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Automated dynamic thermal simulation of houses and housing stocks using readily available reduced data

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ABSTRACT

This paper describes a new method to swiftly model the dynamics of heating energy demand and indoor air temperatures of houses and housing stocks. The Reduced data Energy Model (RdDEM) provides a cost-effective alternative to steady-state modelling by enhancing the input dataset from the Reduced data Standard Assessment Procedure (RdSAP) – the method used to calculate Energy Performance Certificates (EPC) in the UK. This eliminates the main drawbacks associated with dynamic thermal simulation (DTS) of housing stocks, namely the large amount of required input data and the significant time required to model each house.

The RdDEM algorithms create RdSAP-equivalent geometry, construction, thermal mass and boundary conditions in Energy Plus DTS software. The new inferences and methodological enhancements were first tested and then implemented at scale using a sample of 83 semi-detached houses. Most energy results from RdDEM were within 10% of those from RdSAP. The differences are explained by the different ways that indoor air temperature is calculated.

The RdDEM method provides a dynamic alternative to RdSAP for understanding the dynamics of energy demand and indoor air temperatures in homes. This could include assessing the peak demand of a community energy scheme or assessing the summertime overheating risk in individual dwellings. Ultimately, it could provide a dynamic housing stock model using the data already collected from millions of houses to generate EPCs.

1. Introduction

In the UK, residential energy use is responsible for more than a quarter of national greenhouse gas emissions [1]. Hence there is an inevitable need for managing energy demand in UK homes, which has resulted in an increasing interest in managing the dynamic demand of communities of dwellings. A swift way of predicting the dynamic demand of groups of homes, without the need for onerous data collection, is thus needed. Houses and housing stocks are typically modelled using quasi-steady state models based on BS EN ISO 52,016-1:2017 (*Energy performance of buildings. Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads. Calculation procedures*) which provide annual or monthly values for energy demand and mean indoor air temperatures. These simplified models are based on a monthly energy balance of heat losses and gains under steady-state conditions and therefore do not fully account for the dynamics of energy demand. The Reduced-data Standard Assessment Procedure (RdSAP) method in the UK [2] enables existing dwellings to be simply modelled based on a short (c30 minute) physical survey of a dwelling and its heating systems. This cost-effective approach is used for producing energy performance certificates (EPCs) which describe the energy demand, CO_2 emissions and fuel costs for running the home under typical occupancy and weather conditions. The same modelling methodology is used to recommend the most effective energy efficiency refurbishment measures. It also underpins much of UK policy in energy demand reduction from the residential buildings, which is responsible for 40% of GHG emissions [3]. Similar quasi-steady state methods, based on ISO 52,016-1:2017, exist across Europe [4] and in the US [5,6] and China [7].

Dynamic thermal simulation (DTS) predicts energy demand and temperature distribution on sub-hourly basis which offers several advantages over quasi-steady state models but comes at a cost. The sub-hourly predictions describe the transients of energy demand and indoor thermal comfort, which could be required for new applications such as matching demand to supply, modelling demand shifting and thermal storage, and predicting

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overheating risk. However, DTS models require many more data inputs than quasi-steady state models, including 3-dimensional geometry and multiple material properties for each layer of the construction. Compared to quasi-steady state models, DTS requires a much higher level of expertise in the modeller and the production and analysis of reliable predictions is time-consuming. This severely limits the cost-effective application of DTS to individual homes and housing stocks.

This paper describes a method of modelling the heating energy demand and indoor air temperatures of houses using DTS with only readily available reduced data: the Reduced data Dynamic Energy Model (RdDEM). The process is fully automated and so demands no extra time or skill from the end-user than for the RdSAP. In fact, the method uses the EPC XML files that are created when an EPC is generated. This reduced data is used to extrapolate all the geometry, construction, internal boundary conditions and weather needed for the DTS software Energy Plus [8], which is open source, widely used and verified. This paper demonstrates how a DTS model can be created that is equivalent to RdSAP in all the input data, as well as in the results, while expending no additional effort in data entry. A case study of 83 semi-detached houses drawn from the DEFACTO dataset [9] were used in this feasibility assessment. The predicted annual space heating energy demands and indoor air temperatures are compared with those produced by RdSAP. This proof-of-concept version of RdDEM considers only semi-detached houses in the UK but solves many of the most challenging issues and can be expanded to include further dwelling typologies.

