of 21.9 m^2. The space inside the extra block was excluded from thermal and radiance daylighting simulations and therefore it had no impact on model predictions.

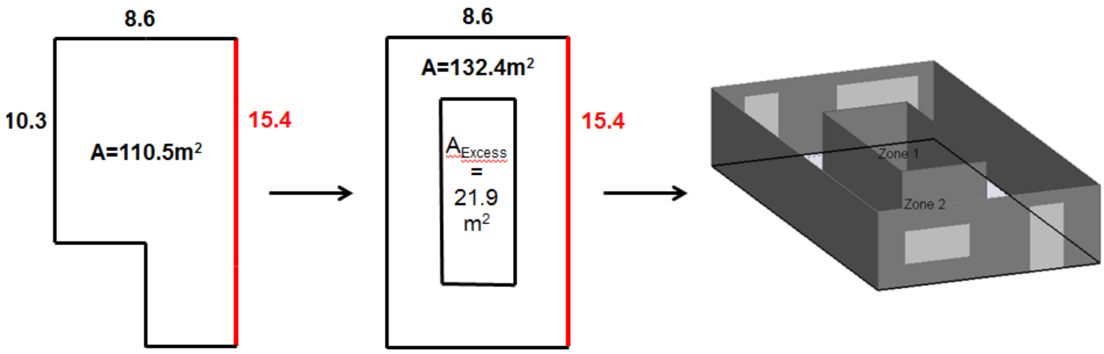


Figure 4.13 Transforming the reference geometry model to design geometry model

4.4.2. Simulation Results

Simulations were run for one complete year on the reference geometry and design geometry models. Predictions from the two models were compared to test the geometry enhancement method. Figure 4.14 shows the comparison of monthly space heating demand, infiltration and solar gain; and Figure 4.15 shows the comparison of daily and monthly internal temperatures. It can be seen that there is very close alignment between monthly infiltration and solar gains. The difference in space heating demand was less than 1% in all months and the annual space heating demand was within 3 kWh/year. The monthly difference between internal air temperature predictions (Figure 4.15) did not exceed 0.5°C. This close alignment of the predictions demonstrated that this method for enhancing the geometry was suitable for use in the RdDEM.

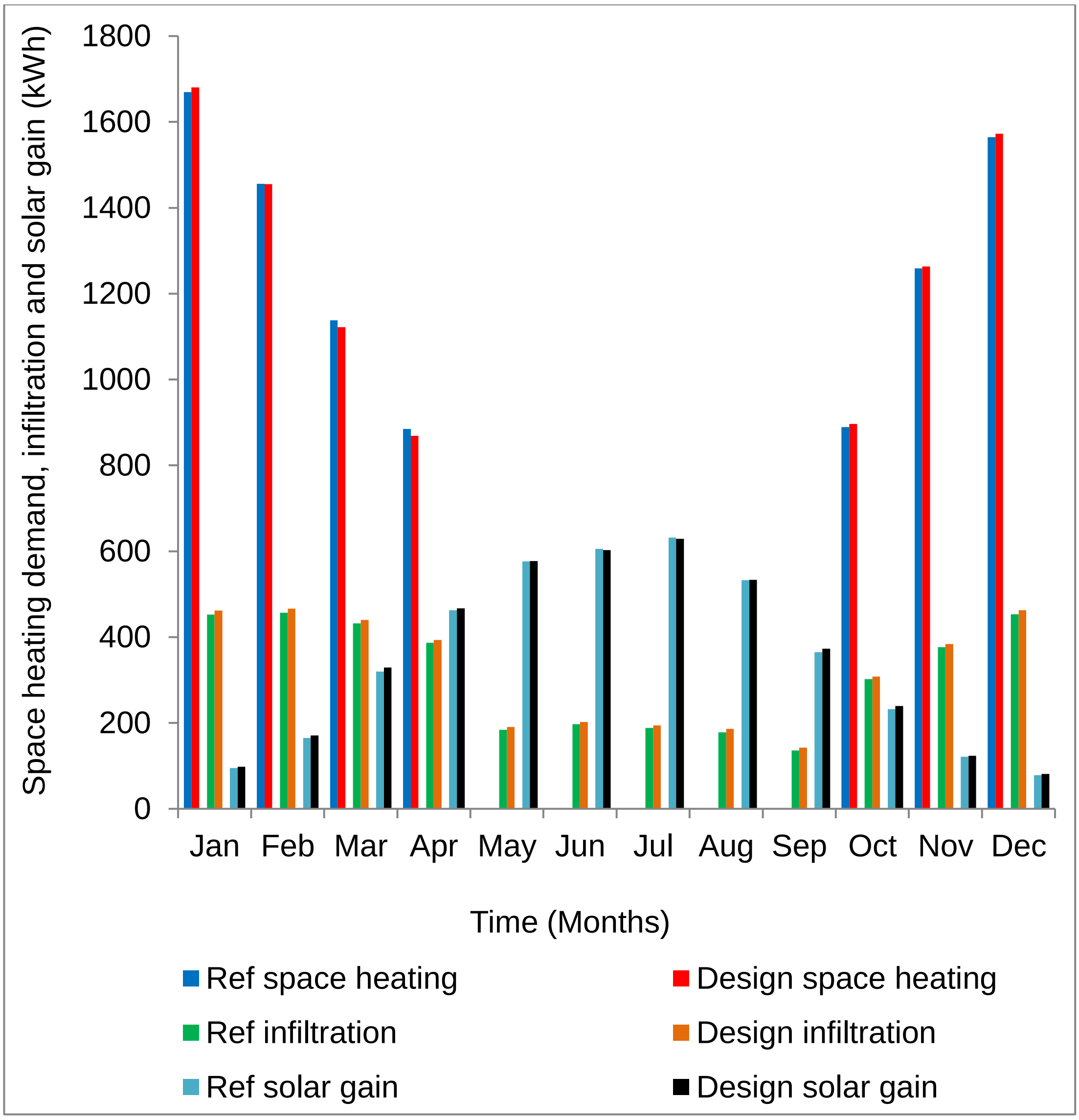


Figure 4.14 Monthly averaged space heating demand, external infiltration and solar gain estimates of the design geometry model compared to the reference geometry model

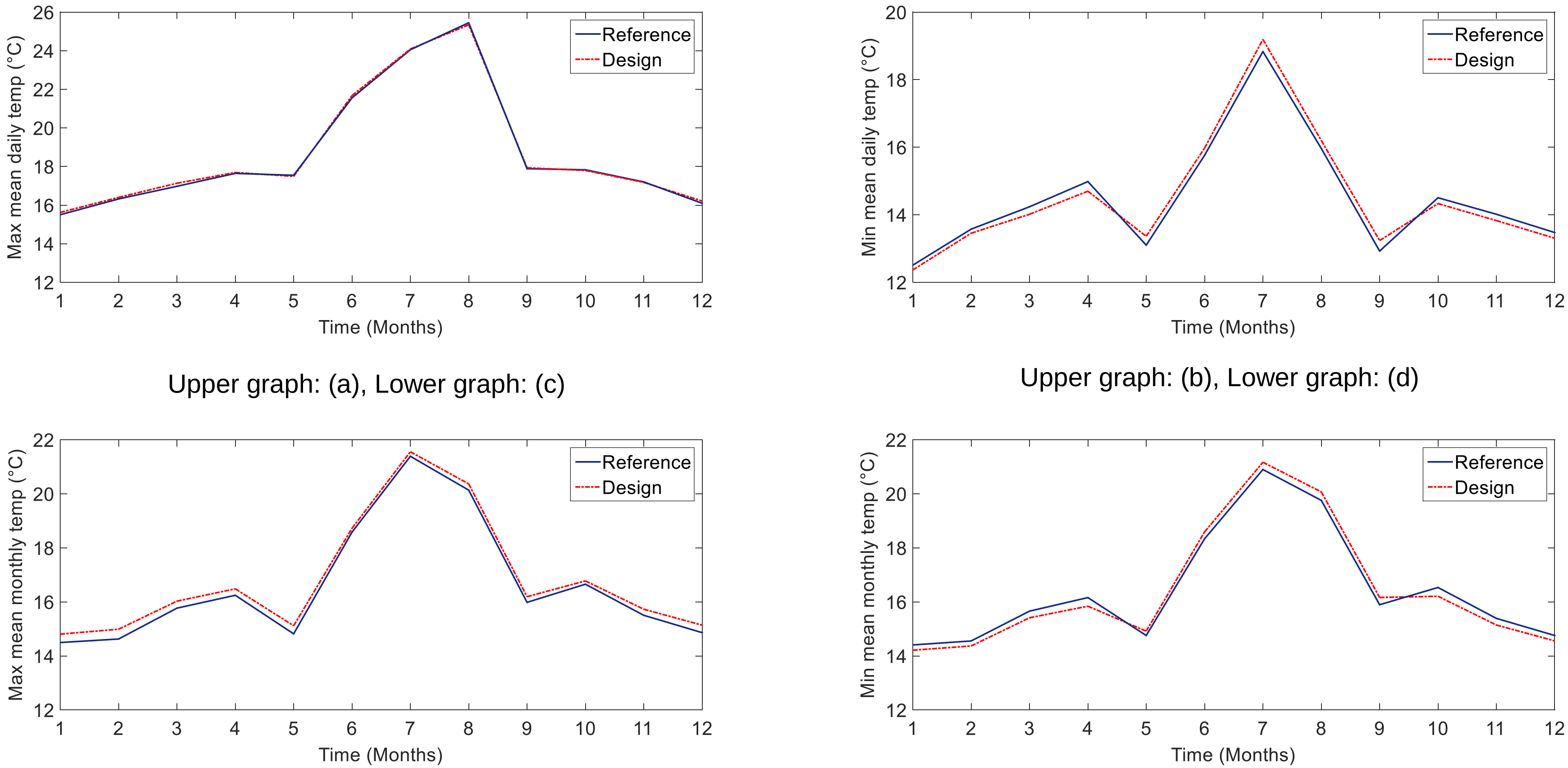


Figure 4.15 Internal temperatures of the reference geometry model and the design geometry model. a) Maximum mean daily temperatures, b) minimum mean daily temperatures c) maximum mean monthly temperatures, d) minimum mean monthly temperatures

4.4.3. Modelling Extensions

More than half of the houses in the modelling dataset have one or more extensions. Extensions are additions to a house that were built after the main building and therefore have a different age band and construction materials compared to the main building. Hence, the methodology was extended to include extensions in the model. This was necessary as the extensions formed a considerable proportion of the dwellings' floor area and would impact model predictions.

The reduced dataset includes age band and wall/floor type for extensions as well as floor area, floor height and heat loss perimeter, but no details on the location of extensions. Figure 4.16 shows five possible ways that extensions could be included. The red lines show external walls of the extensions. The first three solutions consider the extension in different locations. The last two solutions combine the floor area and heat loss perimeter of the extension with that of the main building. A method was chosen to reduce the complexity and preserve the geometry.

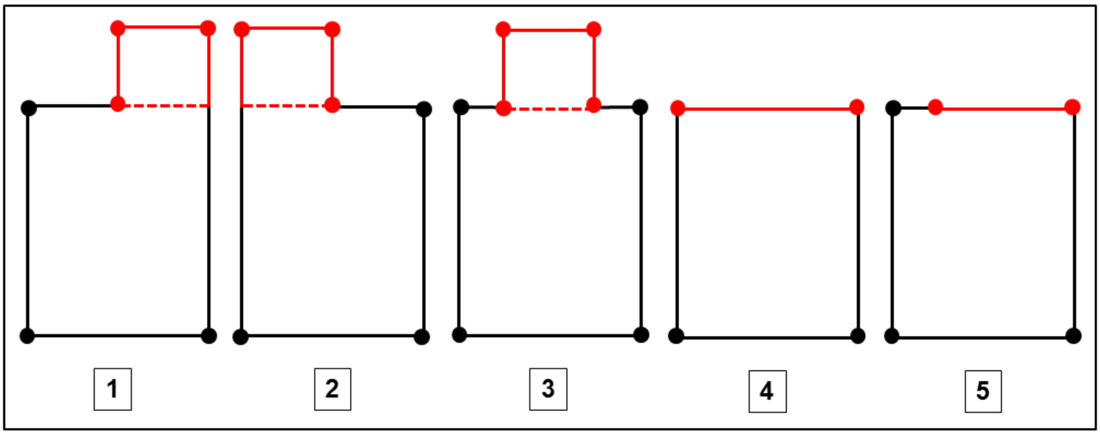


Figure 4.16 Possible solutions to model extensions (red lines represent extension walls)

Solutions four and five introduced the lowest number of vertices compared to the other solutions and were therefore preferred. Also, modelling extensions as separate blocks was problematic as the location was not known and this would impact on the location of fenestration and amount of solar heat gain into the building model. Solution four had the lowest number of vertices and therefore the least complexity but made it difficult to maintain the heat loss perimeter of the main building and extensions. Hence, the five-vertex model was chosen for implementation in the RdDEM.

To better understand the five-vertex solution, imagine a simple rectangular geometry with a square extension (Figure 4.17). The extension has floor area of 4 m^2 and exposed perimeter of 6 m while the main building has floor area of 40 m^2 and exposed perimeter of 16 m. The extension is combined with the main building while keeping the party wall length and increasing the width of rectangular geometry.

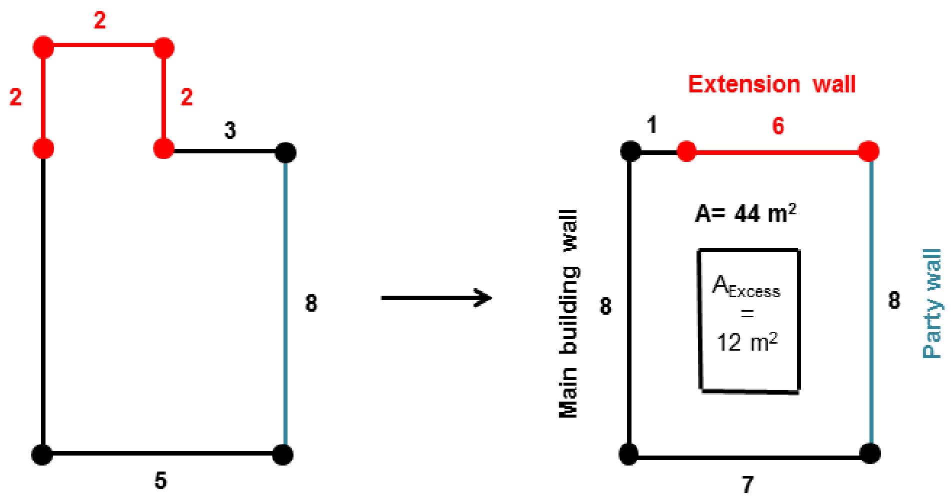


Figure 4.17 Modelling the extensions using five-vertex solution

The resultant five-vertex geometry has an extra area of 12 m^2 which is removed by introducing a block with zero heat capacity (as described in Section 4.4.1). As seen in the five-vertex geometry in Figure 4.17, the exposed perimeter of the extension (shown in red) and exposed perimeter of the main building (shown in black) are both conserved. In this way, different construction materials can be assigned for extension and main building walls, and party wall.

The five-vertex solution to model extensions was tested on the reference model to examine its suitability for modelling the houses in the dataset. Since the original reference model didn't have any extensions, a single-storey and a two-storey extension were added to the reference model (Figure 4.18). The single storey extension's floor area was 25% of the ground floors, and the two storey extensions floor area was 25% of the total floor area. The roof of the extensions was modelled in a similar way to the main building and window areas were increased in proportion with floor area. The total heat gains remained the same and therefore decreased per unit floor area, to 1.6 W/m^2 and 0.9 W/m^2 for ground and first floors.

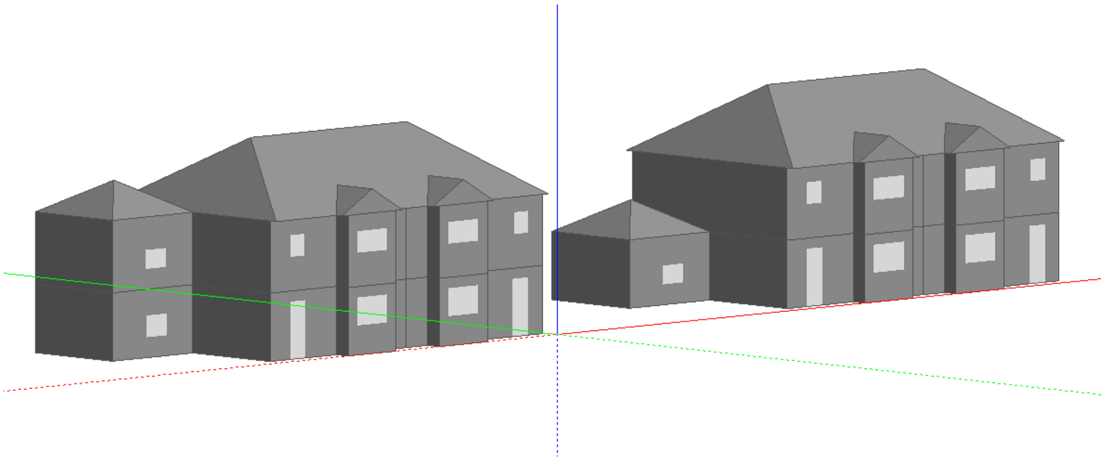


Figure 4.18 The reference model with single storey and two storey extensions

The dwelling models shown in Figure 4.18 were re-created using the five-vertex solution such that the total floor area, party wall length and exposed perimeter of both the main building and extensions were conserved. Simulations were run, and annual space heating demands were compared (Figure 4.19).

As seen in Figure 4.19, the prediction of space heating demand for the five-vertex solution were 2.3% lower than the reference model. The close alignment between predictions was also observed in mean monthly internal temperatures and the five-vertex solution for modelling the houses with extensions was deemed to be suitable for use in the RdDEM.

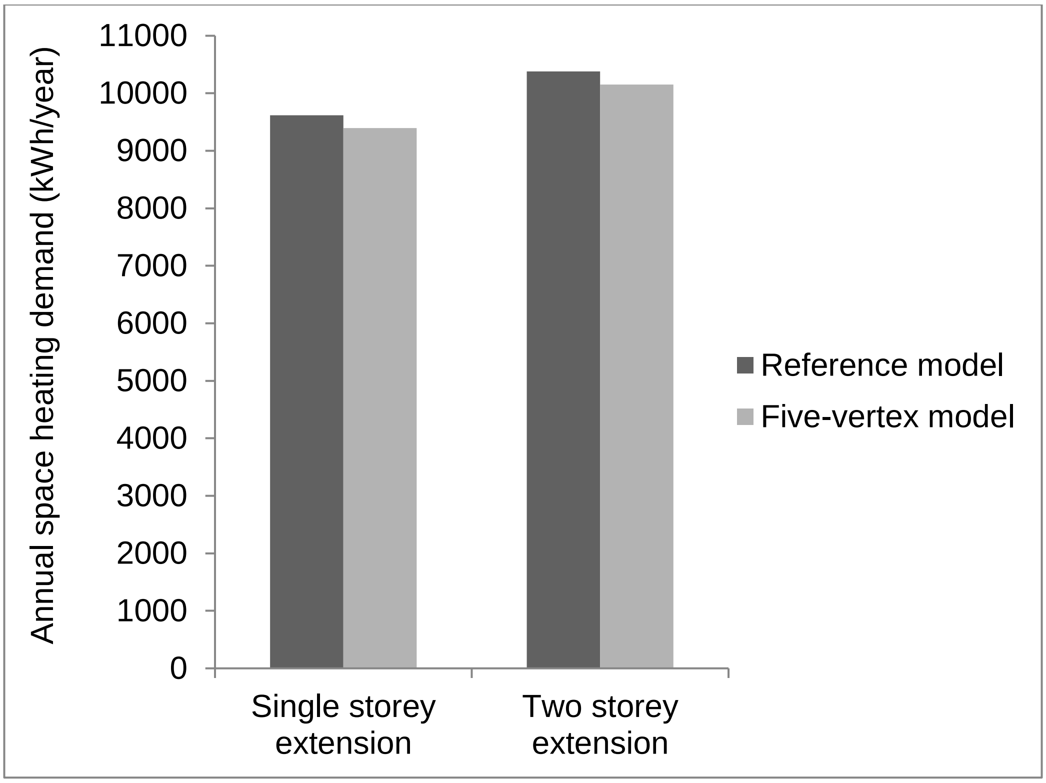


Figure 4.19 Annual space heating demand comparison of the reference model with extensions with five-vertex solution

4.5. Summary

This chapter described the processes that were used to identify the most suitable zoning strategy and the best way to enhance the geometry. These were required because the modelling dataset (reduced data) did not include internal layout of the dwellings or the three-dimensional geometry required for dynamic energy simulation.

A reference model, based on a semi-detached dwelling that was similar to dwellings in the modelling dataset, was defined and modelled in detail. The model results were verified by comparison with results in the literature. The reference dwelling was then used to test zoning strategies and ways to enhance geometry.

Zoning the dwellings floor by floor was found to be better than using a single zone or a separate living room zone. The predictions of annual energy demand and internal temperatures were similar to the detailed model when this zoning strategy was used.

A method was developed to preserve all of the values given in the modelling dataset (floor area, party wall length and heat loss perimeter) while creating full three-dimensional geometry. The method was tested on an extended version of the reference model and a very close alignment was found (within 1%). The methodology was also tested when extensions were present, and a similar close alignment was observed.

The zoning strategy and method for enhancing the geometry were included in the RdDEM. This completed Objectives 3 (*Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation*) and 4 (*Develop and run a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*) in part. The generation of further enhanced and equivalent data for the RdDEM is continued in the next chapter.

5. EQUIVALENT CONSTRUCTION MATERIALS AND BOUNDARY CONDITIONS

5.1. Introduction

This chapter describes the processes used in the RdDEM to derive SAP equivalent input parameters for construction materials, thermal mass, and the internal and external boundary conditions, towards Objective 4 (*Develop and run a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*) and completing Objective 3 (*Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation*). The modelling dataset only provides information on construction types and does not give any details about materials used in different building elements. Section 5.2 explains the process of re-creating construction materials for various building elements based on reduced data such that the U-value of each building element match the values given by SAP. The process of matching the thermal mass to SAP assumptions is also described. The chapter continues with describing the process of deriving SAP equivalent internal boundary conditions: internal heat gains and heating systems, losses, infiltration and ventilation (APPENDIX D). The chapter concludes with describing the methodology used to develop SAP equivalent external boundary conditions, i.e. weather data (Section 5.3).

5.2. Equivalent Construction Materials

The RdDEM contains a library of constructions that are equivalent to those in SAP for the external walls, roofs, ground floors, doors and windows. In this way they have the same U-values as those identified in SAP 2012 (see Section 3.3.3). The constructions were created in DesignBuilder and added to the IDF template (see Section 6.2.1) for use with the RdDEM.

5.2.1. External Walls

In case of the external walls, four set of constructions were required to represent the houses in the modelling dataset, using Table S6 for U-values and Table S3 for wall thickness (SAP, 2012):

i. Solid brick walls in age bands 'B', 'C, and 'D' with U-value of 2.1 W/m^{2}K.

ii. Solid brick walls in age band 'E' with U-value of 1.7 W/m^{2}K.

iii. Cavity walls in age bands 'B', 'C, 'D' and 'E' with U-value of 1.6 W/m^{2}K.

iv. Filled cavity walls in age bands 'B', 'C, 'D' and 'E' with U-value of 0.5 W/m^{2}K.

Each wall type was re-created using DesignBuilder's construction materials library in order to achieve the same overall U-value and thickness of each wall type (Table 5.1). The construction materials created in the DesignBuilder had an increased overall external walls U-value (by 0.15) to account for thermal bridging (see Section 3.3.3). Hence, the four modelled wall types mentioned above had overall U-values of 2.4 W/m^{2}K, 2 W/m^{2}K, 1.8 W/m^{2}K, and 0.6 W/m^{2}K, respectively.

As seen in Table 5.1, a single type of brick, plaster and insulating foam was used to create all four of the external walls. The only difference between solid walls of age bands 'B' to 'D' and solid walls in age band 'E' was addition of a thin air gap. This air gap is added to the plaster board for the purpose of dry-lining and is different from the air gap in cavity walls. Dry-lining is a plaster boarding system where an air gap is created between the wall and the plaster board, improving the U-value of a solid wall by about 25%. Dry-lining adds 20 mm to 40mm to the solid wall thickness (RdSAP mannual, 2012). This addition in the thickness also explains the difference in the thickness of solid brick walls from age bands 'B' to 'D' compared to the solid walls from age band 'E'.

Table 5.1 SAP equivalent external wall constructions, thickness and the physical properties of each layer of materials

Wall type and U-value as created in DB	Construction Details				
	Materials (outermost to innermost layer)	**Thickness (m)**	**Density (kg/m^3)**	**Thermal Conductivity (W/mK)**	**Specific Heat Capacity (J/kgK)**
Solid Brick (U=2.4 W/m^2K)	Brick	0.205	1700	0.77	1000
	Dense plaster	0.015	1300	0.57	1000
Solid Brick (U=2.0 W/m^2K)	Brick	0.205	1700	0.77	1000
	Air gap	0.020	N/A	N/A	N/A
	Dense plaster	0.015	1300	0.57	1000
Cavity (U=1.8 W/m^2K)	Brick	0.105	1700	0.77	1000
	Air gap	0.035	N/A	N/A	N/A
	Brick	0.105	1700	0.77	1000
	Dense plaster	0.015	1300	0.57	1000
Filled Cavity (U=0.6 W/m^2K)	Brick	0.105	1700	0.77	1000
	Foam (phenol-rigid)	0.035	110	0.035	1470
	Brick	0.105	1700	0.77	1000
	Dense plaster	0.015	1300	0.57	1000

Physical properties of all the materials specified in Table 5.1 were checked against CIBSE Guide A, Appendix 3.A7: Properties of materials (CIBSE Guide A, 2017) to ensure the correctness of values reported by DesignBuilder.

5.2.2. Roofs

All of the dwellings in the modelling dataset had pitched roofs. The majority had a known thickness of insulation, ranging from 0mm to 300 mm. The level of roof insulation was unknown for 5 of the dwellings and therefore the thickness was assumed based on Table S10 SAP 2012. This table assumes no insulation for pitched roofs in age bands ‘B’ to ‘D’ and 12 mm of insulation for the pitched roofs in age band ‘E’.

Each of these roofs was re-created in DesignBuilder such that each roof had the same U-value as specified in SAP 2012. The roof U-values given in SAP 2012 accounts for the insulation, the roofing materials and the thermal resistance of the air space in loft. In DesignBuilder, however, the pitched roof construction only includes the external sloped surfaces and loft insulation, consequently the reported overall U-vale doesn’t take into account the resistance of the air space in loft. Hence, in the RdDEM, the roofing materials and loft insulation were modelled explicitly, and the U-values were compared to SAP values using the Equation 5.1.

$$U_{SAP} = \frac{1}{R_{Space} + \frac{1}{U_{DB}}} \qquad 5.1$$

Where U_{DB} is the overall U-value reported by DesignBuilder and U_{SAP} is the U-values in Table S9 SAP 2012 including thermal resistance of loft space (R_{Space}) for pitched roofs. The thermal resistance of the roof space (R_{Space}) for tiled roofs was taken from Table 3.5 in CIBSE Guide A, as 0.06 m^{2}K/W.

The materials used in roof construction were clay tiles, glass fibre quilt and roofing felt. The thickness of insulation layer was adjusted accordingly such that the roofs U-values match the values given in SAP. Physical properties of the materials used in roof construction are presented in Table 5.2.

Table 5.2 Roof construction materials and corresponding density, thermal conductivity and specific heat capacity values

Roof materials (outermost to innermost layer)	Density	Thermal conductivity (W/mK)	Specific heat capacity (J/kgK)
Clay tile	1900	0.85	840
Glass fibre quilt	12	0.04	840
Roofing felt	960	0.19	840

5.2.3. Ground Floors

The dwellings in the modelling dataset had two different types of ground floor construction: solid and suspended timber. In the RdDEM, ground floors were modelled such that they have the same U-values as in SAP. SAP calculates the ground floor U-value according to BS EN ISO 13370 using dwelling's area (A) and exposed perimeter (P) and following parameters:

- wall thickness (w)
- soil type clay (thermal conductivity λg = 1.5 W/mK)
- R_{si} = 0.17 m^2 K/W (Internal surface resistance)
- R_{se} = 0.04 m^2K/W (External surface resistance)
- thickness and conductivity of floor insulation (0.035 W/mK)
- R_f = 0.001 x d_{ins}/0.035 where d_{ins} is insulation thickness in mm (R_f is the thermal resistance of floor deck)

For solid floors, U-value of the ground floor is calculated by SAP as (Equations 5.2 and 5.3):

If $d_t < B$ $$U = 2 \times \lambda_g \times \ln(\pi \times \frac{B}{d_t} + 1)/(\pi \times B + d_t) \quad 5.2$$

If $d_t > B$ $$U = \lambda_g/(0.457 \times B + d_t) \quad 5.3$$

Where d_t and B are calculated from Equations 5.4 and 5.5:

$$d_t = w + \lambda_g \times (R_{si} + R_f + R_{se}) \quad 5.4$$

$$B = 2 \times A/P \quad 5.5$$

Since the solid ground floors in the modelling dataset had no insulation, the value of R_f was inserted as zero in Equation 5.4. The U-values for solid ground floors were calculated individually for each dwelling using dwellings' floor area and exposed perimeter.

In the RdDEM, the solid ground floors were modelled as three layers: underfloor clay, cast concrete, and flooring screed. The thickness of each layer was adjusted in order for the individual ground floors to match the SAP U-values. The physical properties of the materials used in ground floor construction are presented in Table 5.3.

Table 5.3 Ground floor construction materials and corresponding density, thermal conductivity and specific heat capacity values

Ground floor materials (outermost to innermost layer)	**Density**	**Thermal conductivity (W/mK)**	**Specific heat capacity (J/kgK)**
Clay (earth)	1.28	1460	880
Cast concrete	1900	1.4	840
Flooring screed	1200	0.41	1000

SAP uses additional parameters to calculate the U-value of suspended timber ground floors. These parameters include:

- thermal resistance of floor deck R_f = 0.2 m^2 K/W if uninsulated or
  R_f = [(thermal resistance of insulation) + 0.2] if insulated
- height above external ground level h = 0.3 m
- average wind speed at 10 m height v = 5 m/s
- wind shielding factor f_w = 0.05

- ventilation openings per m exposed perimeter $\varepsilon = 0.003\ m^2/m$
- U-value of walls to underfloor space $U_w = 1.5\ W/m^2K$

The suspended ground floor U-value is calculated from Equation 5.6 in SAP:

$$U = 1/(2 \times R_{si} + R_f + 1/(U_g + U_x)) \qquad 5.6$$

Where U_g and U_x are calculated from Equations 5.7 and 5.8:

$$U_g = 2 \times \lambda_g \times \ln(\pi \times \frac{B}{d_g} + 1)/(\pi \times B + d_g) \qquad 5.7$$

$$U_x = \left(2 \times h \times \frac{U_w}{B}\right) + (1450 \times \varepsilon \times \mathrm{v} \times \frac{f_w}{B}) \qquad 5.8$$

And d_g and B are calculated from Equations 5.9 and 5.10:

$$d_g = w + \lambda_g \times (R_{si} + R_{se}) \qquad 5.9$$

$$B = 2 \times A/P \qquad 5.10$$

Since the suspended ground floors had no insulation, the value of R_f was inserted as 0.2 in Equation 5.6. The U-values for suspended ground floors were calculated individually for each dwelling using dwellings' floor area and exposed perimeter.

In the RdDEM, suspended ground floors were modelled as a solid ground floor with an insulation layer. In this way, the thickness of insulation layer was modified accordingly for each dwelling to reflect the SAP equivalent U-value of the suspended ground floor as calculated in above equations. Hence, although all dwellings model had solid ground floor, the U-value of the ground floor was capture correctly for both the dwellings with solid and suspended ground floor. This was simpler than trying to model a ventilated cavity, with uncertain ventilation rates, in EnergyPlus.

5.2.4. Doors and Windows

For the RdDEM, the area of external doors was taken as 1.85 m^2 following the SAP 2012 guidelines. The external doors were modelled on the front and rear walls of each dwelling. Doors were modelled as softwood with, 0.07 m thickness, 0.12 W/mK thermal conductivity, and 230 kg/m^3 density to match the U-value of 2.5 W/m^2K as given by Table S15A SAP 2012 for dwellings with age bands A to J.

Window areas in the RdDEM were the same as in SAP, based on the age band and total floor area (*TFA*) from Table S4 SAP 2012. Table 5.4 shows the related part of table S4 which was used in estimating window area of the modelling dataset houses. Window areas were divided equally onto the front and rear external walls of the dwellings.

Table 5.4 Window area estimated based on age band and total floor area (re-created from Table S4 (SAP, 2012)

Age band	**Window area (m^2)**
A, B, C	0.1220 *TFA* + 6.875
D	0.1294 *TFA* + 5.515
E	0.1239 *TFA* + 7.332

The only known detail in the dataset about windows was that all dwellings had 100% double glazed windows. Hence, based on Table 6E SAP 2012 (SAP, 2012) a double glazed, air filled window with 6 mm gap and U-value of 3.1 W/m^2K was considered for all the dwellings. The windows were modelled with an effective U-value which took account of the assumed use of curtains ($U_{w,effective}$), as show in Equation 5.11 from SAP 2012:

$$U_{w,effective} = \frac{1}{\frac{1}{U_W}+0.04} \qquad 5.11$$

Where U_w is the window U-value without curtains.

5.2.5. Equivalent Thermal Mass

The thermal mass of the ground floor, ceiling, external walls, party walls, windows and doors is captured in the equivalent constructions. However, the modelling dataset does not include any details of internal partitions or furniture that add to a building's thermal mass. These elements may contribute considerably to the total thermal mass and so to make the models equivalent, the SAP 2012 guidelines were used.

In SAP a Thermal Mass Parameter (TMP) is calculated from Equation 5.12 (SAP, 2012).

$$TMP = \frac{\sum(\kappa \times A)}{TFA} \qquad 5.12$$

Where 'κ' is the heat capacity of construction materials (kJ/m^{2}K), and the summation is over the area (A) of all elements (windows, door, external walls, party walls, ground floors and roofs) bounding the dwelling as well as both sides of all internal walls and floors/ceilings. '*TFA*' is the total floor area. The 'κ' values for some typical constructions are given in Table 1e (SAP, 2012).

However, for RdSAP, an indicative value of the TMP is used instead of a detailed calculation. Table 1f (SAP, 2012) gives a fixed value for the TMP of 250 kJ/m^{2}K. The RdDEM used this fixed TMP value to create a dynamic model with equivalent thermal mass by adding internal walls to create a TMP of 250kJ/m2K.

EnergyPlus does not calculate thermal mass in the same way as SAP; instead the materials within each building elements is defined with heat capacity, density and thickness values used to run heat transfer equations. Since the construction details of internal walls was not identified in the modelling dataset, the 'dense block and dense plaster' construction type given in Table 1f SAP 2012 with heat capacity (κ) value of 100 kJ/m^{2}K was assumed. The internal wall area, on the other hand, was derived from Equation 5.12 with the TMP value set to 250 kJ/m^{2}K. To do so, area and heat capacity (κ) values from all other building elements were inserted into Equation 5.12 and then the equation was solved for internal walls area. The area of building elements were derived from geometry details provided in the dataset while the heat capacity (κ) was calculated from Equation 5.13 after the method described in (SAP, 2012).

$$\kappa = 10^{-6} \times \sum (d_j \rho_j c_j) \tag{5.13}$$

Where 'd_j' is the thickness (mm), 'ρ_j' is density (kg/m^3) and 'c_j' is specific heat capacity (J/kgK) of the layers forming each building element. The summation is over all layers in the element from inside to outside until one of the following conditions is met: half way through the element; an insulation layer; total thickness of 100 mm.

5.3. Equivalent External Boundary Conditions: Weather Data

A new weather file, with hourly data suitable for use in dynamic energy simulation, was created for use in the RdDEM. The weather data were created to match the monthly external temperature, wind speed and global solar irradiance values given in SAP 2012 Tables U1 to U3 (SAP, 2012). The International Weather for Energy Calculations (IWEC) weather file for Birmingham was used as the basis of the weather file, since all the dwellings in the modelling dataset were located in UK Midlands.

The IWEC Birmingham weather file is derived from an average of 18 years (1982-1999) of hourly observations archived at the US National Climatic Data Centre. The weather data is supplemented by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly cloud amount information (IWEC, 2015).

The mean monthly external temperature, wind speed and solar irradiance values from IWEC Birmingham weather file were used to calculate conversion factors for each month. Table 5.5 compares the monthly temperature, wind speed and solar irradiance values from SAP Midlands to IWEC Birmingham values. It can be seen that the conversion factors were relatively close to 1, with the biggest difference being 0.35 for solar irradiance in December.

Table 5.5 Mean monthly external temperature, wind speed and solar irradiance from UK average weather data (SAP 2012) and IWEC Birmingham (IWEC, 2001) weather data showing the conversion factors (CF)

Month	External Temp (°C)			Wind speed (m/s)			solar irradiance (W/m^2)		
	SAP	IWEC	CF	SAP	IWEC	CF	SAP	IWEC	CF
Jan	4.3	4.6	0.94	4.5	5.2	0.87	28	67	0.42
Feb	4.8	3.7	1.30	4.5	3.1	1.45	55	96	0.57
Mar	6.6	6.4	1.03	4.4	3.9	1.13	97	150	0.65
Apr	9.0	7.5	1.2	3.9	4.7	0.83	153	169	0.91
May	11.8	11.0	1.07	3.8	4.6	0.83	191	164	1.16
Jun	14.8	14.2	1.04	3.4	3.6	0.94	208	179	1.16
Jul	16.6	17.2	0.97	3.3	3.4	0.97	194	166	1.17
Aug	16.5	16.3	1.01	3.3	3.3	1	163	150	1.09
Sep	14.0	13.2	1.06	3.5	3.3	1.06	121	116	1.04
Oct	10.5	9.9	1.06	3.8	3.6	1.06	69	93	0.74
Nov	7.1	6.9	1.03	3.9	3.9	1	35	76	0.46
Dec	4.2	5.0	0.84	4.1	3.5	1.17	23	65	0.35

The conversion factors were applied to the hourly values in the IWEC Birmingham weather file. For wind direction, relative humidity and atmospheric pressure, the same values in IWEC Birmingham weather file were used. In this way the weather was equivalised to the SAP Midlands data while maintaining the hourly values required for dynamic simulation. Additionally, the Latitude, Longitude and elevation of location from see level for all dwellings were set to 52.6 °N, -1.33 and 116 m, respectively as specified in Table U4 SAP 2012. The SAP Midlands equivalent hourly data was inserted into a CSV file and the EnergyPlus weather convertor programme (EnergyPlus Weather Convertor, 2015) used to generate the EPW file.

5.4. Summary

This chapter described the processes used in the RdDEM to derive SAP equivalent input parameters for construction materials, thermal mass, and the internal and external boundary conditions. Construction materials were defined for all of the different building elements (i.e. external walls, roofs, ground floors, doors and windows) such that the U-values matched those given in SAP.

The RdDEM maintained the same Thermal Mass Parameter (TMP) of 250 kJ/m^{2}K as defined in SAP. This was achieved by calculating the thermal mass in the external walls, party wall, roof and ground floor and then adding sufficient area of internal partition wall to make up the remainder. Internal boundary conditions were defined for use in the RdDEM which matched those given in SAP: internal heat gains, losses, infiltration and heating systems. A weather file from IWEC Birmingham, suitable for dynamic thermal simulation, was modified to match the monthly external temperature, wind speed and solar irradiance values from SAP.

Overall, this completed Objectives 3 (*Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation*). Objective

4 (*Develop and test a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*) is completed in the next chapter.

6. TRANSLATION, SIMULATION AND RESULTS

6.1. Introduction

This chapter describes the translations process used in the RdDEM to convert the reduced data from the XML format used for EPCs into the Input Data File (IDF) format used by EnergyPlus to complete objective 4 (*Develop and test a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*). The translation process was tested and verified. The results of using the RdDEM to simulate 83 dwelling from the DEFACTO dataset were compared with the SAP results in pursuit of the final objective: Objective 5 (*Compare the results of the reduced data dynamic energy model with those from equivalent steady-state models*).

6.2. Translation

Data translation is the part of the RdDEM that converts all of the prepared data into IDF format in readiness for running the EnergyPlus simulations. The translation process was formed of two main elements: the Template Input Data File, which was used for storing fixed input data, and the Translator, to handle varying input data.

The fixed data was written into a standard IDF template which formed the basis of the IDF for all the dwellings. This Template IDF (TIDF) contained all the fixed data and the lines allocated to varying data were left blank to be filled by the translator. The translator wrote the varying input data into the allocated spaces in the TIDF. The following sub-sections provide details of the TIDF and the translator; and the procedures followed to ensure the effective and robust function of translation process.

6.2.1. Template Input Data File (TIDF)

The TIDF was created from a two zone version of the reference model (see Section 4.3) using DesignBuilder, exported as an IDF and then edited to leave only the relevant information required by the RdDEM. The main components of the TIDF are: zoning details, geometrical layout, construction details, heating system details, and simulation details.

The TIDF was developed from the two zone strategy, with each floor of the dwellings modelled as individual heating zones (Section 4.3). In this way, all the details related to internal thermal mass, geometrical details, internal boundary conditions and construction materials were assigned to each floor of the dwellings separately.

Geometry in the TIDF followed the rectangular method, with an excess area block inside (Section 4.4). The geometry of the dwellings were defined in the TIDF through (x,y,z) coordinates (Figure 6.1) of the 16 vertices forming the blocks. The translator for the RdDEM (see Section 6.2.2) would then edit the (x,y,z) coordinates to suit an individual dwelling in the modelling dataset. As seen in Figure 6.1, the origin was set to the bottom left vertex of the main building block so that all other vertices have positive (x,y,z) coordinates.