2. Review of existing housing stock modelling methods

The majority of housing stock models developed in UK are quasi steady-state: BREHOMES [10–12], The Johnston model [13], The UK Carbon Domestic Model [14], The DECarb Model [15], The Energy and Environment Prediction Model [16], The Community Domestic Energy Model [17], The Cambridge Housing Model [18,19], and The Domestic Dwelling Model [20]. These models share the same calculation engine, BREDEM (Building Research Establishment's Domestic Energy Model: a set of heat balance equations and empirical relationships to estimate annual and monthly energy consumption of dwellings), 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 most are capable of predicting future energy demand and savings from proposed scenarios.

Few dynamic thermal simulation models of building stocks have been developed. The Canadian Residential Energy End-use Model (CREEM) [5] initially used the HOT2000 DTS program to calculate energy use for the Canadian housing stock. The work carried out in developing the CREEM evolved over time and with the addition of new datasets to develop a new hybrid model, namely: the Canadian Hybrid Residential End-use Energy and Emissions Model (CHREM) [6]. The CHREM used the ESP-r (an open-sourced building performance energy modelling software) DTS program and assumed only one thermal zone for the main part of the dwellings due to a lack of data on thermal zones. The CHREM also made geometrical simplifications: all houses were modelled as a rectangular block using a constant width to depth ratio [6]. 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 the model predictions.

The He et al. model [7] uses the English Housing Survey (EHS) database as the main source of input data and employs Energy Plus as the simulation engine. The model simulates the housing stock in the North East region of England to examine the possible CO_2 reductions corresponding to different scenarios. All the dwellings were assumed to have East/West orientation and were modelled with two separate zones: the living area and the rest of the dwelling. The results of the model were verified through inter-model comparison with the Cambridge Housing Model [18,19] as both models take inputs from the EHS database and simulate each dwelling individually.

The Energy Systems Research Unit (ESRU) Domestic Energy Model (EDEM) [21,22] is a web-based tool developed to estimate energy consumption and carbon emissions both at individual and national scale. The model used the 2002 Scottish House Condition Survey [23] as the main source of data and was used to rate the energy and carbon performance of individual dwellings as required by the EU Directive on the Energy Performance of Buildings [4]. The EDEM employed the ESP-r DTS program to determine dwelling performance by subjecting the dwelling models to long-term weather sequences. Clarke et al. [21] justified the 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*" [21].

A recent study in UK has developed a reduced data Domestic Operation Rating (DOR) scheme which is complementary to the scheme used in the UK to provide the asset rating of domestic buildings, the Standard Assessment Procedure (SAP), and is in harmony with the method used for the operational rating of non-domestic buildings [24]. The developed scheme only requires household's daily energy demands, the dwelling floor area and the annual degree-days for the region to calculate energy costs and Green House Gas (GHG) emissions. The proposed DOR could therefore readily be produced for all UK homes with daily-metered energy demands. Such scheme is one of the latest efforts to remove the cost and time associated with gathering detailed household data by utilizing available reduced data to produce better energy and environmental ratings of the UK homes.

3. The reduced data dynamic energy model (RdDEM)

The RdDEM (Fig. 1) converts EPC XML files (the Modelling Dataset) into Energy Plus Input Data Files (IDFs), suitable for running a dynamic thermal simulation. There are two distinct stages to the model: the data preparation process, which uses the reduced data to create a more complete building description suitable for DTS; and the translation process which converts the data into a format suitable for Energy Plus IDFs. It would be possible for other translators to be developed that use the same methods to convert the same data into formats suitable for other DTS; Energy Plus was chosen as a widely used and highly validated example.

3.1. The modelling dataset

The modelling dataset comprises EPC XML files. These files have already been created for 18,603,000 homes across the UK since 2008 [25], but access to them is restricted at this time. EPC XML files store information about the property, building parts, heating system and energy sources (Table 1). However, they do not contain the detailed geometrical information, or the construction material properties, required to model the house in a DTS. Geometry is limited to the floor area, ceiling height, heat loss perimeter and party wall length for each storey. There is no geometrical information for windows. Construction provides only a general description of walls, roofs and floor types, for example 'solid wall' or cavity wall', but no details of the construction layers or their material properties.