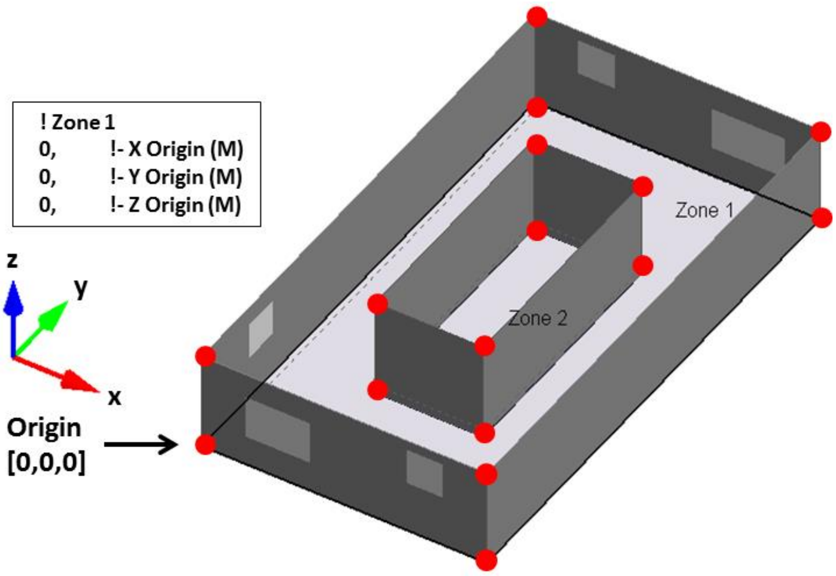


Figure 6.1 Geometrical layout of the dwellings' model with red dots showing the vertices of the rectangular blocks, the origin vertex and the IDF notation

The construction details developed for all of the different external walls, roofs and ground floors (see Section 5.2) were included in the TIDF so that the translator could call the appropriate one for each dwelling. The heating system details and heating periods (see APPENDIX D) were also stored in the TIDF while heating set-point temperatures were left as blank to be completed by the translator.

The last set of fixed data in the TIDF was related to simulation details. All simulations were run with 10-minute time steps (6 time steps per hour) for a full year under the SAP equivalent weather data file (see Section 5.3). The simulation details, the address of the weather (CVS, EPW and 'definition') files, and the commands needed to store all the results in hourly, monthly and annual formats were stored in the TIDF.

In the TIDF unique text strings were added so that the translator could identify the right place for input parameters. These indicators were added as comments which were recognised by the translator but not the EnergyPlus compiler.

6.2.2. Translator

The Translator wrote all of the varying data into a TIDF for each dwelling in the modelling dataset (Figure 6.2). The translator reads each XML files in the modelling dataset and converts them into MATLAB structures. This speeds up the translation process by treating the whole dataset as a MATLAB directory and also removes the complications of handling text files. The translator calculates the internal thermal mass for each dwelling in terms of additional internal wall area (see Section 5.2.5). Then the 16 sets of (x,y,z) coordinates for each floor were calculated based on the rectangular geometry describe in Section 4.4. Finally, the internal boundary conditions were calculated (see APPENDIX D). After completing the data preparation process for each house, the translator wrote the data into the TIDF. The translation process was repeated for all the dwellings in the modelling dataset to create a unique IDF for each.

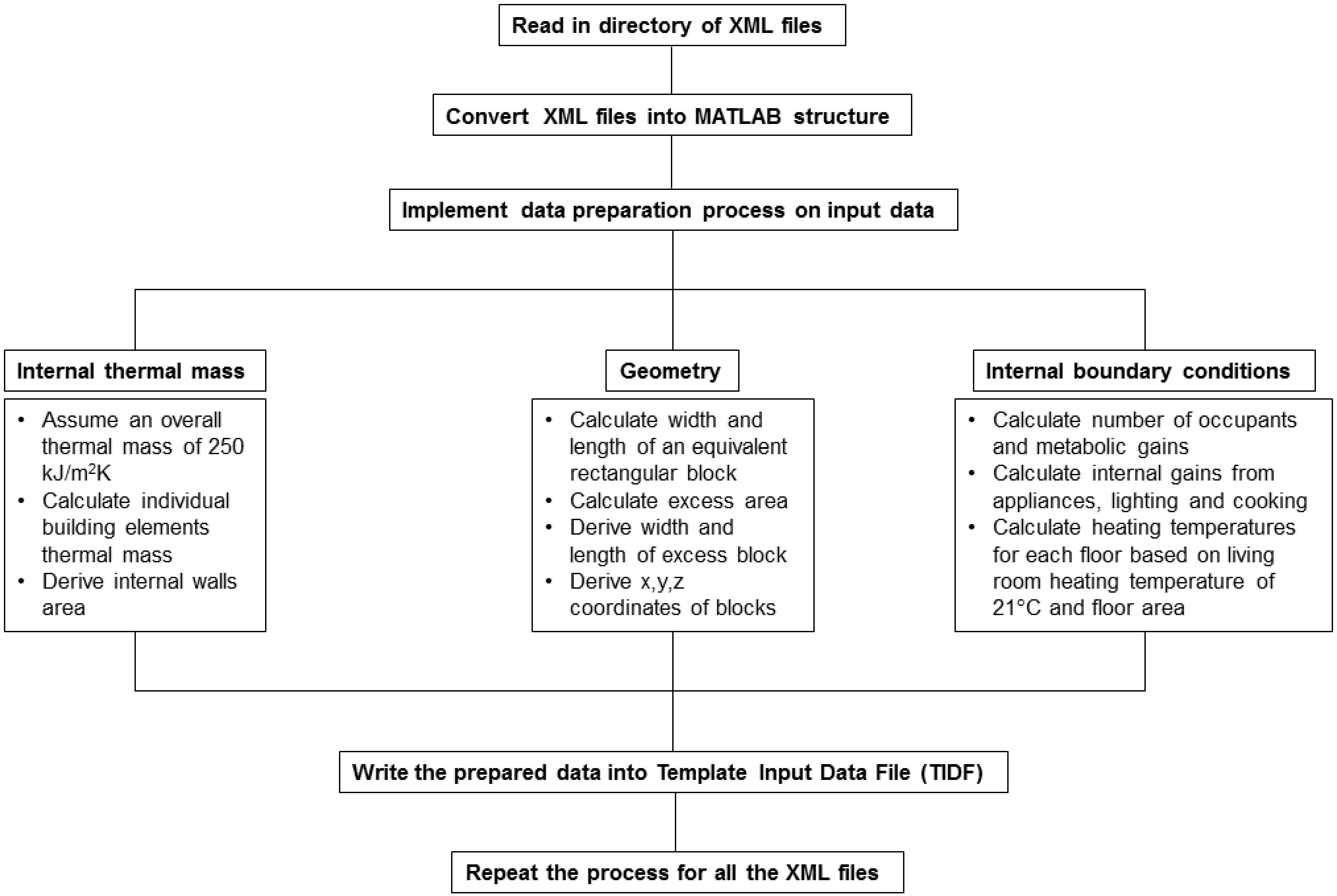


Figure 6.2 Translator framework to process varying data from XML files and write input data into Template IDF (TIDF)

6.3. Process Verification

Two lots of simulations were carried out to verify the translation process: 1) Diagnostic runs, and 2) Final runs. The primary goal of the diagnostic runs was to debug the translator script, troubleshoot any errors that occurred and to ensure that the data preparation process was implemented correctly. The final runs were aimed at verifying both the data preparation and translation processes, including checking the equivalent rectangular geometry, equivalent thermal mass and zoning strategy.

The diagnostic runs were performed on four variants of the reference model:

i. A detailed dynamic model in DesignBuilder.

ii. A manual reduced dynamic model in EnergyPlus.

iii. An automated reduced dynamic model in EnergyPlus, using the RdDEM translator.

iv. A reduced steady-state model in SAP 2012.

The detailed reference model developed in DesignBuilder is described in Section 4.2. All the reduced models were developed based on input data from a reduced XML file including reference model details. In order to have exactly same amount of details as the modelling dataset, the data on the semi-detached Allen and Pinney (1990) house was stored in an EPC XML file format. The SAP model was developed manually using SAP 2012 spreadsheet in APPENDIX B. All the dynamic energy models were simulated with 10-minute time step, for a full year under the SAP equivalent weather data file (see Section 5.3).

The annual space heating demands from the four variants of the reference model were compared (Figure 6.3). The two reduced models developed in EnergyPlus predicted annual space heating demand very close to each other (less than 1% difference). The very close alignment of the two reduced EnergyPlus models verified performance of the translation process.

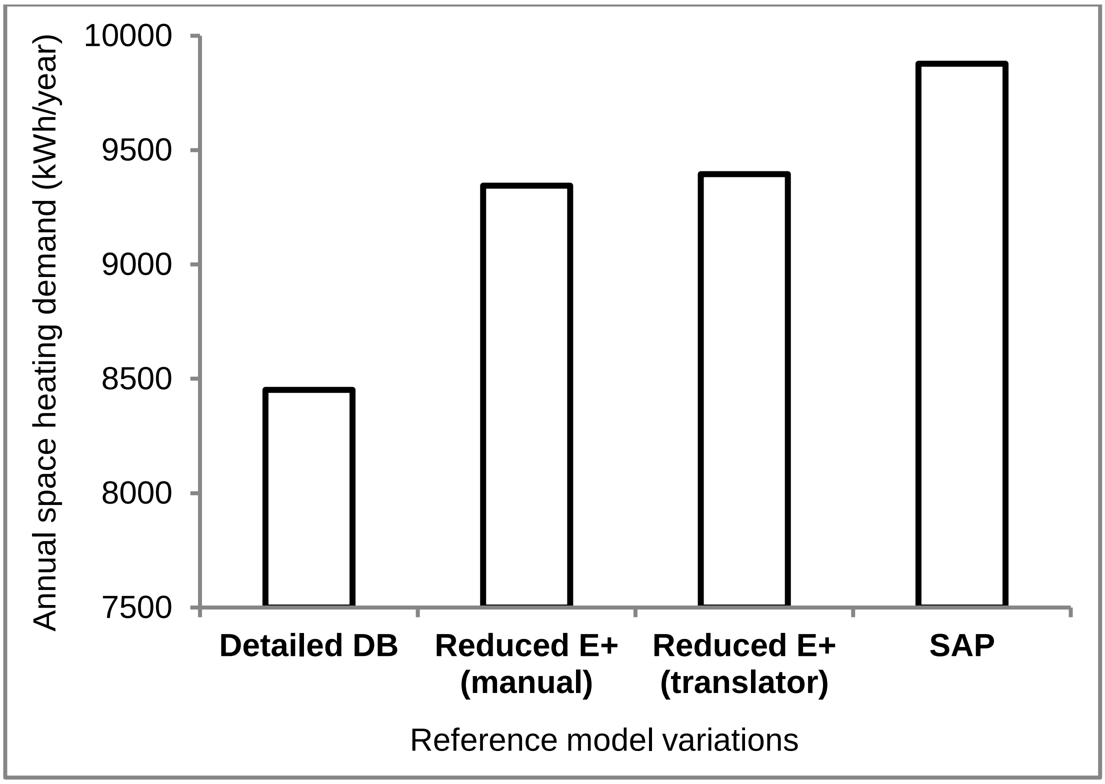


Figure 6.3 Comparison of the space heating demands from different variants of the reference model

The predictions from the two reduced EnergyPlus models were 10% different to the detailed DesignBuilder model and 5% different to the SAP model. The close alignment between reduced EnergyPlus and SAP models supports the decisions made in the data preparation process to develop SAP equivalent data. However, larger difference between reduced EnergyPlus models with the detailed DesignBuilder model highlights the impact that simplifying model has on the model predictions. The main parameters simplified in developing reduced models were: geometry, thermal mass, and zoning. All internal boundary conditions were also simplified after SAP 2012 guidelines, but the close alignment of reduced models with SAP verified these simplifications. Hence, further investigation was necessary to verify geometry, thermal mass, and zoning simplifications.

In order to verify zoning strategy (Section 4.3), enhanced geometry (Section 4.4) and equivalent thermal mass (Section 5.2.5) techniques used to develop the RdDEM, the model predictions of the three of houses in the modelling dataset were compared to predictions of more detailed models of the same houses. These test houses were selected based on their annual space heating demand estimated by SAP, such that they represent bottom, median and top demand values in the batch. The approximate building plans generated by the EPC assessors were available on the three test houses. Hence, the detailed building geometry, thermal mass and zoning configuration of these houses were modelled in DesignBuilder and simulations were run for a full year under the SAP equivalent weather data file. All other aspects of the detailed models were kept similar to the RdDEM.

The annual space heating demand from the RdDEM, detailed DesignBuilder and SAP models were compared (Figure 6.4). A general trend was observed in all of the test houses where the RdDEM and detailed DesignBuilder models underestimated the annual space heating demand compared to the steady-state SAP results and detailed DesignBuilder model underestimated the annual heating demands compared to the RdDEM.

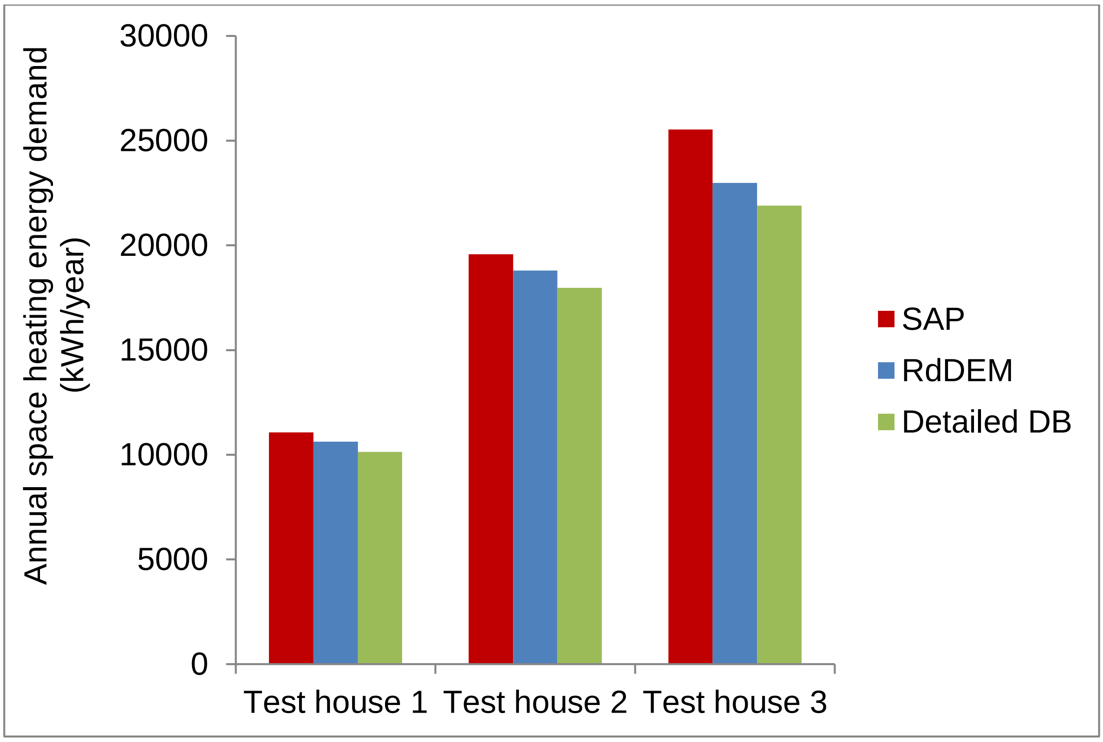


Figure 6.4 Comparison of the space heating demand from SAP, RdDEM and detailed DesignBuilder models of the three test houses

While the difference between RdDEM and SAP results increases with increasing space heating demand, the difference between RdDEM and detailed DesignBuilder model is similar in all the test houses. The increasing difference of SAP predictions with RdDEM and detailed DesignBuilder model predictions highlighted the characteristic differences of the steady-state and dynamic energy models. However, the steady difference between RdDEM and detailed DesignBuilder model predictions, which was less than 5% different in all the studied houses, verified the data preparation process developed to model geometry, thermal mass and zoning using reduced data.

The difference observed between RdDEM and detailed version of the reference model was 10%, while the difference observed between RdDEM and detailed versions of the three test houses was less than 5%. The smaller difference observed in case of the test houses, which were chosen from the modelling dataset, showed that the reduced geometry, thermal mass and zoning strategies worked better on the dataset dwellings.

6.4. Simulation Results

The RdDEM results were compared with SAP predictions for 83 houses in the modelling dataset. This included annual space heating demand (Section 06.4.1), mean monthly internal temperatures (Section 6.4.2) and the estimated potential for improving energy efficiency of the houses (Section 6.4.3). All of the simulations were run in EnergyPlus version 8.3.0 using IDFs created in the RdDEM. Simulation of each house required approximately 8 minutes of single CPU time for a full year simulation at 10-minute time steps on a CORE i5 HP laptop running Microsoft Windows.

6.4.1. Comparison of Energy Demand Results to SAP Estimates

Annual spaces heating demand results from the RdDEM were compared to SAP predictions for the 83 houses in the modelling dataset (Figure 6.5 and Table 6.1). The (x=y) line, shown in blue, is where RdDEM predicts the same space heating demand as SAP. The line of best fit through the data has the equation shown in Equation 6.1 and a coefficient of determination (R^2) of 0.96.

$$y = 0.82x + 1834.6 \qquad 6.1$$

The minimum difference observed between RdDEM and SAP was 74 kWh/year (1%) while the largest difference was 5898 kWh/year (17%). Of the 83 modelled houses, 46 were within 5% difference in annual space heating demand prediction and only 5 had more than 10% difference with only 2 more than 15%. The closest results are for the houses with space heating demand below approximately 15000 kWh/year.

Table 6.1 Comparison of space heating demand predictions between RdDEM and SAP

Over/Under	**By (%)**	**Number of houses (%)**
RdDEM predicts higher space heating demand than SAP	> 10%	2 (2%)
	5-10%	9 (11%)
	< 5%	12 (14%)
RdDEM predicts lower space heating demand than SAP	< 5%	34 (41%)
	5-10%	23 (28%)
	> 10%	3 (4%)

The box-whisker plots (Figure 6.6) shows the differences in the distributions of results from the two models. The RdDEM predictions have lower mean, median, maximum and minimum values of the annual space heating demand for 83 modelled houses. However, the mean and median values are remarkably close.

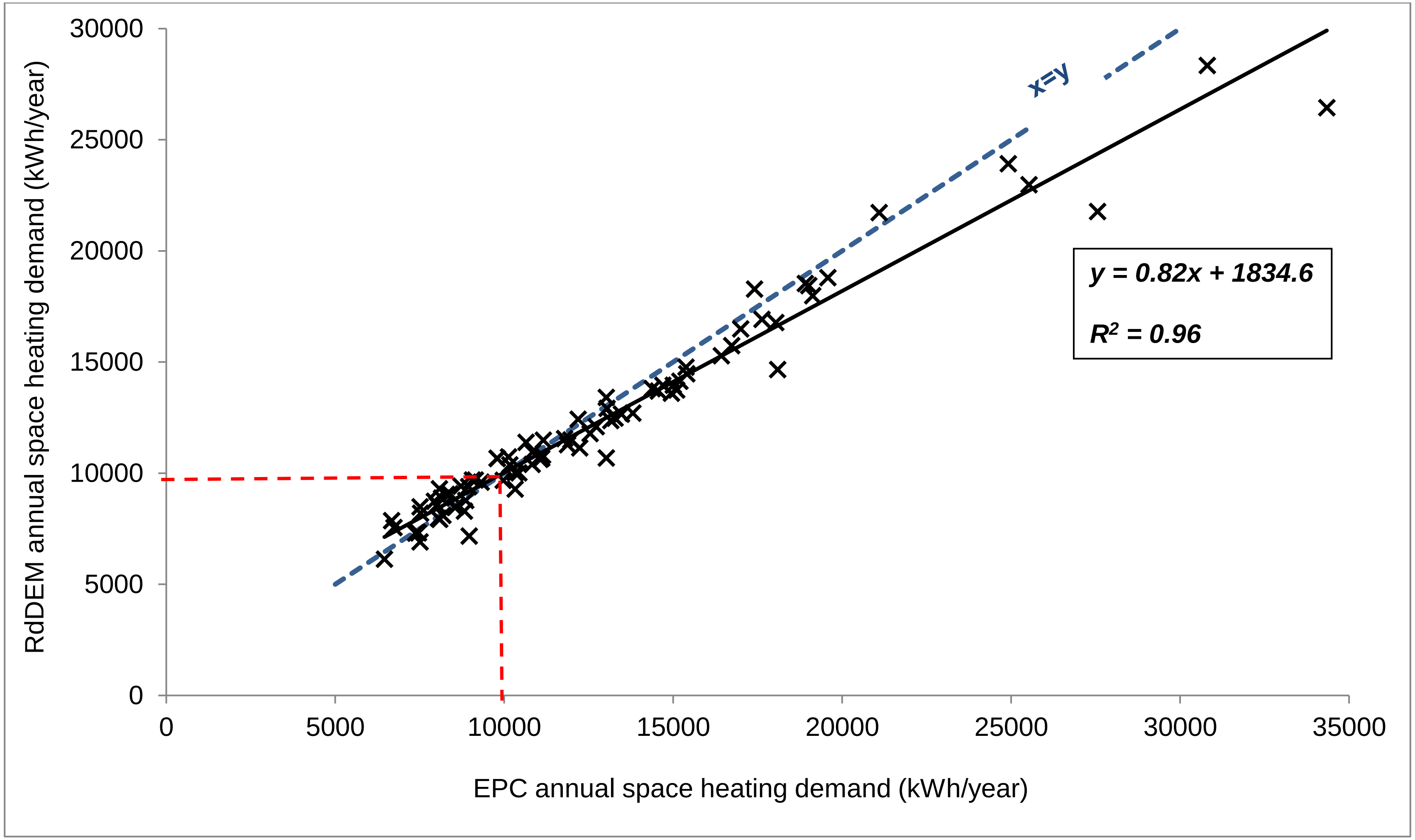


Figure 6.5 Comparison of space heating demand predictions for 83 modelled dwellings

The RdDEM predicts lower mean, median, maximum and minimum values of the annual space heating demand for 83 modelled houses. The overall distribution of annual space heating data was tighter compared to SAP. Bottom half of data (first quartile) showed closer alignment between SAP and RdDEM predictions compared to top half (third quartile) which once again highlights better alignment of RdDEM and SAP estimates in houses with less than 15000 kWh/year annual space heating demand. Despite the larger difference observed in the two models predictions in higher annual space heating demands, the close mean and median values show a close alignment of annual space heating demand in majority of the modelled houses.