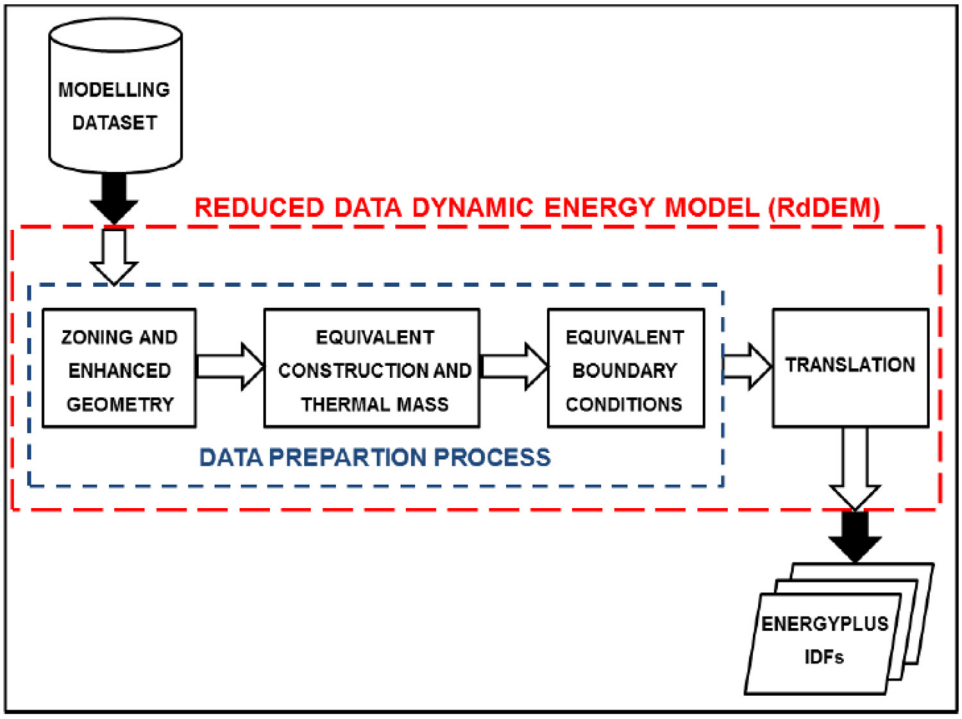

Fig. 1. Schematic of the RdDEM structure for converting the reduced data in EPC XML files into detailed data for Energy Plus IDF files.