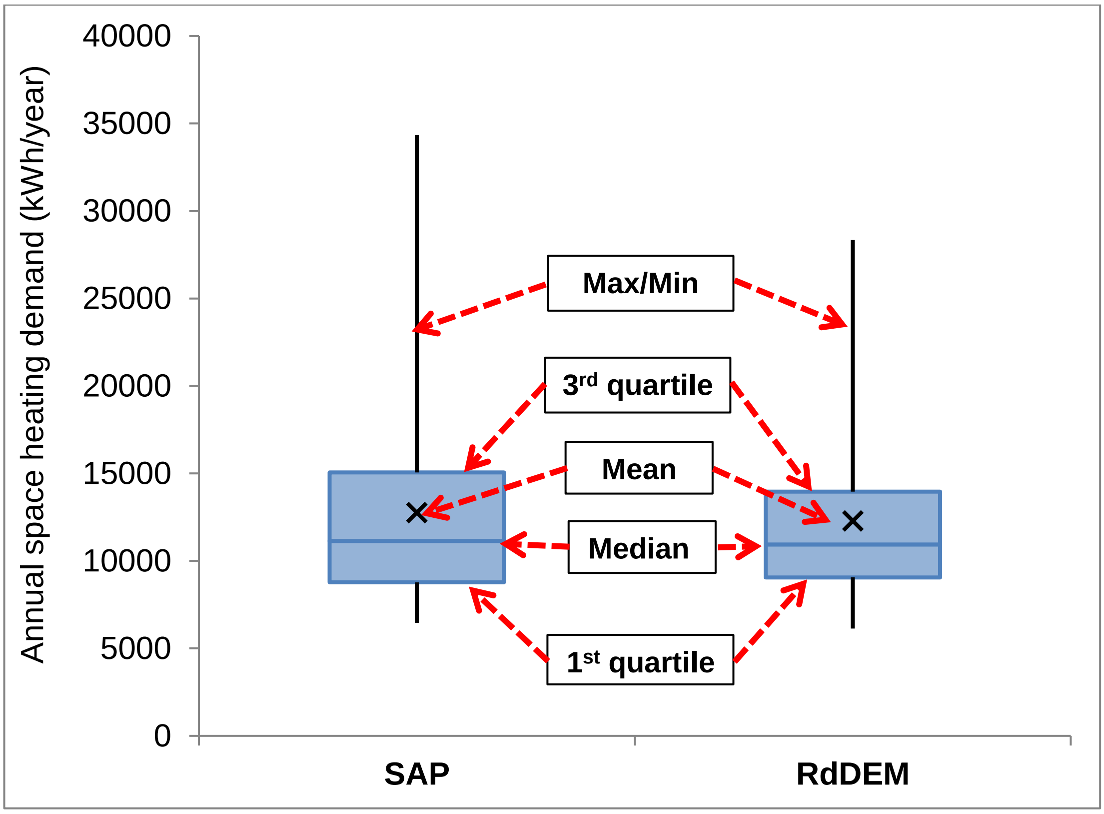


Figure 6.6 Comparison of the distributions of the annual space heating demand predictions for the 83 modelled dwellings

6.4.2. Comparison of Temperature Predictions to SAP Results

The mean monthly internal air temperature predictions from the RdDEM were compare to SAP for the heating season (Figure 6.7). For SAP, the methodology described in the SAP spreadsheet section 7 (see APPENDIX B) was used to calculate mean internal temperatures for each month. The data points shown in Figure 6.7 are categorized into 5 groups based on the comparison of annual space heating demand predictions:

i. The houses with less than 5% difference between RdDEM and SAP predictions of annual space heating demand,

ii. The houses where RdDEM predicts higher annual space heating demand by 5-10%,

iii. The houses where RdDEM predicts lower annual space heating demand by 5-10%,

iv. The houses where RdDEM predicts higher annual space heating demand by more than 10% and,

v. The houses where RdDEM predicts lower annual space heating demand by more than 10%.

As seen in Figure 6.7, RdDEM generally predicts lower mean monthly internal air temperatures throughout the heating season. In most of the months there is a clear difference between data points based on the difference in annual space heating demand predictions. In general, the RdDEM temperatures are higher when the energy demand predictions are also higher. This trend shows that the difference in space heating demand can be explained by the difference in internal air temperatures. The RdDEM tends to predict lower internal air temperatures and consequently lower energy demands.

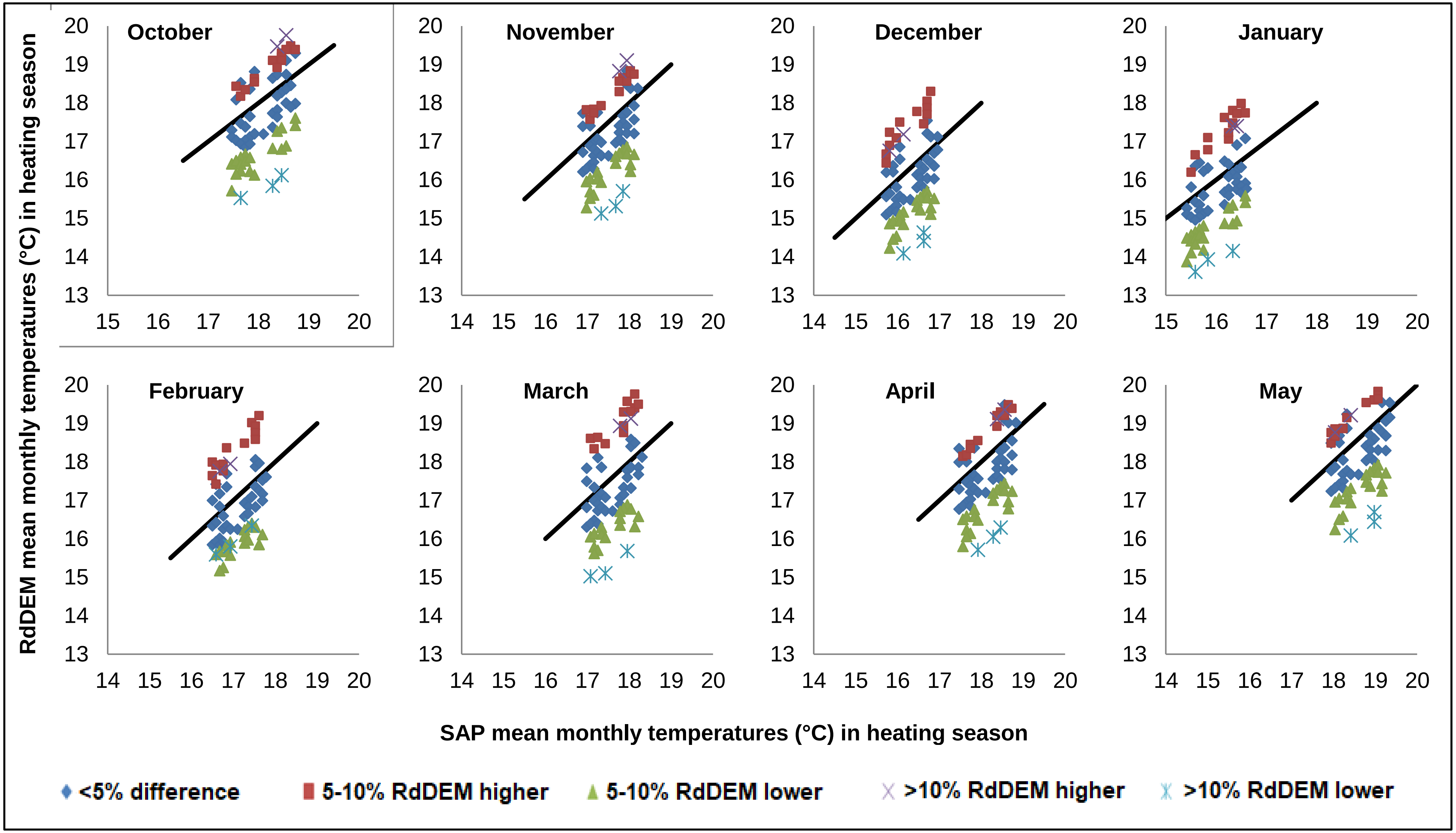


Figure 6.7 Comparison of RdDEM mean monthly internal temperature predictions to SAP (The black line represents x=y)

The house models which predicted lower annual space heating demand by more than 10%, also predicted lower mean monthly internal temperatures to the same amount in all the months except for February. The distribution of the results for February is slightly different to other months and this could be related to relatively higher solar gains compared to December and January. Overall, the RdDEM gives a wider range of temperatures than SAP. The house models which predicted higher annual space heating demand by more than 10%, however, showed a more stable trend throughout the heating season. More work is required to understand these differences and their implications on the accuracy of predictions. This work, as an inter-model comparison, can only highlight the difference but cannot say which is right or wrong.

The average difference between minimum and maximum indoor air temperatures of the houses predicted by RdDEM is 4.6°C which is considerably larger the 1.3°C difference predicted by SAP. As seen in Figure 6.8, RdDEM gives a wider prediction of internal air temperature than SAP in all the heating season months. The RdDEM tends to predict higher maximum mean temperatures and lower minimums. These distributions suggest that SAP constrains the internal temperature estimates more than RdDEM. This trend also suggests RdDEM is more sensitive to external temperatures than SAP.

The mean, median and first quartile predicted by RdDEM (Figure 6.8) is constantly lower than SAP. However, the third quartile is lower in warmer months and higher in colder months. However, some of this variation cancels out when the annual energy demand is considered (Figure 6.6). Future work could look at a comparison of the monthly energy demand predictions of the two models, but the EPC data used in this study only included annual demand.

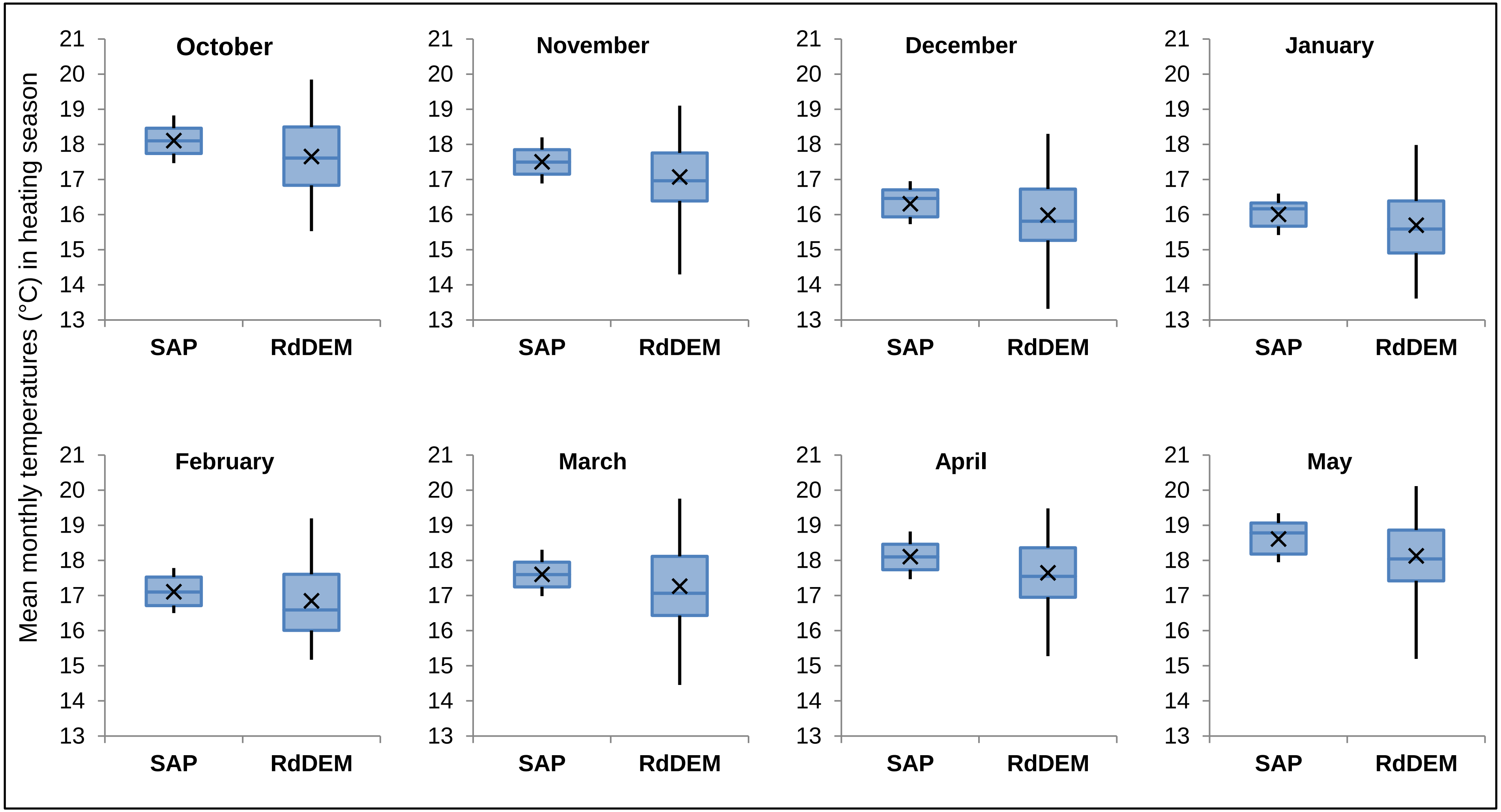


Figure 6.8 Comparison of the distributions of mean monthly internal air temperature

6.4.3. Comparison of the Predicted Energy Improvements

This section compares the RdDEM and SAP predictions of the energy savings that result from improving the energy efficiency of the dwellings in the modelling dataset. The introduced energy saving measure was improving U-values of the external walls by 20% by adding wall insulation. The comparison was done on three of the modelling dataset houses. The same test houses which were employed in verifying the data preparation and translation process (Section 6.3) were used in this part of study. The test houses had different external wall types, U-values, age band, total areas, roof insulation thickness, and ground floor types as shown in Table 6.2. All the dwellings had 100% double glazing, and pitched roof. Test house 1 has no extension while test houses 2 and 3 each have one extension.

Table 6.2 External wall improvements on the three test houses and corresponding wall types, U-values, age bands, total areas, roof insulation, and ground floor types

Improved House	External wall construction	Wall U-value (W/m^{2}K)	Age band	Total area (m^2)	Roof Insulation (mm)	Ground floor type
Test House 1	Filled cavity	0.6	D	79	0	Solid
Test House 2	Solid brick, no insulation	2.4	B	146	100	Suspended
Test House 3	Cavity, no insulation	1.8	D	151	0	Solid

The U-value improvement of external walls was done by improving the filling material of the external walls in test house 1 and by adding insulating layers to test houses 2 and 3 (Table 6.3). The insulating layer used to improve the U-values was the same material used in the filled cavity wall type: phenol-rigid foam. The improved U-values shown in the Table 6.3 take into account the thermal bridging in the external walls (see Section 3.3.3).

Table 6.3 Improved external wall constructions, thickness and the physical properties of each layer of materials

Improved wall types and U-values as modelled in the RdDEM	**Construction Details**				
	Materials (outermost to innermost layer)	**Thickness (m)**	**Density (kg/m^3)**	**Thermal Conductivity (W/mK)**	**Specific Heat Capacity (J/kgK)**
Solid Brick (U=1.9 W/m^2K)	Brick	0.205	1700	0.77	1000
	Foam (phenol-rigid)	0.025	110	0.035	1470
	Dense plaster	0.015	1300	0.57	1000
Cavity (U=1.4 W/m^2K)	Brick	0.105	1700	0.77	1000
	Air gap	0.035	N/A	N/A	N/A
	Brick	0.105	1700	0.77	1000
	Foam (phenol-rigid)	0.035	110	0.035	1470
	Dense plaster	0.015	1300	0.57	1000
Filled Cavity (U=0.5 W/m^2K)	Brick	0.105	1700	0.77	1000
	Foam (phenol-rigid)	0.040	110	0.035	1470
	Brick	0.105	1700	0.77	1000
	Dense plaster	0.010	1300	0.57	1000

The improvements were implemented in both RdDEM and SAP model and resultant energy savings were compared (Table 6.4). Table 6.4 summarises the annual space heating demand predictions before and after implementing the external wall improvements.

Table 6.4 Annual space heating demands from SAP and RdDEM, before and after external wall improvements in the test houses and the percentage reductions

Improved House	Annual space heating demand (kWh/year)				SAP demand reduction	RdDEM demand reduction
	SAP	**RdDEM**	**Improved SAP**	**Improved RdDEM**		
Test house 1	11067	10624	10713	10221	3.2%	3.8%
Test house 2	19581	18798	18250	17256	6.8%	8.2%
Test house 3	25533	22980	24180	21624	5.3%	5.9%

As seen in Table 6.4, both models estimated the largest improvements for the test house 2 and the lowest for test house 1.

Similar to the annual space heating demand estimates before improvements (Figure 6.5), RdDEM predicted lower improved annual space heating demand compared to SAP. In general, RdDEM predictions for space heating demand were lower than SAP but the savings predictions were slightly higher.

The very small differences (less than 2%) observed in the space heating reduction predictions of the RdDEM and SAP once again verified the data preparation and translation process used for developing a SAP equivalent dynamic energy model. The tendency of RdDEM to predict lower demand improvements, on the other hand, highlighted the characteristic differences of the dynamic and steady-state models.

6.5. Summary

This chapter described the translations process used in the RdDEM to convert the reduced data from the XML format used for EPCs into the Input Data File (IDF) format used by EnergyPlus and completes objective 4 (*Develop and test a reduced data dynamic energy model of UK dwellings that* *translates the prepared data into a form suitable for dynamic simulation using established models*). The results of using the RdDEM to simulate 83 dwelling from the DEFACTO dataset were compared with the SAP completing the final objective: Objective 5 (*Compare the results of the reduced data dynamic energy model with those from equivalent steady-state models*).

The translation process used a template IDF (TIDF) which included all of the fixed data required for creating individual IDFs for the dwellings in the modelling dataset. The translator handled the varying data and implemented all of the data preparation process in readiness for being written into the TIDF. The translation and data preparation processes were successfully verified: the process of enhancing the reduced data resulted in predictions that were around 5% higher than a more detailed model.

The RdDEM was successfully used to run EnergyPlus simulations of the 83 dwellings in the modelling dataset, using just the EPC XML data. The RdDEM predicted lower space heating demand in 60 dwellings. The minimum difference between predictions was 74 kWh/year (1%) while the largest difference was 5898 kWh/year (17%). The majority of the results were within 5% and only 5 were estimated with more than 10% difference. It was found that the difference in energy results could largely be explained by differences in the predicted internal air temperatures. The RdDEM predicted lower internal air temperatures in the majority of the modelled dwellings and gave a wider range of mean monthly temperatures in the heating season compared to SAP. Predictions of the energy savings from wall insulation in three of the houses showed reasonable agreement, though the RdDEM predicted lower energy demand and slightly higher percentage savings.

7. DISCUSSION

7.1. Introduction

This chapter provides an overview of the body of work presented in this thesis. The achievements against the aim and objectives are highlighted alongside the contributions to knowledge. The limitations of the work are quantified and finally, the application of the modelling framework presented here is expanded for academia, policy makers and industry.

7.2. Overview of Thesis and Achievements

Saving energy in the residential sector and in particular heating energy is essential to achieve the UK's 2050 carbon emissions reduction target. In recent years, a variety of models have been developed to analyse energy and environmental performance of domestic buildings, and investigate impact of different strategies that are designed to reduce energy consumption, reduce carbon emissions, and improve occupant's thermal comfort. In the UK, as part of government's plans to achieve carbon emission targets, the Energy Performance Certificates (EPCs) were introduced and it was made compulsory to present EPC and improvement recommendations when an existing or new home was let or sold. This initiative resulted in collection of vast majority of EPC data on the UK dwellings. EPCs are developed using government's Standards Assessment Procedure (SAP) which is based on steady-state BREDEM calculations to predict energy consumption and carbon emissions in the dwellings. A critical analysis of UK based domestic energy and emission models, and dynamic energy models of different housing stocks were carried out to complete the Objective 1 (*Identify and review literature on the modelling approaches that could be used to forecast energy use and CO_2 emissions in the UK dwellings, and perform a critical analysis of the work that has been undertaken to utilize available reduced data for energy modelling purposes*)

The dataset used for modelling was formed of XML files which were created for producing EPCs for 83 semi-detached dwellings located in Midlands region of the UK. In choosing this dataset a few points were considered:

i. The dataset was conveniently accessible as it was collected by DEFACTO project which was running in the School of Architecture, Building and Civil Engineering, Loughborough University at the time of this research.

ii. The XML files provided great advantages in handling and modifying data compared to traditional text based datasets in hard copy format.

iii. The amount of data provided in the dataset was suitable for modelling the dwellings using the freely available SAP spreadsheet without any need for further modification of data or assumptions, which provided a great opportunity for inter-model comparison of results.

iv. Besides the XML files, the dataset included approximate floor plans which were used in developing more detailed models of the dwellings to verify the results from the reduced data dynamic energy model.

Selecting the EPC XML files as modelling dataset completed Objective 2 (*Identify a suitable dataset of UK dwellings to be used as the source of modelling data*).

Faced with the problems regarding availability of required data for running dynamic simulations of the UK dwellings, a great deal of time and effort was spent on developing suitable algorithms to enhance the reduced data available in EPC datasets in order to be used in dynamic simulation of the dwellings. The outcome of this part of the work was development of a set of SAP equivalent data which, while remaining equivalent to the original EPC datasets, contained enough details to run dynamic simulations.

In order to develop the equivalent dataset, the areas with insufficient details in the modelling dataset had to be enhanced. Two main issues were identified: Zoning and Geometry. SAP and majority of UK steady-state domestic energy models (described in Section 2.4) are two zone models separating the living area from rest of the house while a few models use only one zone to model whole dwelling. As for dynamic energy models, the Canadian Residential Energy End-use Model (CREEM) developed by Farahbakhsh, Ugursal and Fung (1998) assumed only one thermal zone for main building parts of the modelled dwellings. The He et al. Model developed by He, Lee, Taylor, Firth and Lomas (2014), on the other hand, followed SAP approach in zoning and considered two zones separating the living area from rest of the house. These authors justified their choice of zoning strategy by highlighting the lack of necessary zoning details and identifying literature with suitable outputs to support their choice of zoning strategy.

Prior to this research there was a research gap in identifying the suitable zoning strategy to model the UK dwellings using dynamic simulation. This research investigated different zoning strategies and provided evidence on suitability of the two zone models in dynamic simulation of the UK dwellings, where each floor was assigned with an individual thermal zone. The zoning strategies investigated included: a single zoning strategy, floor zoning and SAP zoning (see Section 4.3). These strategies were compared to a detailed reference model where each habitable room was assigned with an individual thermal zone (see Section 4.2).

The considerable difference in annual and monthly demand estimates of the models with different zoning strategies highlighted the importance of zoning configuration in modelling exercises. The sensitivity of whole building energy models like RdDEM to zoning configuration was observed in the model results. Such sensitivity analysis was missing in the previous modelling studies which added to the uncertainty of model outputs. The sensitivity of zoning configuration was investigated in this thesis using a reference semi-detached dwelling. Expanding the zoning sensitivity analysis findings to other dwelling types would require further investigation which wasn't in the scope of this research.

The reference model used in this study to investigate zoning strategies was created based on Allen and Pinney (1990) Standard Dwellings Types. This document describes the common UK house types with enough detail that could be modelled without further need for assumptions. Allen and Pinney Standard Dwellings Types document is a well-known source of reference and has been used previously in many other modelling studies. Firth, Lomas and Wright (2010) used it to identify the archetypes in Community Domestic Energy Model (CDEM); Taylor, Allinson, Firth and Lomas (2013) modelled the period terraced house from Allen and Pinney (1990) Standard Dwellings Types at nine different levels of detail to study the impacts on energy consumption; Yilmaz, Allinson, Taylor and Lomas (2014) modelled the semi-detached house from Allen and Pinney (1990) Standard Dwellings Types and compared the space heating energy predictions from SAP, EnergyPlus, ESP-r, SERI-RES, BREDEM-8, and BREDEM-12 models.

The reference model was extended to investigate the approach used for modelling detailed geometry using reduced data (see Section 4.4). Lacking geometry details in the datasets is one of the main issues raised by previous dynamic energy modelling studies (Farahbakhsh et al., 1998; Swan et al., 2009; He et al., 2014) and each study dealt with this issue in different way. Swan et al. (2009) assumed a rectangular geometry layout and developed an average width to length ratio which was applied to all the modelled dwellings. He et al. (2014) considered two geometrical layouts: a rectangular and an L-shaped layout. In this PhD the rectangular approach proposed by Swan et al. (2009) was adopted but the width to length ratio which was found to add a considerable uncertainty to model outputs was improved. Instead of applying a fixed ratio to all dwellings, the 'Excess Area Block' approach was developed (see Section 04.4.1). This approached made it possible to model the exact floor area, exposed perimeter, and party wall length as identified in the dataset. The approach was tested on an extended form of the reference model by comparing main outputs from a detailed L-shaped reference model to outputs from a reduced geometry model incorporating the 'Excess Area Block' approach. The monthly mean internal temperatures and space heating demand predictions from the two models were closely matching.

Prior to this study no peer reviewed or documented research had looked into creating detailed geometries in dynamic simulation while staying completely loyal to the reduced dataset. The models developed by Farahbakhsh et al., 1998; Swan et al., 2009, and He et al., 2014 all made assumptions to handle lacking geometry details in the model without presenting a sensitivity analysis of the assumptions made. Consequently, the uncertainty added to model outputs in these studies wasn't quantified. This research, in contrary to previous modelling exercises, avoided introducing new assumptions to model geometry and dealt with the missing geometry details in a novel and efficient way.

Development of the equivalent dataset and enhancing zoning and geometry details made the results from RdDEM comparable to SAP and completed Objective 3 (*Develop and test a data preparation process that will enhance the reduced data in order to produce an equivalent set of detailed data that is suitable for dynamic energy simulation*).

The prepared data was written into EnergyPlus Input Data Files (IDFs) through the Template IDF (TIDF) and the translator developed in MATLAB (see Section 6.2). The data preparation and translation process were tested twice: once using the reference model, and once using three actual dwellings from the modelling dataset. The first test compared model outputs from 4 different models of the reference model with different levels of details. These models were: a detailed DesignBuilder model, a reduced EnergyPlus model with manual data input, a reduced EnergyPlus model with translator data input, and an SAP model. The second test was run on three dataset dwellings which represented the three cuts of the dataset based on space heating demand as reported in EPCs. The RdDEM outputs of these dwellings were compared to more detailed dynamic energy models.

The inter-model comparison with more detailed models has been used by other modelling exercises as well to verify model results. Clarke, Johnstone, Kim and Tuohy (2009) verified results of The Energy Systems Research Unit (ESRU) Domestic Energy Model (EDEM) using detailed models of 5 real houses. The results indicated discrepancies ranging from 3% to -13%, indicating that their modelling approach is a reasonable proxy for the real situation (Clarke et al., 2009).

The development of this model eliminated the additional time and cost associated with collecting further data and modelling each of the homes individually; and completed Objective 4 (*Develop and run a reduced data dynamic energy model of UK dwellings that translates the prepared data into a form suitable for dynamic simulation using established models*). The methods used in developing equivalent data enabled a unique inter-model comparison to be carried out across 83 buildings. Similar results were obtained from dynamic and steady-state models when the equivalent inputs were fed to each model.

This was the first dynamic energy modelling exercise to be undertaken using the EPC data for a set of UK dwellings. The reduced data dynamic energy model introduces a set of new methods for enhancing reduced data in order to create equivalent detailed geometry and zoning information. Ultimately, the techniques developed here can be used to provide new insights into the transient aspects of energy use and indoor air temperatures in the UK housing stock and therefore has value as both a policy and a research tool.

7.3. Model Predictions and Comparison with SAP

Simulations were run using the completed RdDEM and results were compared to equivalent steady-state SAP model to complete the Objective 5 of this study (*Compare the results of the reduced data dynamic energy model with those from equivalent steady-state models*). The model predictions showed RdDEM predicts lower annual space heating demand compared to SAP in majority of the houses. The RdDEM predicted higher annual space heating demand only in 28% of the houses and predicted lower annual demand in 72% of the houses compared to SAP results. The RdDEM's tendency to predict lower space heating demand was previously observed in other studies comparing a dynamic energy model to a steady-state one. Shorrock et al. (1996) modelled the semi-detached dwelling described by

Allen and Pinney (1990) in dynamic energy software ESP-r and SERI-RES, and compared the annual space heating demands to steady-state BREDEM-8 and BREDEM-12 models of the same dwelling. Both dynamic energy models underestimated the annual space heating demand compared to both BREDEM-8 and BREDEM-12 steady-state models. Yilmaz et al. (2014) modelled the same semi-detached dwelling in SAP 2009 and EnergyPlus where the dynamic EnergyPlus model underestimated the annual space heating demand compared to steady-state SAP model.

The RdDEM predicted annual space hating demand in 94% of the houses in the dataset within 10% margin of SAP estimates. The close alignment between RdDEM and SAP predictions verified the data preparation process to develop SAP equivalent input data. When compared to steady-state model estimates, the RdDEM with SAP equivalent input data performed better that the dynamic energy models developed by Shorrock et al. (1996) and Yilmaz et al. (2014). The ESP-r model developed by Shorrock et al. (1996) and the EnergyPlus model developed by Yilmaz et al. (2014) underestimated annual space heating demand with more than 18% difference to BREDEM and SAP steady-state models.

The rate of reduction in space heating demand predicted by RdDEM when subjected to same set of improvements were less than 1.4% different to steady-state SAP predictions. Shorrock et al. (1996) and Yilmaz et al. (2014) also investigated the potential savings from improving building fabric. The difference they found between dynamic and steady-state models ranged from 1.7% to 11.2%. The closer alignment between RdDEM and SAP in predicting space heating demand reduction compared to previous modelling exercises once again approves the successful data preparation process which has resulted in two equivalent models with close results. In the previous studies by Shorrock et al. (1996) and Yilmaz et al. (2014) the dynamic models predicted smaller improvements in space heating demand compared to steady-state models. In contrary to these studies, the RdDEM predicted larger improvement in space heating demand compared to SAP.

7.4. Limitations of the Research

This research addressed limitations of the previous energy models developed for UK houses (summarised in Section 2.7) by introducing a transparent dynamic alternative to traditional steady-state BREDEM calculations. The RdDEM was capable of taking into consideration the complex and dynamic nature of the energy consumption in the dwellings while using the same input data source as the steady-state SAP. However, this research had limitations which should be addressed by the future work. The limitations of this research can be summarised as follows:

- This research used the semi-detached dwelling description from Allen and Pinney (1990) Standard Dwellings Types to develop the reference model which was used to investigate the zoning and geometry enhancements. The Standard Dwellings Types by Allen and Pinney (1990) is a relatively old document and the house descriptions specified in this document had some major differences to the dwellings modelled in this study. These differences were observed in level of external wall insulation, loft insulation, and glazing types. Consequently, the outcomes of zoning and geometry studies were based on an old semi-detached dwellings type with poorer insulation and air tightness which increased the level of uncertainty when the same outcomes were applied to modelled dwellings.

- Despite including the most common semi-detached dwelling types, the model developed in this research doesn't take into account the dwellings with conservatories, room in roofs, and dwellings with more than one extension.

- The SAP equivalent weather data was re-created based on the details provided in SAP 2012 and a typical weather data file for Midlands region of UK. Although this weather file was the closest that could have been achieved to SAP weather data, it includes uncertainty due to insufficient amount of weather details provided by SAP.

- Despite the close alignment achieved between RdDEM and SAP results, this study was not able to conclude which model predicted the space heating demand more accurately and closer to actual consumption of the dwellings.

- The RdDEM was constructed on MATLAB platform. Although this platform is suitable for prototyping, it has not been possible to develop a user interface for the model.

7.5. Implications of the Research

The model developed based on reduced data will have a number of important implications for academia, industry and policy makers. The findings presented in this thesis provided insight into the complex relationship between amount of input data available and the level of complexity of models. Prior to this research many studies had identified the lack of real life data required for energy modelling as main issue in developing robust and detailed models. This study for the first time investigated the possibility of developing detailed dynamic energy models based on reduced data suitable for simple steady-state models. The data preparation process described in this thesis was able to develop a set of SAP equivalent data which was suitable for dynamic simulation. The most important implication of this research for academia and policy makers is that regardless of level of complexity the model has, if the required input data is not fed to the model, the model will fail to capture the reality of energy consumption in buildings. Although dynamic models are capable of solving more complex and detailed heat transfer equations, feeding these models with reduced data will transform them into simple reduced level models which are not capable of using their full potentials to predict realistic energy consumption in dwellings. Hence, the similar performance gap observed between steady-state model results and real life data will be observed in dynamic energy model results as well.

This research also established the grounds to use dynamic energy simulation in evaluating energy and environmental performance of dwellings for policy making decisions and developing more detailed EPCs. Current regulations only make use of dynamic simulation compulsory for commercial buildings due to higher cost associated with gathering required data and also higher level of expertise and time required for developing dynamic energy models. The possibility of using reduced data, which is already available on the UK dwellings, for dynamic simulation purposes provides a great opportunity to use capacities of dynamic models in introducing robust policies. The algorithms developed for producing SAP equivalent input data for dynamic energy simulation proved to be capable of predicting energy consumption and temperature distribution of dwellings with close alignment to SAP predictions. The use of dynamic energy simulation will enable policy makers to use wider range of hourly and sub-hourly model predictions to put stronger and more practical policies into action.

The capacities of a reduced data dynamic energy model will also benefit energy providers by providing hourly consumption predictions which will enable the energy providers to identify peaks of consumption in district or national level. A good example of the implications this research has in energy management industry is the capability of the RdDEM to predict space heating and hot water energy demand of groups of existing dwellings, which are heated by community energy systems. The model can predict likely consumption of community dwellings for the next day or two which will enhance the energy management process by providing energy forecast data for a specific group of dwellings. In this way, the RdDEM will pave the way for developing better community energy management systems, especially in urban areas.

7.6. Summary

This chapter discussed the process of developing SAP equivalent input data for dynamic simulation and development of the reduced data dynamic energy model (RdDEM). The chapter started with revisiting the methodology employed to investigate the possible design solutions and decisions made in developing the model. The choice of modelling dataset and the reference model used to examine design solutions was discussed and related literature were cited to support the decisions made in the process of preparing data. The two main methodological enhancements made to model zoning and geometrical aspects of the dwellings were also discussed.

The chapter continued with discussion of model results (Section 7.3). Annual space heating demand and mean monthly internal temperature predictions from the model was compared to other modelling studies. The difficulties of data preparation process and developing SAP equivalent input data for dynamic simulation and the limitation of the research were explained in Section 7.4. Finally, the possible implications that the model described in this thesis has for the academia, the policy makers, and the industry were presented in Section 7.4.

8. CONCLUSIONS

8.1. Introduction

This thesis has described the development of a Reduced Data Dynamic Energy Model (RdDEM) for simulating the energy performance of UK houses. The RdDEM eliminates the main drawback associated with dynamic energy modelling, namely: the large amount of required input data compared to steady-state models, by employing a reduced set of data which was originally collected for EPC models. The enhanced zoning and geometry details together with SAP equivalent constructions and boundary conditions were used to develop the RdDEM which is equivalent to the steady-state SAP and the results are comparable.

8.2. Summary of the Main Conclusions

The critical analysis of existing energy models of the UK dwellings revealed the incapability of these models in fully capturing the reality of energy consumption in the dwellings. All the steady-state models developed for UK housing stock were criticised for their low level of transparency. These models were not capable of taking into consideration the complex, interdependencies, and dynamic nature of the energy consumption and carbon emission. Furthermore, the uniformity of the assumptions made by these models resulted in systematic errors that could have negative consequences for energy policy making, and the targeting of energy efficiency measures.

This thesis presented the work undertaken to use a dynamic energy simulation software to overcome the limitations of the steady-state models like SAP. The main concern in using the dynamic simulation to predict energy consumption of the domestic buildings is the larger amount of required input data compared to steady-state models. This issue was overcome by employing the existing EPC datasets as main source of data. Prior to this research, there was no peer reviewed published literature to indicate potential of reduced datasets like EPC, which was originally developed for steady-state models, for dynamic simulation purpose.

The two main area for improvements were identified as zoning and geometry. The methods developed by previous studies to handle reduced zoning and geometry details were improved and employed in the RdDEM.

8.2.1. Methodological Conclusions

The most suitable zoning and geometry modelling strategies using the reduced zoning and geometry details in the modelling dataset were investigated. The reference model, which was developed based on common UK semi-detached dwelling described by Allen and Pinney (1990), was used as a base case and a comparator in investigating suitability of different zoning strategies and geometry modelling techniques. Three different zoning strategies were investigated: a single zone strategy, a two zone strategy assigning individual thermal zones to each floor of the dwellings (floor zoning), and a two zone strategy assigning the living area with one and the rest of the house with another thermal zone (SAP zoning). The summer and winter results were studied and compared to the reference model:

- Under summer conditions, the choice of zoning didn't have significant impact on temperatures but evidence showed that 'Floor' zoning had closer estimates to the reference model. Under winter conditions, choice of zoning showed a more significant impact on indoor temperatures. 'SAP' zoning gave closer estimates to the reference model under winter conditions.

- The 'Floor' zoning strategy showed the closest space heating demand to the reference model. Considering both internal temperatures and space heating demand estimates of the three zoning strategies, choice of 'Floor' zoning was shown to be the most suitable strategy to model the dataset houses. ‘Floor’ zoning was also preferred over ‘SAP’ zoning due to unknown location of the living room in the dataset houses.

- Hence, the ‘Floor’ zoning was found to be better suited to modelling the UK semi-detached dwellings available in the modelling dataset and this method was chosen for implementation in the RdDEM.

A methodology was developed to preserve all the geometrical details given in the modelling dataset, while creating the full three-dimensional geometry which could be used in dynamic simulation of the dwellings. The proposed methodology introduced an ‘Excess Area Block’ to the model. In this way the correct floor area, heat-loss perimeter and party wall length, as identified in the modelling dataset, was conserved for all the dwellings. The suitability of this method was tested on an extended version of the reference model.

- The predictions from the model with reduced geometry details were compared to that of the detailed reference model, and a very close alignment within 1% difference was achieved.

- The methodology was also tested when extensions were present and a similar close alignment was observed between the predictions of the model with reduced geometry and detailed reference model. The close alignment of models predictions showed that this methodology was suited to be used in the RdDEM.

8.2.2. Model Verification

The method developed for creating SAP equivalent input data, zoning strategy, and enhanced geometry details were tested and verified through comparison with more detailed models. The verification process was carried out in two steps: once using the detailed reference model and once using detailed models of three actual dwellings from the modelling dataset.

The close alignment of the results from RdDEM with SAP verified the developed methodology for creating SAP equivalent input data. On the other hand, the close alignment between RdDEM and more detailed dynamic model predictions, which was less than 5% different in all the studied houses, verified the data preparation process developed to model geometry, thermal mass and zoning using reduced data.

8.2.3. RdDEM Results and Comparison with SAP

Simulations were run on the 83 modelled houses. The annual space heating demand and monthly internal temperatures predictions from the RdDEM were compared to the SAP results. The estimated reductions in the annual space heating demand from the two models when subjected to same set of external wall improvements were also compared. Following is a summary of main conclusions from the comparisons of the RdDEM and SAP predictions:

- The RdDEM predicted higher annual space heating demand in 28% of the modelling dataset houses and lower annual space heating demand in 72% of the houses compared to SAP estimates. The differences observed between RdDEM and SAP was 1-17%.

- Annual space hating demand in 55% of the houses in the modelling dataset was predicted with less than 5% difference to SAP, in 39% of the houses with 5-10% difference and only in 6% of the houses the predicted annual space heating was more than 10% different to SAP results.

- The RdDEM as a dynamic simulation tool predicted slightly lower internal temperatures and consequently the lower energy demands compared to SAP in majority of the modelled dwellings.

- The RdDEM gave a wider range of mean monthly temperatures in heating season compared to SAP which suggested the assumption made in SAP constrains the temperature predictions.

- The RdDEM predicted lower improved space heating demand compared to SAP for the three studied test house.

8.3. Recommendation for Future Research

The work undertaken within this thesis is an important first step towards understanding the potential of equivalent dynamic energy models over currently used steady-state models for building evaluation and policy making decisions. In this context, several areas of future research have been identified:

- The work presented here has concentrated on the development of equivalent SAP data for a set of semi-detached dwellings. All the decisions were made based on studies performed on the UK common semi-detached dwellings. To get this model to work for entire housing stock, one of the most important areas of future work would be to include other dwellings types (Detached, terraced, and flats) in the data preparation process for the model. This would require identifying further construction materials, new geometries and zoning configurations.

- The model results were verified through comparison of space heating demand and indoor temperatures to more detailed models and to SAP predictions. The other very important area of future work would be to compare the RdDEM predictions with measurements in the modelled dwellings when heating system settings and internal gains are matched.

- The model predictions provide a great opportunity for future studies to investigate impact of future weather conditions on existing dwellings. A detailed overheating analysis based on hourly results when the internal boundary conditions are matched with TM59 would provide insight into the measures that will be required to be taken in the future in order to maintain occupant's comfort in the dwellings.

- Once this model is completed, the algorithms developed for creating SAP equivalent inputs from reduced data will be of significant value as a dynamic alternative to current steady-state policy making tools when transient variations in energy demand and indoor air temperatures are required.