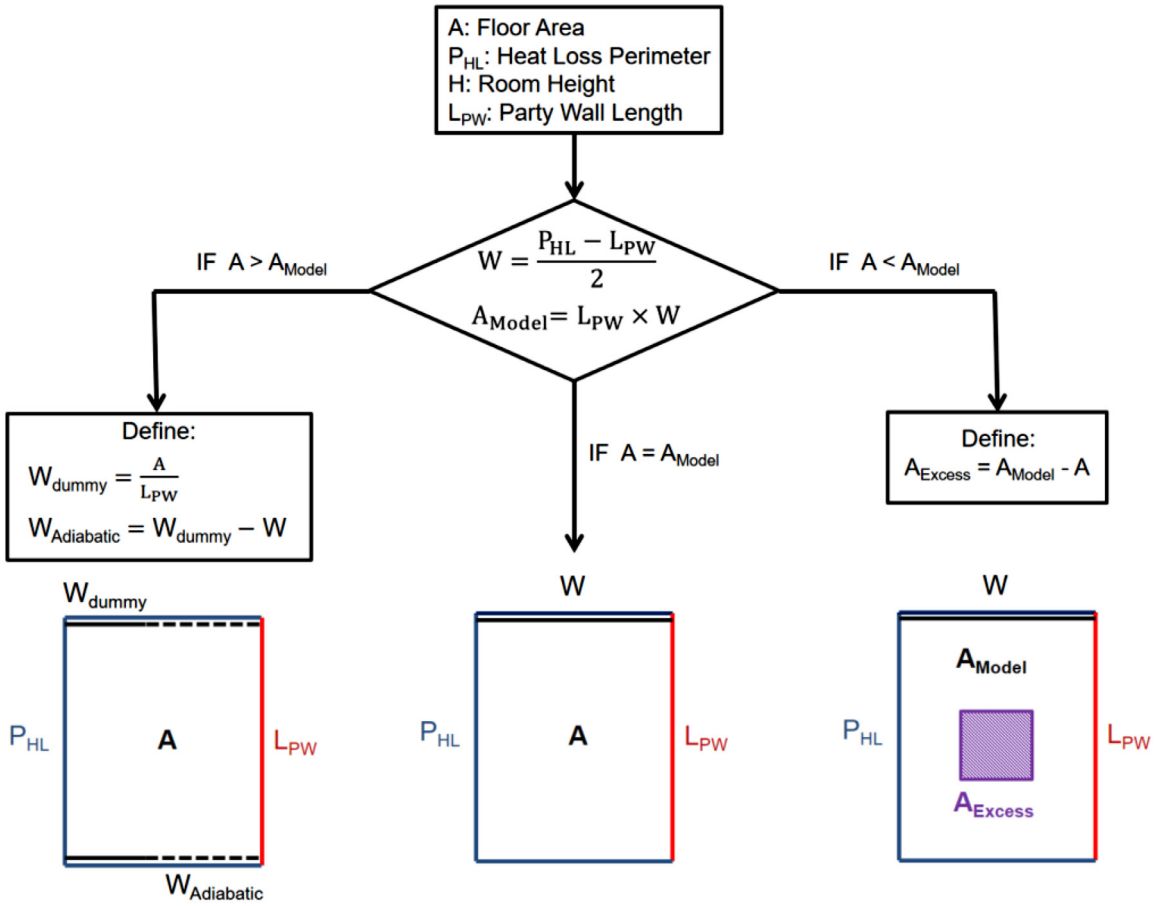

Fig. 2. The methodology to create 3-dimensional geometry suitable for dynamic thermal simulation from the reduced data in the EPC XML file.

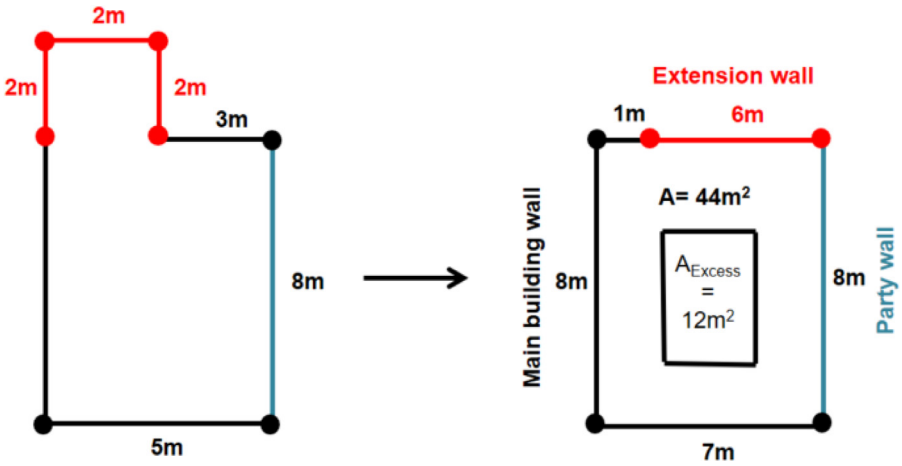

Fig. 3. Example of how RdDEM simplifies the more complex geometry of a house with an extension.

Fig. 4. Floor plans of the reference house used to test zoning strategy and geometry simplification (left: ground floor, right: first floor).

Table 1
Data stored in the EPC XML files designed for use with RdSAP 2012 to produce EPCs.

Category	Data
Property details	Property type, Built form, Glazing (type, area, frame), Extension count, Percent draught proofed, Habitable room count, Fixed lighting outputs count, Low energy lighting count, Mechanical ventilation, Open fireplaces, Solar water heating, Conservatory count
Building parts	Age band, Wall construction, Wall insulation type, Wall thickness, Party wall construction, Roof construction, Roof insulation location, Roof insulation thickness, Wall dry lined, Wall insulation thickness For each storey: Floor construction, Floor insulation, Heat loss perimeter, Floor area, Room height, Party wall length
Heating	Main heating details: Number of systems, Type of system, Main heating fuel, Main heating controls, Boiler flue type, Fan and heat recovery, Central heating pump age, Heat emitter type, Emitter temperature, Secondary heating type, Secondary heating fuel, Water heating type, Water heating fuel, Water storage cylinder size, Fixed air conditioning, Waste water heat recovery, Immersion heating, Meter type
Energy sources	Mains gas, Electricity, Wind turbines, PV

The EPC XML files used here to develop the RdDEM were collected by professional energy assessors generating EPCs as part of the DEFACTO research project [9]. All the DEFACTO houses were semi-detached and located in the Midlands region of the UK. The homes had central heating with a gas boiler and radiators as the main heating and hot water system. The main heating control was boiler programmer with room thermostat. Semi-detached houses are the most common house type in England representing 26% of the housing stock with over 30% built between 1919 and 1944 [26] and layouts and construction methods which remained largely unchanged from the 1930s to the late 1960s [27].

A batch of 83 DEFACTO XML files was chosen for the research reported here, such that all the houses had cavity or solid external wall constructions, pitched roofs with varying insulation thickness (50 mm to 300 mm), solid or suspended ground floors, and double-glazed windows. The floor areas ranged from 62 m^2 to 191 m^2

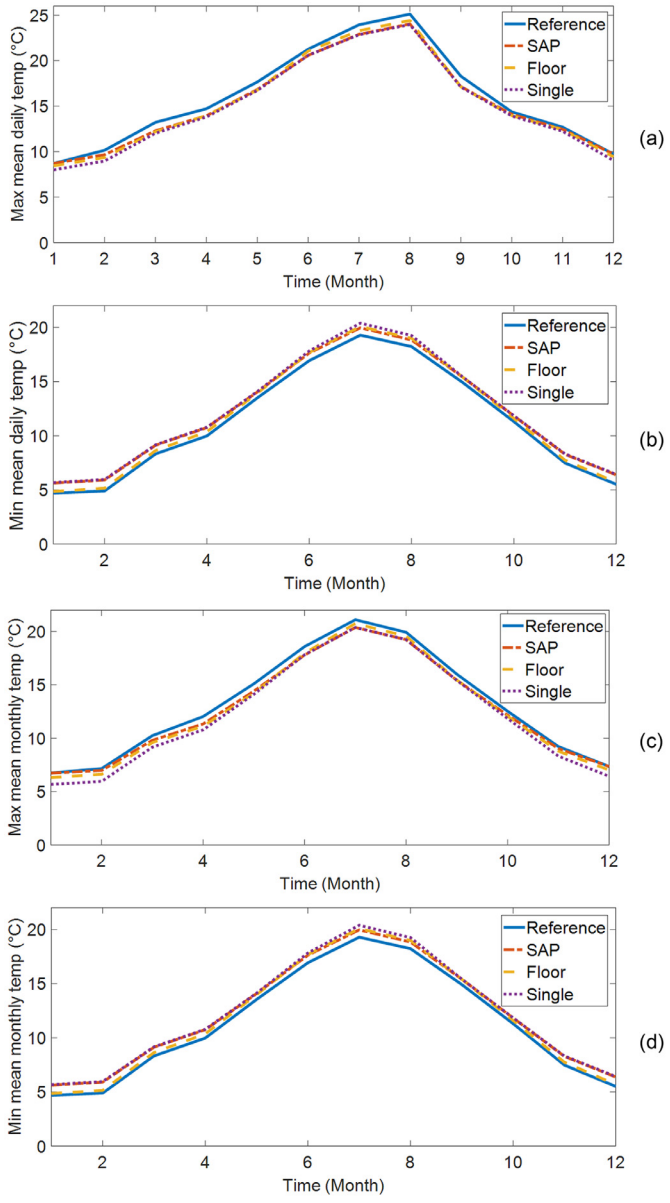

Fig. 5. Internal temperature results from the three zoning strategies and the detailed model (Reference) under summer conditions.