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APPENDIX A

Example of Energy Performance Certificate (EPC)

Energy Performance Certificate (EPC)

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17 Any Street, District, Any Town, B5 5XX

Dwelling type:	Detached house	**Reference number:**	0000-0000-0000-0000-0000
Date of assessment:	15 August 2011	**Type of assessment:**	RdSAP, existing dwelling
Date of certificate:	12 December 2011	**Total floor area:**	165 m²

Use this document to:

- Compare current ratings of properties to see which properties are more energy efficient
- Find out how you can save energy and money by installing improvement measures

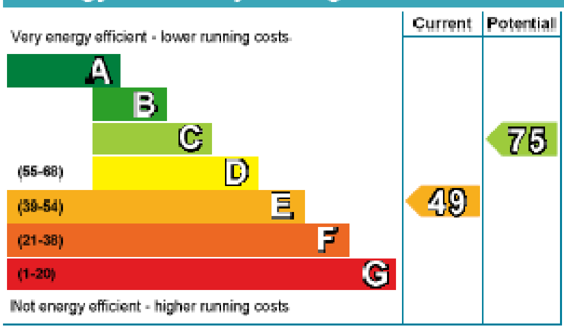
Estimated energy costs of dwelling for 3 years	**£5,367**
Over 3 years you could save	**£2,763**

Estimated energy costs of this home

	Current costs	Potential costs	Potential future savings
Lighting	£375 over 3 years	£207 over 3 years	You could save £2,763 over 3 years
Heating	£4,443 over 3 years	£2,067 over 3 years	
Hot water	£549 over 3 years	£330 over 3 years	
Totals	**£5,367**	**£2,604**	

These figures show how much the average household would spend in this property for heating, lighting and hot water. This excludes energy use for running appliances like TVs, computers and cookers, and any electricity generated by microgeneration.

Energy Efficiency Rating



The graph shows the current energy efficiency of your home.

The higher the rating the lower your fuel bills are likely to be.

The potential rating shows the effect of undertaking the recommendations on page 3.

The average energy efficiency rating for a dwelling in England and Wales is band D (rating 60).

Top actions you can take to save money and make your home more efficient

Recommended measures	Indicative cost	Typical savings over 3 years	Available with Green Deal
1 Increase loft insulation to 270 mm	£100 - £350	£141	✔
2 Cavity wall insulation	£500 - £1,500	£537	✔
3 Draughtproofing	£80 - £120	£78	✔

See page 3 for a full list of recommendations for this property.

When the Green Deal launches, it may allow you to make your home warmer and cheaper to run at no up-front cost. To find out more, contact the Green Deal Advice Service on **0800 XXX XXX** or visit **www.greendealadvice.org**.

17 Any Street, District, Any Town, B5 5XX
12 December 2011 RRN: 0000-0000-0000-0000-0000 **Energy Performance Certificate**

Summary of this home's energy performance related features

Element	Description	Energy Efficiency
Walls	Cavity wall, as built, partial insulation (assumed)	★★★☆☆
Roof	Pitched, 75 mm loft insulation	★★★☆☆
Floor	Solid, no insulation (assumed)	–
Windows	Partial double glazing	★★☆☆☆
Main heating	Boiler and radiators, mains gas	★★★☆☆
Main heating controls	Programmer, room thermostat and TRVs	★★★★☆
Secondary heating	None	–
Hot water	From main system	★★★☆☆
Lighting	Low energy lighting in 17% of fixed outlets	★★☆☆☆

Current primary energy use per square metre of floor area: 298 kWh/m² per year

The assessment does not take into consideration the physical condition of any element. 'Assumed' means that the insulation could not be inspected and an assumption has been made in the methodology based on age and type of construction.

Low and zero carbon energy sources

Low and zero carbon energy sources are sources of energy that release either very little or no carbon dioxide into the atmosphere when they are used. Installing these sources may help reduce energy bills as well as cutting carbon. There are none provided for this home.

Opportunity to benefit from a Green Deal on this property

When the Green Deal launches, it may enable tenants or owners to improve the property they live in to make it more energy efficient, more comfortable and cheaper to run, without having to pay for the work upfront. To see which measures are recommended for this property, please turn to page 3. You can choose which measures you want and ask for a quote from an authorised Green Deal provider. They will organise installation by an authorised installer. You pay for the improvements over time through your electricity bill, at a level no greater than the estimated savings to energy bills. If you move home, the Green Deal charge stays with the property and the repayments pass to the new bill payer.

For householders in receipt of income-related benefits, additional help may be available.

To find out more, contact the Green Deal Advice Service on **0800 XXX XXX** or visit **www.greendealadvice.org**.

Recommendations

The measures below will improve the energy performance of your dwelling. The performance ratings after improvements listed below are cumulative; that is, they assume the improvements have been installed in the order that they appear in the table. Further information about the recommended measures and other simple actions you could take today to save money is available at **[link to remote advice centre].** Before installing measures, you should make sure you have secured the appropriate permissions, where necessary. Such permissions might include permission from your landlord (if you are a tenant) or approval under Building Regulations for certain types of work.

Measures with a green tick ✓ are likely to be fully financed through the Green Deal, when the scheme launches, since the cost of the measures should be covered by the energy they save. Additional support may be available for homes where solid wall insulation is recommended. If you want to take up measures with an orange tick ✓ be aware you may need to contribute some payment up-front.

Recommended measures	Indicative cost	Typical savings per year	Rating after improvement	Green Deal finance
Increase loft insulation to 270 mm	£100 - £350	£47	E 51	✓
Cavity wall insulation	£500 - £1,500	£179	D 59	✓
Draughtproofing	£80 - £120	£26	D 60	✓
Low energy lighting for all fixed outlets	£50	£43	D 61	
Replace boiler with new condensing boiler	£2,200 - £3,000	£339	C 74	✓
Replace single glazed windows with low-E double glazing	£3,300 - £6,500	£41	C 75	✓ (orange)

Alternative measures

There are alternative measures below which you could also consider for your home.

- External insulation with cavity wall insulation
- Biomass boiler (Exempted Appliance if in Smoke Control Area)
- Air or ground source heat pump
- Air or ground source heat pump with underfloor heating
- Micro CHP

Choosing the right package

Visit **www.epcadviser.direct.gov.uk**, our online tool which uses information from this EPC to show you how to save money on your fuel bills. You can use this tool to personalise your Green Deal package.

Directgov
Public services all in one place

Green Deal package	Typical annual savings
Loft insulation	**Total savings of £587**
Cavity wall insulation	
Draughtproofing	
Condensing boiler	
Electricity/gas/other fuel savings	£0 / £587 / £0

You could finance this package of measures under the Green Deal. It could **save you £587 a year** in energy costs, based on typical energy use. Some or all of this saving would be recouped through the charge on your bill.

17 Any Street, District, Any Town, B5 5XX
12 December 2011 RRN: 0000-0000-0000-0000-0000 **Energy Performance Certificate**

About this document

The Energy Performance Certificate for this dwelling was produced following an energy assessment undertaken by a qualified assessor, accredited by [scheme name]. You can get contact details of the accreditation scheme at [scheme website address], together with details of their procedures for confirming authenticity of a certificate and for making a complaint. A copy of this EPC has been lodged on a national register. It will be publicly available and some of the underlying data may be shared with others for the purposes of research, compliance and direct mailing of relevant energy efficiency information. The current property owner and/or tenant may opt out of having this information disclosed.

Assessor's accreditation number: [accredition number]
Assessor's name: [assessor name]
Phone number: [phone]
E-mail address: [e-mail]
Related party disclosure: No related party

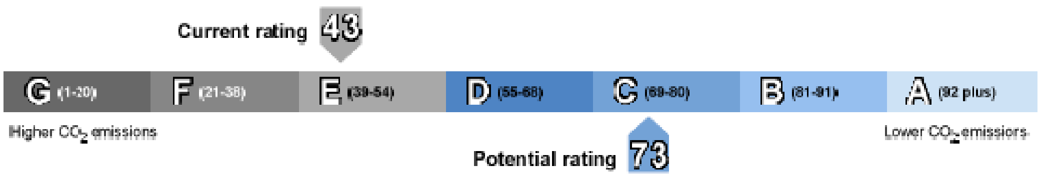
Further information about Energy Performance Certificates can be found under Frequently Asked Questions at **www.epcregister.com.**

About the impact of buildings on the environment

One of the biggest contributors to global warming is carbon dioxide. The energy we use for heating, lighting and power in homes produces over a quarter of the UK's carbon dioxide emissions.

The average household causes about 6 tonnes of carbon dioxide every year. Based on this assessment, your home currently produces approximately 9.5 tonnes of carbon dioxide every year. Adopting the recommendations in this report can reduce emissions and protect the environment. If you were to install these recommendations you could reduce this amount by 5.3 tonnes per year. You could reduce emissions even more by switching to renewable energy sources.

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.



Your home's heat demand

For most homes, the vast majority of energy costs derive from heating the home. Where applicable, this table shows the energy that could be saved in this property by insulating the loft and walls, based on typical energy use (shown within brackets as it is a reduction in energy use).

Heat demand	Existing dwelling	Impact of loft insulation	Impact of cavity wall insulation	Impact of solid wall insulation
Space heating (kWh per year)	22,154	(725)	(4494)	N/A
Water heating (kWh per year)	2,792			

Addendum

This dwelling may have narrow cavities and so requires further investigation to determine which type of cavity wall insulation is best suited.

APPENDIX B

SAP Worksheet (Version 9.92)

SAP WORKSHEET (Version 9.92)

1. Overall dwelling dimensions

	Area (m²)		Average storey height (m)		Volume (m³)
Basement	(1a)	×	(2a)	=	(3a)
Ground floor	(1b)	×	(2b)	=	(3b)
First floor	(1c)	×	(2c)	=	(3c)
Second floor	(1d)	×	(2d)	=	(3d)
Third floor	(1e)	×	(2e)	=	(3e)
Other floors *(repeat as necessary)*	(1n)	×	(2n)	=	(3n)

Total floor area TFA = (1a)+(1b)+(1c)+(1d)+(1e)…(1n) = (4)

Dwelling volume (3a)+(3b)+(3c)+(3d)+(3e)…(3n) = (5)

2. Ventilation rate

	main heating		secondary heating		other		total		m³ per hour	
Number of chimneys		+		+		=		× 40 =		(6a)
Number of open flues		+		+		=		× 20 =		(6b)
Number of intermittent fans								× 10 =		(7a)
Number of passive vents								× 10 =		(7b)
Number of flueless gas fires								× 40 =		(7c)

Air changes per hour

Infiltration due to chimneys, flues, fans, PSVs (6a)+(6b)+(7a)+(7b)+(7c) = ÷ (5) = (8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (n_s) (9)

Additional infiltration [(9) – 1] × 0.1 = (10)

Structural infiltration: *0.25 for steel or timber frame or 0.35 for masonry construction* (11)

if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35

If suspended wooden ground floor, enter *0.2 (unsealed) or 0.1 (sealed)*, else enter 0 (12)

If no draught lobby, enter 0.05, else enter 0 (13)

Percentage of windows and doors draught proofed (14)

Window infiltration 0.25 - [0.2 × (14) ÷ 100] = (15)

Infiltration rate (8) + (10) + (11) + (12) + (13) + (15) = (16)

Air permeability value, q_{50}, expressed in cubic metres per hour per square metre of envelope area (17)

If based on air permeability value, then (18) = [(17) ÷ 20]+(8), otherwise (18) = (16) (18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered (19)

Shelter factor (20) = 1 - [0.075 × (19)] = (20)

Infiltration rate incorporating shelter factor (21) = (18) × (20) = (21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table U2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$(22)_m$ =	$(22)_1$	$(22)_2$	$(22)_3$	$(22)_4$	$(22)_5$	$(22)_6$	$(22)_7$	$(22)_8$	$(22)_9$	$(22)_{10}$	$(22)_{11}$	$(22)_{12}$

Wind Factor $(22a)_m = (22)_m \div 4$

$(22a)_m$ =	$(22a)_1$	$(22a)_2$	$(22a)_3$	$(22a)_4$	$(22a)_5$	$(22a)_6$	$(22a)_7$	$(22a)_8$	$(22a)_9$	$(22a)_{10}$	$(22a)_{11}$	$(22a)_{12}$

Adjusted infiltration rate (allowing for shelter and wind speed) = $(21) \times (22a)_m$

$(22b)_m$ =	$(22b)_1$	$(22b)_2$	$(22b)_3$	$(22b)_4$	$(22b)_5$	$(22b)_6$	$(22b)_7$	$(22b)_8$	$(22b)_9$	$(22b)_{10}$	$(22b)_{11}$	$(22b)_{12}$

Calculate effective air change rate for the applicable case:

If mechanical ventilation: air change rate through system 0.5 (23a)

If exhaust air heat pump using Appendix N, (23b) = (23a) × F_{mv} (equation (N4)) , otherwise (23b) = (23a) (23b)

If balanced with heat recovery: efficiency in % allowing for in-use factor (from Table 4h) = (23c)

a) If balanced mechanical ventilation with heat recovery (MVHR) $(24a)_m = (22b)_m + (23b) \times [1 - (23c) \div 100]$

$(24a)_m$ =	$(24a)_1$	$(24a)_2$	$(24a)_3$	$(24a)_4$	$(24a)_5$	$(24a)_6$	$(24a)_7$	$(24a)_8$	$(24a)_9$	$(24a)_{10}$	$(24a)_{11}$	$(24a)_{12}$	(24a)

b) If balanced mechanical ventilation without heat recovery (MV) $(24b)_m = (22b)_m + (23b)$

$(24b)_m$ =	$(24b)_1$	$(24b)_2$	$(24b)_3$	$(24b)_4$	$(24b)_5$	$(24b)_6$	$(24b)_7$	$(24b)_8$	$(24b)_9$	$(24b)_{10}$	$(24b)_{11}$	$(24b)_{12}$	(24b)

c) If whole house extract ventilation or positive input ventilation from outside

if $(22b)_m < 0.5 \times (23b)$, then (24c) = (23b); otherwise $(24c) = (22b)_m + 0.5 \times (23b)$

$(24c)_m$ =	$(24c)_1$	$(24c)_2$	$(24c)_3$	$(24c)_4$	$(24c)_5$	$(24c)_6$	$(24c)_7$	$(24c)_8$	$(24c)_9$	$(24c)_{10}$	$(24c)_{11}$	$(24c)_{12}$	(24c)

d) If natural ventilation or whole house positive input ventilation from loft

if $(22b)_m \geq 1$, then $(24d)_m = (22b)_m$ otherwise $(24d)_m = 0.5 + [(22b)_m^2 \times 0.5]$

$(24d)_m$ =	$(24d)_1$	$(24d)_2$	$(24d)_3$	$(24d)_4$	$(24d)_5$	$(24d)_6$	$(24d)_7$	$(24d)_8$	$(24d)_9$	$(24d)_{10}$	$(24d)_{11}$	$(24d)_{12}$	(24d)

Effective air change rate - enter (24a) or (24b) or (24c) or (24d) in (25)

$(25)_m$ =	$(25)_1$	$(25)_2$	$(25)_3$	$(25)_4$	$(25)_5$	$(25)_6$	$(25)_7$	$(25)_8$	$(25)_9$	$(25)_{10}$	$(25)_{11}$	$(25)_{12}$	(25)

If Appendix Q applies in relation to air change rate, the effective air change rate is calculated via Appendix Q and use the following instead:

Effective air change rate from Appendix Q calculation sheet:

$(25)_m$ =	$(25)_1$	$(25)_2$	$(25)_3$	$(25)_4$	$(25)_5$	$(25)_6$	$(25)_7$	$(25)_8$	$(25)_9$	$(25)_{10}$	$(25)_{11}$	$(25)_{12}$	(25)

3. Heat losses and heat loss parameter

Items in the table below are to be expanded as necessary to allow for all different types of element e.g. 4 wall types.
The κ-value is the heat capacity per unit area, see Table 1e

Element	Gross area, m²	Openings m²	Net area A, m²	U-value W/m²K	= A × U W/K	κ-value kJ/m²·K	A × κ kJ/K	
Solid door				×				(26)
Semi-glazed door				×				(26a)
Window				× * below	=			(27)
Roof window				× * below	=			(27a)
Basement floor				×	=			(28)
Ground floor				×	=			(28a)
Exposed floor				×	=			(28b)
Basement wall		-	=	×	=			(29)
External wall		-	=	×	=			(29a)
Roof		-	=	×	=			(30)
Total area of external elements ΣA, m²			(31)					
Party wall				×	=			(32)
(party wall U-value from Table 3.6, κ according to its construction)								
Party floor								(32a)
Party ceiling								(32b)
Internal wall **								(32c)
Internal floor								(32d)
Internal ceiling								(32e)

* *for windows and roof windows, use effective window U-value calculated using formula 1/[(1/U-value)+0.04] as given in paragraph 3.2*
** *include the areas on both sides of internal walls and partitions*

Fabric heat loss, W/K $= \Sigma (A \times U)$ (26)…(30) + (32) = (33)

Heat capacity $C_m = \Sigma(A \times \kappa)$ (28)…(30) + (32) + (32a)…(32e) = (34)

Thermal mass parameter (TMP = C_m ÷ TFA) in kJ/m²K = (34) ÷ (4) = (35)

For design assessments where the details of the construction are not known precisely the indicative values of TMP in Table 1f can be used instead of a detailed calculation. Also TMP calculated separately can be used in (35).

Thermal bridges : Σ (L × Ψ) calculated using Appendix K (36)

if details of thermal bridging are not known (36) = 0.15 × (31)

Total fabric heat loss (33) + (36) = (37)

Ventilation heat loss calculated monthly $(38)_m = 0.33 \times (25)_m \times (5)$

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(38)_m$ =	$(38)_1$	$(38)_2$	$(38)_3$	$(38)_4$	$(38)_5$	$(38)_6$	$(38)_7$	$(38)_8$	$(38)_9$	$(38)_{10}$	$(38)_{11}$	$(38)_{12}$	(38)

Heat transfer coefficient, W/K $(39)_m = (37) + (38)_m$

$(39)_m$ =	$(39)_1$	$(39)_2$	$(39)_3$	$(39)_4$	$(39)_5$	$(39)_6$	$(39)_7$	$(39)_8$	$(39)_9$	$(39)_{10}$	$(39)_{11}$	$(39)_{12}$	

Average = $\Sigma(39)_{1...12}/12$ = (39)

Heat loss parameter (HLP), W/m²K (40)m = (39)m ÷ (4)

(40)m =	(40)1	(40)2	(40)3	(40)4	(40)5	(40)6	(40)7	(40)8	(40)9	(40)10	(40)11	(40)12

Average = $\Sigma(40)_{1...12}/12$= (40)

Number of days in month (Table 1a)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
(41)m =	(41)1	(41)2	(41)3	(41)4	(41)5	(41)6	(41)7	(41)8	(41)9	(41)10	(41)11	(41)12	(41)

4. Water heating energy requirement **kWh/year**

Assumed occupancy, N (42)

if TFA > 13.9, N = 1 + 1.76 × [1 - exp(-0.000349 × (TFA -13.9)²)] + 0.0013 × (TFA -13.9)

if TFA ≤ 13.9, N = 1

Annual average hot water usage in litres per day $V_{d,average}$ = (25 × N) + 36 (43)

Reduce the annual average hot water usage by 5% if the dwelling is designed to achieve a water use target of not more that 125 litres per person per day (all water use, hot and cold)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Hot water usage in litres per day for each month $V_{d,m}$ = factor from Table 1c × (43)

(44)m =	(44)1	(44)2	(44)3	(44)4	(44)5	(44)6	(44)7	(44)8	(44)9	(44)10	(44)11	(44)12

Total = $\Sigma(44)_{1...12}$ = (44)

Energy content of hot water used = 4.18 × $V_{d,m}$ × n_m × ΔT_m / 3600 kWh/month (see Tables 1b, 1c, 1d)

(45)m =	(45)1	(45)2	(45)3	(45)4	(45)5	(45)6	(45)7	(45)8	(45)9	(45)10	(45)11	(45)12

Total = $\Sigma(45)_{1...12}$= (45)

If instantaneous water heating at point of use (no hot water storage), enter "0" in (46) to (61)

For community heating include distribution loss whether or not hot water tank is present

Distribution loss (46)m = 0.15 x (45)m

(46)m =	(46)1	(46)2	(46)3	(46)4	(46)5	(46)6	(46)7	(46)8	(46)9	(46)10	(46)11	(46)12	(46)

Storage volume (litres) including any solar or WWHRS storage within same vessel (47)

If community heating and no tank in dwelling, enter 110 litres in (47)

Otherwise if no stored hot water (this includes instantaneous combi boilers) enter '0' in (47)

Water storage loss:

a) If manufacturer's declared loss factor is known (kWh/day): (48)

Temperature factor from Table 2b (49)

Energy lost from water storage, kWh/day (48) × (49) = (50)

b) If manufacturer's declared loss factor is not known :

Hot water storage loss factor from Table 2 (kWh/litre/day) (51)

If community heating see section 4.3

Volume factor from Table 2a (52)

Temperature factor from Table 2b (53)

Energy lost from water storage, kWh/day (47) × (51) × (52) × (53) = (54)

Enter (50) or (54) in (55) (55)

Water storage loss calculated for each month (56)m = (55) × (41)m

(56)m =	(56)1	(56)2	(56)3	(56)4	(56)5	(56)6	(56)7	(56)8	(56)9	(56)10	(56)11	(56)12	(56)

If the vessel contains dedicated solar storage or dedicated WWHRS storage, (57)m = (56)m × [(47) – V_s] ÷ (47), else (57)m = (56)m where V_s is V_{ww} from Appendix G3 or (H11) from Appendix H (as applicable).