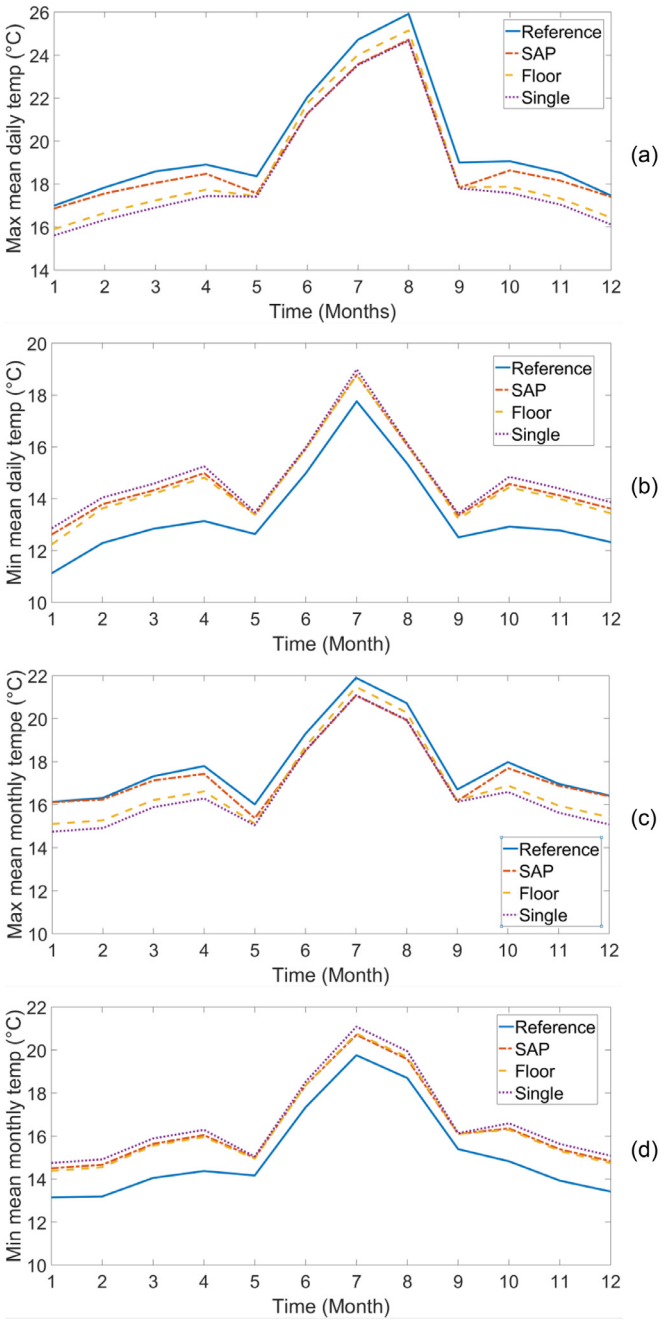

Fig. 6. Internal temperatures of the three zoning strategies and the detailed model (Reference) under winter conditions.

with 65% of houses having total floor area of 50–100 m^2, 25% 100–150 m^2 and 10% 150–200 m^2. The dwellings have age bands of B-E (1900–1975) and three external wall types: Solid brick, Cavity and Filled cavity. The detailed description of the houses are presented in Section 3.2. This sub-set was chosen to reduce the amount of code that would be needed to model every house while still providing the key technical challenges: zoning and enhanced geometry, defining equivalent construction and thermal mass, and defining equivalent boundary conditions

3.2. The data preparation process

The data preparation process (Fig. 1) includes three steps: zoning and enhanced geometry, defining equivalent construction and thermal mass, and defining equivalent boundary conditions.

3.2.1. Zoning and enhanced geometry

The EPC XML files in the dataset do not contain enough information to model each room as a thermal zone – there are no details of room sizes or layouts. Therefore, the RdDEM models each house as two thermal zones, as described in Section 4.1.

The RdDEM uses the floor areas, heights, exposed perimeters and party wall lengths of each house to create a three-dimensional rectangular prism that preserves the heat loss area of each element: external walls, ground floor, roof and party wall (Fig. 2). The length of the base of the prism is equal to the party wall length (L_{PW}) and its width (W) then derived to maintain the correct heat loss perimeter (P_{HL}: the length of the other three sides of the base of the prism). Room Height (H) is given in the EPC XML files and therefore, heat loss areas are preserved for all walls.

If the actual building was a rectangular prism, then the modelled floor and ceiling heat loss areas would match those given in the EPC XML files. However, this will not always be the case and

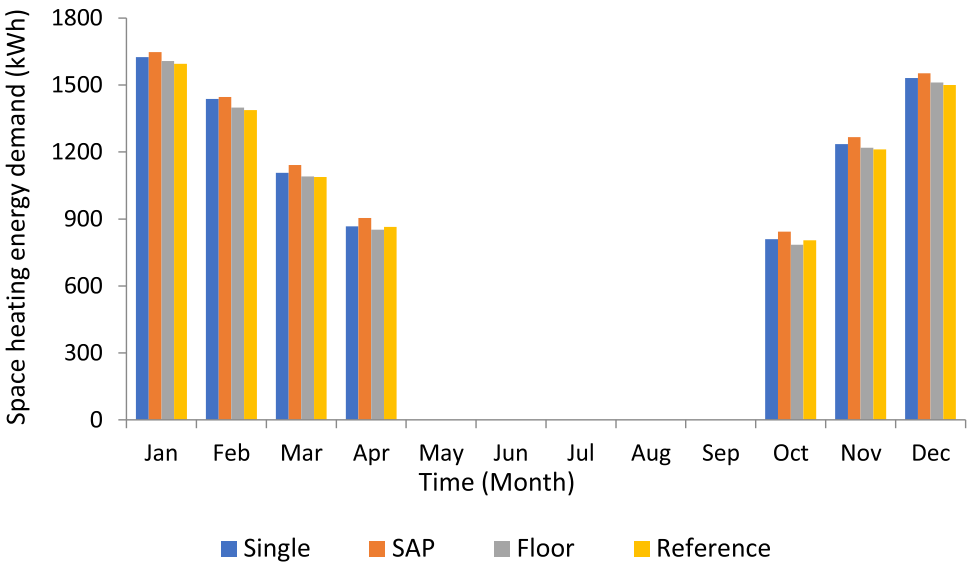

Fig. 7. Monthly space heating energy demand of the three zoning strategies and the detailed model (Reference).

the re-created geometry may have a larger, or smaller, floor and roof heat loss area. When the floor area of the model is smaller than that given in the EPC XML files (left branch of the graph in Fig. 2), the width of the modelled building was increased to preserve Floor Area (A) and party wall area at the expense of a larger external wall area. An adiabatic wall ($W_{Adiabatic}$) section was then added to the modelled geometry to reduce the external wall heat loss area. When the floor area of the model is larger than that given in the EPC XML files (right branch of the graph in Fig. 2), a block with zero heat capacity was added to the middle of the modelled building to remove the Excess Floor Area (A_{Excess}) and additional zone volume.

The methodology was further developed to include extensions of a different wall type in the rectangular prism (Fig. 3). As seen in Fig. 3, the extension has floor area of 4m^2 and exposed perimeter of 6 m while the main building has floor area of 40m^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 the rectangular geometry. The methodology was tested and verified through comparison with a more detailed model (see Section 4.2). The resultant geometry (Fig. 3) has an extra area of 12m^2 which is removed by introducing a block with zero heat capacity (as described in Fig. 2). 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.

Window area in the RdDEM was calculated from floor area in the same way as for RdSAP [2] (Table 2). In the absence of any information, windows were divided equally between floors and between the front and rear external walls of the houses. Due to the unknown orientation of houses in the EPC XML files, every house was modelled east facing (as suggested by SAP) in the RdDEM. This assumption could be updated if orientation data were collected in future and may be important for overheating assessment.

3.2.2. Equivalent construction and thermal mass

The RdDEM generates equivalent constructions required to simulate the external wall, roof, ground floor windows and doors in a DTS. The EPC XML files contain only limited information: the age band of the house, the type of each element and whether insulation has been retrofitted. The equivalent constructions for external walls were created to match the U-values given in Table S6 of RdSAP [2]. Houses in the dataset used here had three external wall types and belonged to four age bands (Table 3). Hence, four sets of equivalent constructions were required (Table 4). Each wall type was re-created using Design Builder's construction materials library and the thermal conductivity of brick adjusted to achieve the overall U-value. The U-value was increased by 0.15 W/m^{2}K in every case, to account for thermal bridging to match what is done in RdSAP Appendix K [2].

A party wall construction was developed with an equivalent U-value of 0.5 W/m^{2}K to account for the thermal by-pass from cavity party wall construction as described in SAP 2012 [2]. Roofs were modelled as pitched with insulation at joists to match the RdSAP U-value (Appendix K [2]) with thermal bridging. Ground floors were always modelled as a solid ground floor and insulation added to match the U-value with thermal bridging that would be calculated following the RdSAP method (Appendix K [2]). External doors of 1.85 m^2 were modelled on the front and rear walls of each house, following the RdSAP guidelines for U-value with thermal bridging (Appendix S [2]). All windows were modelled as

Table 2
Calculation of window area from total floor area (TFA) used by the RdDEM after the method described in Table S4 of RdSAP [2].

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

Age bands in England and Wales:
band B: 1900–1929;
band C: 1930–1949;
band D: 1950–1966;
band E: 1967–1975.

Table 3
U-values of the wall types in the modelling dataset, from Table S6 of RdSAP [2].

	U-value (W/m^{2}K) for the given age band			
Wall type	B (1900–1929)	C (1930–1949)	D (1950–1966)	E (1967–1975)
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

Table 4
Equivalent constructions that were created to match the U-values (including thermal bridging) of the walls in the modelling dataset.