(57)m =	(57)1	(57)2	(57)3	(57)4	(57)5	(57)6	(57)7	(57)8	(57)9	(57)10	(57)11	(57)12	(57)

Primary circuit loss for each month from Table 3

(modified by factor from Table H4 if there is solar water heating and a cylinder thermostat, although not for community DHW systems)

(59)m =	(59)1	(59)2	(59)3	(59)4	(59)5	(59)6	(59)7	(59)8	(59)9	(59)10	(59)11	(59)12	(59)

Combi loss for each month from Table 3a, 3b or 3c (enter "0" if not a combi boiler)

$(61)_m$ =	$(61)_1$	$(61)_2$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_{12}$	(61)

Total heat required for water heating calculated for each month $(62)_m = 0.85 \times (45)_m + (46)_m + (57)_m + (59)_m + (61)_m$

$(62)_m$ =	$(62)_1$	$(62)_2$	$(62)_3$	$(62)_4$	$(62)_5$	$(62)_6$	$(62)_7$	$(62)_8$	$(62)_9$	$(62)_{10}$	$(62)_{11}$	$(62)_{12}$	(62)

Solar DHW input calculated using Appendix G or Appendix H (negative quantity) (enter "0" if no solar contribution to water heating)
(add additional lines if FGHRS and/or WWHRS applies, see Appendix G)

$(63)_m$ =	$(63)_1$	$(63)_2$	$(63)_3$	$(63)_4$	$(63)_5$	$(63)_6$	$(63)_7$	$(63)_8$	$(63)_9$	$(63)_{10}$	$(63)_{11}$	$(63)_{12}$	(63)

Output from water heater for each month, kWh/month $(64)_m = (62)_m + (63)_m$

$(64)_m$ =	$(64)_1$	$(64)_2$	$(64)_3$	$(64)_4$	$(64)_5$	$(64)_6$	$(64)_7$	$(64)_8$	$(64)_9$	$(64)_{10}$	$(64)_{11}$	$(64)_{12}$	

Total per year (kWh/year) = $\Sigma(64)_{1...12}$ = (64)

if $(64)_m$ < 0 then set to 0

Heat gains from water heating, kWh/month $0.25 \times [0.85 \times (45)_m + (61)_m] + 0.8 \times [(46)_m + (57)_m + (59)_m]$

$(65)_m$ =	$(65)_1$	$(65)_2$	$(65)_3$	$(65)_4$	$(65)_5$	$(65)_6$	$(65)_7$	$(65)_8$	$(65)_9$	$(65)_{10}$	$(65)_{11}$	$(65)_{12}$	(65)

include $(57)_m$ in calculation of $(65)_m$ only if hot water store is in the dwelling or hot water is from community heating

5. Internal gains (see Tables 5 and 5a)

Metabolic gains (Table 5), watts

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(66)_m$ =	$(66)_1$	$(66)_2$	$(66)_3$	$(66)_4$	$(66)_5$	$(66)_6$	$(66)_7$	$(66)_8$	$(66)_9$	$(66)_{10}$	$(66)_{11}$	$(66a)_{12}$	(66)

Lighting gains (calculated in Appendix L, equation L9 or L9a), also see Table 5

$(67)_m$ =	$(67)_1$	$(67)_2$	$(67)_3$	$(67)_4$	$(67)_5$	$(67)_6$	$(67)_7$	$(67)_8$	$(67)_9$	$(67)_{10}$	$(67)_{11}$	$(67)_{12}$	(67)

Appliances gains (calculated in Appendix L, equation L13 or L13a), also see Table 5

$(68)_m$ =	$(68)_1$	$(68)_2$	$(68)_3$	$(68)_4$	$(68)_5$	$(68)_6$	$(68)_7$	$(68)_8$	$(68)_9$	$(68)_{10}$	$(68)_{11}$	$(68)_{12}$	(68)

Cooking gains (calculated in Appendix L, equation L15 or L15a), also see Table 5

$(69)_m$ =	$(69)_1$	$(69)_2$	$(69)_3$	$(69)_4$	$(69)_5$	$(69)_6$	$(69)_7$	$(69)_8$	$(69)_9$	$(69)_{10}$	$(69)_{11}$	$(69)_{12}$	(69)

Pumps and fans gains (Table 5a)

$(70)_m$ =	$(70)_1$	$(70)_2$	$(70)_3$	$(70)_4$	$(70)_5$	$(70)_6$	$(70)_7$	$(70)_8$	$(70)_9$	$(70)_{10}$	$(70)_{11}$	$(70)_{12}$	(70)

Losses e.g. evaporation (negative values) (Table 5)

$(71)_m$ =	$(71)_1$	$(71)_2$	$(71)_3$	$(71)_4$	$(71)_5$	$(71)_6$	$(71)_7$	$(71)_8$	$(71)_9$	$(71)_{10}$	$(71)_{11}$	$(71)_{12}$	(71)

Water heating gains (Table 5)

$(72)_m$ =	$(72)_1$	$(72)_2$	$(72)_3$	$(72)_4$	$(72)_5$	$(72)_6$	$(72)_7$	$(72)_8$	$(72)_9$	$(72)_{10}$	$(72)_{11}$	$(72)_{12}$	(72)

Total internal gains = $(66)_m + (67)_m + (68)_m + (69)_m + (70)_m + (71)_m + (72)_m$

$(73)_m$ =	$(73)_1$	$(73)_2$	$(73)_3$	$(73)_4$	$(73)_5$	$(73)_6$	$(73)_7$	$(73)_8$	$(73)_9$	$(73)_{10}$	$(73)_{11}$	$(73)_{12}$	(73)

6. Solar gains

Solar gains are calculated using solar flux from U3 in Appendix U and associated equations to convert to the applicable orientation. Rows (74) to (82) are used 12 times, one for each month, repeating as needed if there is more than one window type.

	Access factor Table 6d		Area m²		Solar flux W/m²		g⊥ Specific data or Table 6b		FF Specific data or Table 6c		Gains (W)	
North		×		×		× 0.9 ×		×		=		(74)
Northeast		×		×		× 0.9 ×		×		=		(75)
East		×		×		× 0.9 ×		×		=		(76)
Southeast		×		×		× 0.9 ×		×		=		(77)
South		×		×		× 0.9 ×		×		=		(78)
Southwest		×		×		× 0.9 ×		×		=		(79)
West		×		×		× 0.9 ×		×		=		(80)
Northwest		×		×		× 0.9 ×		×		=		(81)
Roof windows	1.0	×		×		× 0.9 ×		×		=		(82)

Solar gains in watts, calculated for each month $(83)_m = \Sigma(74)_m \ldots (82)_m$

$(83)_m$ =	$(83)_1$	$(83)_2$	$(83)_3$	$(83)_4$	$(83)_5$	$(83)_6$	$(83)_7$	$(83)_8$	$(83)_9$	$(83)_{10}$	$(83)_{11}$	$(83)_{12}$	(83)

Total gains – internal and solar $(84)_m = (73)_m + (83)_m$, watts

$(84)_m =$	$(84)_1$	$(84)_2$	$(84)_3$	$(84)_4$	$(84)_5$	$(84)_6$	$(84)_7$	$(84)_8$	$(84)_9$	$(84)_{10}$	$(84)_{11}$	$(84)_{12}$	(84)

7. Mean internal temperature (heating season)

Temperature during heating periods in the living area from Table 9, T_{h1} (°C) | 21 | (85)

Utilisation factor for gains for living area, $\eta_{1,m}$ (see Table 9a)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(86)_m =$	$(86)_1$	$(86)_2$	$(86)_3$	$(86)_4$	$(86)_5$	$(86)_6$	$(86)_7$	$(86)_8$	$(86)_9$	$(86)_{10}$	$(86)_{11}$	$(86)_{12}$	(86)

Mean internal temperature in living area T_1 *(follow steps 3 to 7 in Table 9c)*

$(87)_m =$	$(87)_1$	$(87)_2$	$(87)_3$	$(87)_4$	$(87)_5$	$(87)_6$	$(87)_7$	$(87)_8$	$(87)_9$	$(87)_{10}$	$(87)_{11}$	$(87)_{12}$	(87)

Temperature during heating periods in rest of dwelling from Table 9, T_{h2} (°C)

$(88)_m =$	$(88)_1$	$(88)_2$	$(88)_3$	$(88)_4$	$(88)_5$	$(88)_6$	$(88)_7$	$(88)_8$	$(88)_9$	$(88)_{10}$	$(88)_{11}$	$(88)_{12}$	(88)

Utilisation factor for gains for rest of dwelling, $\eta_{2,m}$ (see Table 9a)

$(89)_m =$	$(89)_1$	$(89)_2$	$(89)_3$	$(89)_4$	$(89)_5$	$(89)_6$	$(89)_7$	$(89)_8$	$(89)_9$	$(89)_{10}$	$(89)_{11}$	$(89)_{12}$	(89)

Mean internal temperature in the rest of dwelling T_2

(follow steps 8 to 9 in Table 9c, if two main heating systems see futher notes in Table 9c)

$(90)_m =$	$(90)_1$	$(90)_2$	$(90)_3$	$(90)_4$	$(90)_5$	$(90)_6$	$(90)_7$	$(90)_8$	$(90)_9$	$(90)_{10}$	$(90)_{11}$	$(90)_{12}$	(90)

Living area fraction f_{LA} = Living area ÷ (4) = | | (91)

Mean internal temperature (for the whole dwelling) = $f_{LA} \times T_1 + (1 - f_{LA}) \times T_2$

$(92)_m =$	$(92)_1$	$(92)_2$	$(92)_3$	$(92)_4$	$(92)_5$	$(92)_6$	$(92)_7$	$(92)_8$	$(92)_9$	$(82)_{10}$	$(92)_{11}$	$(92)_{12}$	(92)

Apply adjustment to the mean internal temperature from Table 4e, where appropriate

$(93)_m =$	$(93)_1$	$(93)_2$	$(93)_3$	$(93)_4$	$(93)_5$	$(93)_6$	$(93)_7$	$(93)_8$	$(93)_9$	$(93)_{10}$	$(93)_{11}$	$(93)_{12}$	(93)

8. Space heating requirement

Set T_i to the mean internal temperature obtained at step 11 of Table 9b, so that $T_{i,m}=(93)_m$ and re-calculate the utilisation factor for gains using Table 9a

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Utilisation factor for gains, η_m:													
$(94)_m =$	$(94)_1$	$(94)_2$	$(94)_3$	$(94)_4$	$(94)_5$	$(94)_6$	$(94)_7$	$(94)_8$	$(94)_9$	$(94)_{10}$	$(94)_{11}$	$(94)_{12}$	(94)
Useful gains, $\eta_m G_m$, W = $(94)_m \times (84)_m$													
$(95)_m =$	$(95)_1$	$(95)_2$	$(95)_3$	$(95)_4$	$(95)_5$	$(95)_6$	$(95)_7$	$(95)_8$	$(95)_9$	$(95)_{10}$	$(95)_{11}$	$(95)_{12}$	(95)
Monthly average external temperature from Table U1													
$(96)_m =$	$(96)_1$	$(96)_2$	$(96)_3$	$(96)_4$	$(96)_5$	$(96)_6$	$(96)_7$	$(96)_8$	$(96)_9$	$(96)_{10}$	$(96)_{11}$	$(96)_{12}$	(96)
Heat loss rate for mean internal temperature, L_m , W = $(39)_m \times [(93)_m - (96)_m]$													
$(97)_m =$	$(97)_1$	$(97)_2$	$(97)_3$	$(97)_4$	$(97)_5$	$(97)_6$	$(97)_7$	$(97)_8$	$(97)_9$	$(97)_{10}$	$(97)_{11}$	$(97)_{12}$	(97)
Space heating requirement for each month, kWh/month = $0.024 \times [(97)_m - (95)_m] \times (41)_m$													
$(98)_m =$	$(98)_1$	$(98)_2$	$(98)_3$	$(98)_4$	$(98)_5$	–	–	–	–	$(98)_{10}$	$(98)_{11}$	$(98)_{12}$	

Total per year (kWh/year) = $\Sigma(98)_{1...5,10...12}$ = | | (98)

Space heating requirement in kWh/m²/year $(98) \div (4)$ = | | (99)

For range cooker boilers where efficiency is obtained from the Product Characteristics Database, multiply the results in $(98)_m$ by $(1 - \Phi_{case}/\Phi_{water})$ where Φ_{case} is the heat emission from the case of the range cooker at full load (in kW); and Φ_{water} is the heat transferred to water at full load (in kW). Φ_{case} and Φ_{water} are obtained from the database record for the range cooker boiler. Where there are two main heating systems, this applies if the range cooker boiler is system 1 or system 2.

8c. Space cooling requirement

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Heat loss rate L_m (calculated using 24°C internal temperature and external temperature for the applicable climate (see Appendix U)														
$(100)_m$ =						$(100)_6$	$(100)_7$	$(100)_8$						(100)
Utilisation factor for loss η_m														
$(101)_m$ =						$(101)_6$	$(101)_7$	$(101)_8$						(101)
Useful loss, $\eta_m L_m$ (watts) = $(100)_m \times (101)_m$														
$(102)_m$ =						$(102)_6$	$(102)_7$	$(102)_8$						(102)
Gains (internal gains as for heating except that column (A) of Table 5 is always used; solar gains calculated for the applicable climate, see Appendix U)														
$(103)_m$ =						$(103)_6$	$(103)_7$	$(103)_8$						(103)
Space cooling requirement for month, whole dwelling, continuous (kWh) = 0.024 × $[(103)_m - (102)_m] \times (41)_m$														
$(104)_m$ =						$(104)_6$	$(104)_7$	$(104)_8$						
												Total = $\Sigma(104)_{6..8}$ =		(104)
Cooled fraction												f_C = cooled area ÷ (4) =		(105)
Intermittency factor (Table 10b)														
$(106)_m$						$(106)_6$	$(106)_7$	$(106)_8$						
												Total = $\Sigma(106)_{6..8}$ =		(106)
Space cooling requirement for month = $(104)_m \times (105) \times (106)_m$														
$(107)_m$						$(107)_6$	$(107)_7$	$(107)_8$						
												Total = $\Sigma(107)_{6..8}$ =		(107)
Space cooling requirement in kWh/m²/year												(107) ÷ (4) =		(108)

8f. Fabric Energy Efficiency (calculated only under special conditions, see section 11)

Fabric Energy Efficiency	(99) + (108) =		(109)

9a. Energy requirements – Individual heating systems including micro-CHP

For any space heating, space cooling or water heating provided by community heating use the alternative worksheet 9b.

Space heating:

Fraction of space heat from secondary/supplementary system (Table 11)	*"0" if none*		(201)
Fraction of space heat from main system(s)	(202) = 1 – (201) =		(202)
Fraction of main heating from main system 2	*if no second main system enter "0"*		(203)
Fraction of total space heat from main system 1	(204) = (202) × [1 – (203)] =		(204)
Fraction of total space heat from main system 2	(205) = (202) × (203) =		(205)
Efficiency of main space heating system 1 (in %) *(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c; for gas and oil boilers see 9.2.1)*			(206)
If there is a second main system complete (207) Efficiency of main space heating system 2 (in %) *(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c; for gas and oil boilers see 9.2.1)*			(207)
Efficiency of secondary/supplementary heating system, % *(from Table 4a or Appendix E)*			(208)
Cooling System Energy Efficiency Ratio (see Table 10c)			(209)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	kWh/year	
Space heating requirement (calculated above)	$(98)_1$	$(98)_2$	$(98)_3$	$(98)_4$	$(98)_5$	–	–	–	–	$(98)_{10}$	$(98)_{11}$	$(98)_{12}$		
Space heating fuel (main heating system 1), kWh/month $(211)_m = (98)_m \times (204) \times 100 \div (206)$														
$(211)_m$	$(211)_1$	$(211)_2$	$(211)_3$	$(211)_4$	$(211)_5$	–	–	–	–	$(211)_{10}$	$(211)_{11}$	$(211)_{12}$		
												Total (kWh/year) $=\Sigma(211)_{1..5,10..12}$ =		(211)
Space heating fuel (main heating system 2), kWh/month, omit if no second main heating system $(213)_m = (98)_m \times (205) \times 100 \div (207)$														
$(213)_m$	$(213)_1$	$(213)_2$	$(213)_3$	$(213)_4$	$(213)_5$	–	–	–	–	$(213)_{10}$	$(213)_{11}$	$(213)_{12}$		
												Total (kWh/year) $=\Sigma(213)_{1..5,10..12}$ =		(213)
Space heating fuel (secondary), kWh/month $(215)_m = (98)_m \times (201) \times 100 \div (208)$														
$(215)_m$	$(215)_1$	$(215)_2$	$(215)_3$	$(215)_4$	$(215)_5$	–	–	–	–	$(215)_{10}$	$(215)_{11}$	$(215)_{12}$		
												Total (kWh/year) $= \Sigma(215)_{1..5,10..12}$ =		(215)

Water heating

Output from water heater (calculated above)	$(64)_1$	$(64)_2$	$(64)_3$	$(64)_4$	$(64)_5$	$(64)_6$	$(64)_7$	$(64)_8$	$(64)_9$	$(64)_{10}$	$(64)_{11}$	$(64)_{12}$		
Efficiency of water heater														(216)

(From database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'DHW efficiency adjustment' column of Table 4c, for gas and oil boilers use the summer efficiency, see 9.2.1)

if water heating by a hot-water-only boiler, $(217)_m$ = value from database record for boiler or Table 4a

otherwise if gas/oil boiler main system used for water heating, $(217)_m$ = value calculated for each month using equation (8) in section 9.2.1

otherwise if separate hot water only heater (including immersion) $(217)_m$ = applicable value from Table 4a

otherwise (other main system 1 or 2 used for water heating) $(217)_m$ = (216)

$(217)_m$ =	$(217)_1$	$(217)_2$	$(217)_3$	$(217)_4$	$(217)_5$	$(217)_6$	$(217)_7$	$(217)_8$	$(217)_9$	$(217)_{10}$	$(217)_{11}$	$(217)_{12}$		(217)
Fuel for water heating, kWh/month $(219)_m = (64)_m \times 100 \div (217)_m$														
$(219)_m$	$(219)_1$	$(219)_2$	$(219)_3$	$(219)_4$	$(219)_5$	$(219)_6$	$(219)_7$	$(219)_8$	$(219)_9$	$(219)_{10}$	$(219)_{11}$	$(219)_{12}$		
												Total $= \Sigma(219a)_{1..12}$ =		(219)

(for a DHW-only community scheme use (305), (306) and (310a) or (310b), with (304a)=1.0 or (304b)=1.0, instead of (219)

Space cooling

Space cooling fuel, kWh/month

$(221)_m = (107)_m \div (209)$

$(221)_m$						$(221)_6$	$(221)_7$	$(221a)_8$				

Total = $\Sigma(221)_{6..8}$ = [ ] (221)

Annual totals	kWh/year	kWh/year	
Space heating fuel used, main system 1		(211)	
Space heating fuel used, main system 2		(213)	
Space heating fuel used, secondary		(215)	
Water heating fuel used		(219)	
Space cooling fuel used (if there is a fixed cooling system, if not enter 0)		(221)	
Electricity for pumps, fans and electric keep-hot (Table 4f):			
mechanical ventilation fans - balanced, extract or positive input from outside			(230a)
warm air heating system fans			(230b)
central heating pump or water pump within warm air heating unit			(230c)
oil boiler pump			(230d)
boiler flue fan			(230e)
maintaining electric keep-hot facility for gas combi boiler			(230f)
pump for solar water heating			(230g)
pump for storage WWHRS (see section G3.3)			(230h)
Total electricity for the above, kWh/year	sum of (230a)…(230h) =		(231)
Electricity for lighting (calculated in Appendix L)			(232)
Energy saving/generation technologies (Appendices M ,N and Q)			
Electricity generated by PVs (Appendix M) (negative quantity)			(233)
Electricity generated by wind turbine (Appendix M) (negative quantity)			(234)
Electricity used or net electricity generated by micro-CHP (Appendix N) (negative if net generation)			(235)
Electricity generated by hydro-electric generator (Appendix M) (negative quantity)			(235a)

Appendix Q items: annual energy (items not already included on a monthly basis)	Fuel	kWh/year	
Appendix Q, <item 1 description>			
energy saved or generated (enter as negative quantity)			(236a)
energy used (positive quantity)			(237a)
Appendix Q, <item 2 description>			
energy saved or generated (enter as negative quantity)			(236b)
energy used (positive quantity)			(237b)
(continue this list if additional items)			

Total delivered energy for all uses (211)...(221) + (231) + (232)...(237b) = [ ] (238)

10a. Fuel costs – Individual heating systems including micro-CHP						
	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	(211)	×		× 0.01 =		(240)
Space heating - main system 2	(213)	×		× 0.01 =		(241)
Space heating - secondary	(215)	×		× 0.01 =		(242)
Water heating (electric off-peak tariff)						
High-rate fraction (Table 13, or Appendix F for electric CPSU)					(243)	
Low-rate fraction	1.0 – (243) =				(244)	
High-rate cost	(219) × (243)	×		× 0.01 =		(245)
Low-rate cost	(219) × (244)	×		× 0.01 =		(246)
Water heating cost (other fuel)	(219)	×		× 0.01 =		(247)
(for a DHW-only community scheme use (342a) or (342b) instead of (247)						
Space cooling	(221)	×		× 0.01 =		(248)
Pumps, fans and electric keep-hot	(231)	×		× 0.01 =		(249)
(if off-peak tariff, list each of (230a) to (230g) separately as applicable and apply fuel price according to Table 12a						
Energy for lighting	(232)	×		× 0.01 =		(250)
Additional standing charges (Table 12)						(251)
Energy saving/generation technologies	(233) to (235a) as applicable, repeat line (252) as needed					
<description>	one of (233) to (235a)	×		× 0.01 =		(252)
Appendix Q items:	repeat lines (253) and (254) as needed					
<description>, energy saved	one of (236a) etc	×		× 0.01 =		(253)
<description>, energy used	one of (237a) etc	×		× 0.01 =		(254)
Total energy cost			(240)...(242) + (245)...(254) =			(255)

11a. SAP rating – Individual heating systems including micro-CHP			
Energy cost deflator (Table 12):		0.42	(256)
Energy cost factor (ECF)	[(255) × (256)] ÷ [(4) + 45.0] =		(257)
SAP rating (Section 13)			(258)

12a. CO_2 emissions – Individual heating systems including micro-CHP

	Energy kWh/year		Emission factor kg CO_2/kWh		Emissions kg CO_2/year	
Space heating - main system 1	(211)	×		=		(261)
Space heating - main system 2	(213)	×		=		(262)
Space heating - secondary	(215)	×		=		(263)
Energy for water heating	(219)	×		=		(264)
(for a DHW-only community scheme use (361) to (373) instead of (264)						
Space and water heating	(261) + (262) + (263) + (264)			=		(265)
Space cooling	(221)	×		=		(266)
Electricity for pumps, fans and electric keep-hot	(231)	×		=		(267)
Electricity for lighting	(232)	×		=		(268)
Energy saving/generation technologies (233) to (235a) as applicable, repeat line (269) as needed						
<description>	one of (233) to (235a)	×		=		(269)
Appendix Q items repeat lines (270) and (271) as needed						
<description>, energy saved *	one of (236a) etc	×		=		(270)
<description>, energy used *	one of (237a) etc	×		=		(271)
* where the item is concerned only with CO_2 emissions use the right-hand column only.						
Total CO_2, kg/year	sum of (265)...(271)			=		(272)
Dwelling CO_2 Emission Rate	(272) ÷ (4)			=		(273)
El rating (section 14)						(274)

13a. Primary energy – Individual heating systems including micro-CHP

Same as 12a using primary energy factor instead of CO_2 emission factor to give primary energy in kWh/year

Community heating

9b. Energy requirements – Community heating scheme

This part is used for space heating, space cooling or water heating provided by a community scheme.

Fraction of space heat from secondary/supplementary heating (Table 11)	*"0" if none*		(301)
Fraction of space heat from community system	1 – (301) =		(302)

The community scheme may obtain heat from several sources. The procedure allows for CHP and up to four other heat sources; the latter includes boilers, heat pumps, geothermal and waste heat from power stations. See Appendix C.

Fraction of heat from community CHP	*(fractions obtained from operational records or plant design specification; omit line if not applicable)*		(303a)
Fraction of community heat from heat source 2			(303b)
Fraction of community heat from heat source 3			(303c)
Fraction of community heat from heat source 4			(303d)
Fraction of community heat from heat source 5			(303e)
Fraction of total space heat from community CHP	(302) × (303a) =		(304a)
Fraction of total space heat from community heat source 2 <description>	(302) × (303b) =		(304b)
Fraction of total space heat from community heat source 3 <description>	(302) × (303c) =		(304c)
Fraction of total space heat from community heat source 4 <description>	(302) × (303d) =		(304d)
Fraction of total space heat from community heat source 5 <description>	(302) × (303e) =		(304e)
Factor for control and charging method (Table 4c(3)) for community space heating			(305)
Factor for charging method (Table 4c(3)) for community water heating			(305a)
Distribution loss factor (Table 12c) for community heating system			(306)

Space heating

			kWh/year	
Annual space heating requirement		(98)		
Space heat from CHP	(98) × (304a) × (305) × (306) =			(307a)
Space heat from heat source 2	(98) × (304b) × (305) × (306) =			(307b)
Space heat from heat source 3	(98) × (304c) × (305) × (306) =			(307c)
Space heat from heat source 4	(98) × (304d) × (305) × (306) =			(307d)
Space heat from heat source 5	(98) × (304e) × (305) × (306) =			(307e)
Efficiency of secondary/supplementary heating system in % *(from Table 4a or Appendix E)*				(308)
Space heating fuel for secondary/supplementary system	(98) × (301) × 100 ÷ (308) =			(309)

Water heating

Annual water heating requirement		(64)		
If DHW from community scheme:				
Water heat from CHP	(64) × (303a) × (305a) × (306) =			(310a)
Water heat from heat source 2	(64) × (303b) × (305a) × (306) =			(310b)
Water heat from heat source 3	(64) × (303c) × (305a) × (306) =			(310c)
Water heat from heat source 4	(64) × (303d) × (305a) × (306) =			(310d)
Water heat from heat source 5	(64) × (303e) × (305a) × (306) =			(310e)
If DHW by immersion or instantaneous heater within dwelling:				
Efficiency of water heater				(311)
Water heated by immersion or instantaneous heater	(64) × 100 ÷ (311) =			(312)
Electricity used for heat distribution	0.01 × [(307a)…(307e) + (310a)…(310e)] =			(313)
Cooling System Energy Efficiency Ratio				(314)
Space cooling (if there is a fixed cooling system, if not enter 0)	= (107) ÷ (314) =			(315)
Electricity for pumps and fans within dwelling (Table 4f):				
mechanical ventilation - balanced, extract or positive input from outside				(330a)
warm air heating system fans				(330b)
pump for solar water heating				(330g)

pump for storage WWHRS (see section G3.3)			(330h)
Total electricity for the above, kWh/year	(330a) + … + (330h) =		(331)
Electricity for lighting (calculated in Appendix L)			(332)
Energy saving/generation technologies (Appendices M and Q)			
Electricity generated by PVs (Appendix M) (negative quantity)			(333)
Electricity generated by wind turbine (Appendix M) (negative quantity)			(334)
Electricity generated by hydro-electric generator (Appendix M) (negative quantity)			(335a)
Appendix Q items: annual energy (items not already included on a monthly basis)	Fuel	kWh/year	
Appendix Q, <item 1 description>			
energy saved or generated (enter as negative quantity)			(336a)
energy used (positive quantity)			(337a)
Appendix Q, <item 2 description>			
energy saved or generated (enter as negative quantity)			(336b)
energy used (positive quantity)			(337b)
(continue this list if additional items)			
Total delivered energy for all uses	(307) + (309) + (310) + (312) + (315) + (331) + (332)…(237b) =		(338)

10b. Fuel costs – Community heating scheme

	Heat or fuel required kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating from CHP	(307a)	×		× 0.01 =		(340a)
Space heating from heat source 2	(307b)	×		× 0.01 =		(340b)
Space heating from heat source 3	(307c)	×		× 0.01 =		(340c)
Space heating from heat source 4	(307d)	×		× 0.01 =		(340d)
Space heating from heat source 5	(307e)	×		× 0.01 =		(340e)
Space heating (secondary)	(309)	×		× 0.01 =		(341)
Water heating from CHP	(310a)	×		× 0.01 =		(342a)
Water heating from heat source 2	(310b)	×		× 0.01 =		(342b)
Water heating from heat source 3	(310c)	×		× 0.01 =		(342c)
Water heating from heat source 4	(310d)	×		× 0.01 =		(342d)
Water heating from heat source 5	(310e)	×		× 0.01 =		(342e)

If water heated by immersion heater:

High-rate fraction (Table 13)			(343)
Low-rate fraction	1.0 - (343) =		(344)

			Fuel price			
High-rate cost, or cost for single immersion	(312) × (343)	×		× 0.01 =		(345)
Low-rate cost	(312) × (344)	×		× 0.01 =		(346)
If water heated by instantaneous water heater	(312)	×		× 0.01 =		(347)
Space cooling (community cooling system)	(315)	×		× 0.01 =		(348)
Pumps and fans	(331)	×		× 0.01 =		(349)

(if off-peak tariff, list each of (330a) to (330g) separately as applicable and apply fuel price according to Table 12a

Electricity for lighting	(332)	×		× 0.01 =		(350)
Additional standing charges (Table 12)						(351)
Energy saving/generation technologies	(333) to (335a) as applicable, repeat line (352) as needed					
<description>	one of (333) to (335a)	×		× 0.01 =		(352)
Appendix Q items:	repeat lines (253) and (259) as needed					
<description>, energy saved	one of (336a) etc	×		× 0.01 =		(353)
<description>, energy used	one of (337a) etc	×		× 0.01 =		(354)
Total energy cost	= (340a)...(342e) +(345)...(354) =					(355)

11b. SAP rating – Community heating scheme

Energy cost deflator (Table 12):		0.42	(356)
Energy cost factor (ECF)	[(355) × (356)] ÷ [(4) + 45.0] =		(357)
SAP rating (Section 13)			(358)

12b. CO_2 Emissions – Community heating scheme

CO_2 from CHP (space and water heating) *Omit (361) to (366) if no CHP*

Power efficiency of CHP unit (e.g. 25%) *from operational records or design spec.*		(361)
Heat efficiency of CHP unit (e.g. 50%) *from operational records or design specification*		(362)

		Energy used kWh/year		Emission factor $kgCO_2/kWh$		CO_2 emission $kgCO_2/year$	
Space heating from CHP	(307a) × 100 ÷ (362) =		×	*Note A*	=		(363)
less credit emissions for electricity	–(307a) × (361) ÷ (362) =		×	*Note B*	=		(364)
Water heated by CHP	(310a) × 100 ÷ (362) =		×	*Note A*	=		(365)
less credit emissions for electricity	–(310a) × (361) ÷ (362) =		×	*Note B*	=		(366)

Note A: factor for CHP fuel. Note B: factor for electricity generated by CHP

CO_2 from other sources of space and water heating (not CHP)

Efficiency of heat source 2 (%)	*If there is CHP using two fuels repeat (361) to (366) for the second fuel*	(367b)
Efficiency of heat source 3 (%)		(367c)
Efficiency of heat source 4 (%)		(367d)
Efficiency of heat source 5 (%)		(367e)

CO_2 associated with heat source 2	[(307b)+(310b)] × 100 ÷ (367b) ×		=		(368)
CO_2 associated with heat source 3	[(307c)+(310c)] × 100 ÷ (367c) ×		=		(369)
CO_2 associated with heat source 4	[(307d)+(310d)] × 100 ÷ (367d) ×		=		(370)
CO_2 associated with heat source 5	[(307e)+(310e)] × 100 ÷ (367e) ×		=		(371)
Electrical energy for heat distribution	(313) ×		=		(372)
Total CO_2 associated with community systems	(363)…(366) + (368)…(372)		=		(373)
if it is negative set (373) to zero (unless condition in C7 of Appendix C is met)					(373)
Space heating (secondary)	(309) ×		=		(374)
Water heating by immersion heater or instantaneous heater	(312) ×		=		(375)
Total CO_2 associated with space and water heating	(373) + (374) + (375)		=		(376)
Space cooling	(315) ×		=		(377)
Electricity for pumps and fans within dwelling	(331) ×		=		(378)
Electricity for lighting	(332) ×		=		(379)
Energy saving/generation technologies	(333) to (334) as applicable, repeat line (380) as needed				
<description>	one of (333) to (334) ×		=		(380)
Appendix Q items	repeat lines (381) and (382) as needed				
<description>, energy saved	one of (336a) etc ×		=		(381)
<description>, energy used	one of (337a) etc ×		=		(382)
Total CO_2, kg/year	sum of (376)…(382) =				(383)
Dwelling CO_2 Emission Rate	(383) ÷ (4) =				(384)
EI rating (section 14)					(385)

13b. Primary energy – Community heating scheme

Same as 12b using primary energy factor instead of CO_2 emission factor to give primary energy in kWh/year

APPENDIX C

Example of EPC XML File

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APPENDIX D

Equivalent Internal Boundary Conditions

Equivalent Internal Boundary Conditions

The modelling dataset does not include any details on the internal boundary conditions of the dwellings. EPCs are calculated based on SAP guidelines for estimating internal heat gains, losses and heating temperatures. Table 5 of SAP 2012 (SAP, 2012) identifies seven sources of internal heat gain: metabolic, lighting, appliances, cooking, losses, water heating and heat gains from pumps and fans in the heating system. For the RdDEM, the heating system, set-point temperatures and heating periods were all taken from Table 9 of SAP 2012 (SAP, 2012).

Metabolic Gains

Following the method described in SAP (SAP, 2012), the number of occupants and the resultant metabolic gains were calculated from the floor area (Equation D1):

$$N = 1 + 1.76 \times [1 - \exp(-0.000349 \times (TFA - 13.9)^2)] + 0.00013 \times (TFA - 13.9) \quad \text{D1}$$

Where *N* is the number of occupants, *TFA* is the total floor area of the dwelling. This equation gives a non-integer number for the assumed number of occupants.

Knowing the number of occupants, the metabolic gains were estimated from Equation D2 (Table 5 SAP 2012).

$$Metabolic\ Heat\ Gains = 60 \times N \text{ Watts} \quad \text{D2}$$

The above equation gives the average metabolic gain in watts (W) for the entire dwelling.

Lighting Gains

The calculation of lighting use was based on the proportion of fixed low energy lighting outlets installed, and on the contribution of daylight as described in Appendix L of SAP 2012. The average annual energy consumption for lighting (E_B) if no low-energy lighting is used can be derived from Equation D3 based on total floor area (*TFA*) and the number of occupants (*N*) (SAP, 2012):

$$E_B = 59.73 \times (TFA \times N)^{0.4714} \quad \text{kWh/year} \qquad \text{D3}$$

Appendix L SAP 2012 gives two correction factors: C_1 to take account of fixed lighting outlets with low-energy lamps, as shown in Equation D4:

$$C_1 = 1 - 0.5 \times L_{LE}/L \qquad \text{D4}$$

Where L_{LE} is the number of fixed low energy lighting outlets and C_2 to take account of daylighting, as shown in Equations D5 and D6:

$$C_2 = 52.2\, {G_L}^2 - 9.94 G_L + 1.433 \quad \text{if } G_L \leq 0.095 \qquad \text{D5}$$

$$C_2 = 0.96 \quad \text{if } G_L > 0.095 \qquad \text{D6}$$

Where G_L is calculated from Equation D7:

$$G_L = \frac{\sum 0.9 \times A_W \times g_L \times FF \times Z_L}{TFA} \qquad \text{D7}$$

Where *FF* is the frame factor, taken as 0.7 for all dwellings, A_W is the window area, g_L *is the* light transmittance factor taken as 0.80 for all dwellings and Z_L is the light access factor taken as 0.83 for all dwellings.

The correction factors were then used to calculate the annual energy used for lighting (E_L) from Equation D8:

$$E_L = E_B \times C_1 \times C_2 \text{ kWh/year} \quad \text{D8}$$

The monthly lighting energy use in kWh then can be derived from Equation D9:

$$E_{L,m} = E_L \times [1 + 0.5 \times \cos\left(\frac{2\pi(m-0.2)}{12}\right)] \times n_m/365 \text{ kWh/year} \quad \text{D9}$$

Where n_m is number of days in month m. The associated internal heat gain for each month in watts then becomes (Equation D10):

$$G_{L,m} = E_{L,m} \times 0.85 \times 1000/(24 \times n_m) \text{ Watts/month} \quad \text{D10}$$

The factor 0.85 is an allowance for 15% of the total lighting usage being external to the dwelling.

Following this method, the average heat gains from lighting were calculated for each month of the year. These values were used in the RdDEM to create equivalent lighting gains in the dynamic simulation. The gains were proportioned between zones based on the ratio of the floor areas. To keep the model simple, no diurnal pattern was included; rather the gains were assumed to be spread evenly over the day.

Appliances Gains

Similar to lighting gains, electrical appliances gains were derived from their annual energy consumption (E_A) in kWh using equations D11 from SAP 2012:

$$E_A = 207.8 \times (TFA \times N)^{0.4714} \text{ kWh/year} \quad \text{D11}$$

The annual energy consumption of appliances is a function of total floor area (*TFA*) and number of occupants (*N*) in each dwelling. The annual consumption then was spread over 12 months of year by equation D12 after SAP 2012:

$$E_{A,m} = E_A \times [1 + 0.157 \times \cos\left(\frac{2\pi(m-1.78)}{12}\right)] \times n_m/365 \text{ kWh/year} \qquad \text{D12}$$

Where n_m is the number of days in month m. From monthly energy consumption of appliances, the corresponding monthly heat gains were calculated as shown in D13 after SAP 2012:

$$G_{A,m} = E_{A,m} \times 1000/(24 \times n_m) \text{ Watts/month} \qquad \text{D13}$$

The resulting values were used in the RdDEM to model equivalent appliance gains. The gains were proportioned between zones based on the ratio of the floor areas. To keep the model simple, no daily pattern was included; rather the gains were assumed to be spread evenly over the day.

Cooking Gains

Cooking gains were estimated based on assumed number of occupants, as shown in equation D14 after SAP 2012:

$$Cooking\ Heat\ Gains = 35 + 7 \times N \text{ Watts} \qquad \text{D14}$$

In the RdDEM, the cooking gains were assigned to the ground floor zone only and were assumed to be spread evenly over the day.

Heat Losses

Table 5 SAP 2012 also includes a heat loss factor which comprises heat to incoming cold water and evaporation. This factor was calculated based on number of assumed occupants from Equation D15**Error! Reference source not found.**:

$$Heat\ Losses = -40 \times N \text{ Watts} \quad \text{D15}$$

These losses were considered in dynamic simulation as reductions to the overall internal heat gains in each dwelling.

Infiltration and ventilation

Infiltration was modelled explicitly in the RdDEM. In the absence of any airtightness pressure test data in the reduced dataset, the SAP algorithm was used to calculate the infiltration rate based on the information on chimneys, fans, open flues and passive vents, available in the modelling dataset. The associated infiltration rate was calculated based on quantity of each item present in the dwellings and the associated ventilation rates, as shown in following Table.

A further infiltration rate of 0.1 ACH for two storey dwellings; and 0.35 ACH for masonry construction was added to dwellings' model as specified by SAP 2012.

Ventilation rates of chimneys, open flues, intermittent extract fans, passive vents and flueless gas fires required to calculate infiltration rate of dwellings (recreated from Table 2.1 (SAP, 2012))

Item	Ventilation rate m^3/hour
Chimney	40
Open flue	20
Intermittent extract fan	10
Passive vent	10
Flueless gas fire	40

Since no information was available on number of sheltered sides for dwellings, two partially and one full sheltered sides was assumed for all dwellings. It was assumed that the dwellings were sheltered from one side due to presence of adjacent buildings and partially sheltered due to the buildings on the front and back of the dwellings. The two partially sheltered sides (front and back) were counted as one sheltered side after SAP 2012 Section 2.5 guidelines (SAP, 2012). The corresponding shelter factor was calculated based on two sheltered sides from Equation D16 after SAP 2012:

$$Shelter\ factor = 1 - [0.075 \times (sheltered\ sides)] \qquad \text{D16}$$

The infiltration rate for each dwelling, as modified by the shelter factor, was used as the infiltration rate of the building envelope in EnergyPlus, using the scheduled natural ventilation option. Any ventilation from window opening was not included in RdDEM.

Space Heating

All dwellings in the modelling dataset had a gas powered central heating system with a programmer and room thermostat to control it. For the RdDEM, the heating system was modelled using DesignBuilder's simple HVAC option with a condensing combination boiler and the resulting IDF was used in the template IDF (see Section 6.2.1) for all dwellings.

DesignBuilder provides three options to model heating systems (Designbuilder, 2015):

i. Simple: where heating system is modelled using ideal loads.

ii. Compact: where heating system is modelled parametrically.

iii. Detailed: where heating system is defined in detail with each component placed on a schematic diagram and connected to other components using air and water flow networks.

Considering the limited amount of data available in the modelling dataset, the simple option was the most suitable. EnergyPlus then auto-sizes the system in order that it provides enough heat to meet the requirements of each zone.

Heating set-point temperatures were derived from the guidelines in Table 9 SAP 2012 with 21°C in the living area and a lower temperature for elsewhere in the dwelling which was calculated from the Heat Loss Parameter (HLP) as shown in Equation D17:

$$T_h = 21 - 0.5 \times HLP \quad ^{\circ}\mathrm{C} \qquad \text{D17}$$

Where T_h is the heating set-point of elsewhere in the house.

The *HLP* is calculated from the heat loss coefficient of the whole dwelling divided by the floor area as shown in the SAP worksheet (version 9.92) section 3 (SAP, 2012).

Since the dwellings in RdDEM were modelled with different heating zones to SAP (ground floor and first floor as explained in Section 4.3), the set-point temperature for each of the zones was calculated from a floor area weighted average. The living room area was estimated using the same method as SAP by using the number of habitable rooms as shown in following Table. It was assumed that the living room was located on ground floor in all dwellings and floor area averaged heating temperature set-points were derived based on the fraction of living area to ground floor area.

Living area fraction based on number of habitable rooms (re-created from Table S16 (SAP, 2012))

Number of rooms	1	2	3	4	5	6	7	8
Living area fraction	0.75	0.50	0.30	0.25	0.21	0.18	0.16	0.14

Heating periods in the RdDEM were assigned based on Table 9 SAP 2012: 07:00 to 09:00 and 16:00 to 23:00 on weekdays; and 07:00 to 23:00 on weekends. This was the same for all dwellings.