Wall type	U-value including thermal bridging (W/m^2K)	Materials	Thickness (m)	Density (kg/m^3)	Thermal Conductivity (W/mK)	Specific Heat Capacity (J/kgK)
Solid Brick Age band B-D	2.25	Brick	0.205	1700	0.70	1000
		Dense plaster	0.015	1300	0.57	1000
Solid Brick Age band E	1.85	Brick	0.205	1700	0.70	1000
		Air gap	0.020	–	–	–
		Dense plaster	0.015	1300	0.57	1000
Cavity Age band B-E	1.75	Brick	0.105	1700	0.75	1000
		Air gap	0.035	–	–	–
		Brick	0.105	1700	0.75	1000
		Dense plaster	0.015	1300	0.57	1000
Filled Cavity Age band B-E	0.65	Brick	0.105	1700	0.79	1000
		Insulation	0.035	110	0.035	1470
		Brick	0.105	1700	0.79	1000
		Dense plaster	0.015	1300	0.57	1000

Table 5
Mean monthly external air temperature, wind speed and solar irradiance from SAP 2012 and IWEC Birmingham (IWEC, 2001) with corresponding conversion factor (CF).

Month	Air temperature (°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

double glazed, air filled with 6 mm gap and U-value that matched RdSAP (Appendix S [2]). The windows were modelled with an effective U-value which took account of the assumed use of curtains ($U_{w,effective}$), as shown in Eq. (1) (where U_w is the window U-value without curtains) from SAP 2012 and 0.15 W/m^2K was then added to include thermal bridging.

$$U_{w,effective} = \frac{1}{\frac{1}{U_w} + 0.04} + 0.15 \quad (1)$$

In RdSAP, the overall thermal mass parameter of all existing houses is assumed to be 250 kJ/m^2K. This same convention was used in the RdDEM: the thermal mass of each element of the building was derived from its equivalent constructions (Table 4) and then hanging partitions added to make up the remainder of the thermal mass required to achieve 250 kJ/m^2K total.

3.2.3. Equivalent boundary conditions

The internal boundary conditions in the RdDEM were designed to exactly match those in SAP (Appendices K, L, P, S, and U) to enable direct inter-model comparison. Internal heat gains from occupants, appliances, lighting and cooking were the same as defined in SAP Table 5 [2] 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 total floor area. The heating system, heating periods and set-point temperatures, in the living room and the rest of the dwelling, were derived as described in SAP [2].

A SAP equivalent weather file was developed for external boundary conditions using "typical weather year" data from the International Weather for Energy Calculations (IWEC) [28]. Since all houses in the dataset were in the Midlands region of the UK, the IWEC weather data for Birmingham was used. Monthly values of external air temperature, wind speed and solar radiation were compared with the monthly SAP values to produce a scaling factor that was then applied to the hourly values to produce the SAP equivalent dynamic weather file (Table 5). The conversion factors ranged from 0.84 to 1.30 for temperature, 0.83 to 1.45 for wind speed, and 0.35 to 1.17 for solar irradiance.

3.3. The translator

The RdDEM translates the prepared data into the IDF format required for running Energy Plus simulations. The RdDEM translator script was written in MATLAB R2015a software package to create Energy Plus version 8.3.0 Input Data File (IDF).

Energy Plus IDFs are text based and in the translation process there were two types of data used to create the IDF. The first set of data were the same for all of the houses and therefore were written into the IDF template once only (for example, all dwellings were modelled as two storey, two zone rectangular blocks). 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 house to house and was translated individually for each one. This varying set of data comprised: internal mass, geometry and internal boundary condition details.

4. Testing and verification of the RdDEM methods

The RdDEM methods described in Section 3.2.1 for simplifying zoning and enhancing geometry were tested and verified by comparing the resulting Energy Plus predictions of energy demand and internal air temperature to those from a detailed model of the same reference house. The reference house was a two storey, semi-detached house, as described by Allen and Pinney [29] (Table 6 and Fig. 4)

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 [17] used it to identify the archetypes in Community Domestic Energy Model (CDEM); Taylor et al. [30] modelled the period terraced house from Allen and Pinney [29] Standard Dwellings Types at nine different levels of detail to study the impacts on energy consumption; and Yilmaz et al. [31] modelled the semi-detached house from Allen and Pinney Standard Dwellings Types and compared the space heating energy predictions from SAP, Energy Plus, ESP-r, SERI-RES, BREDEM-8, and BREDEM-12 models.

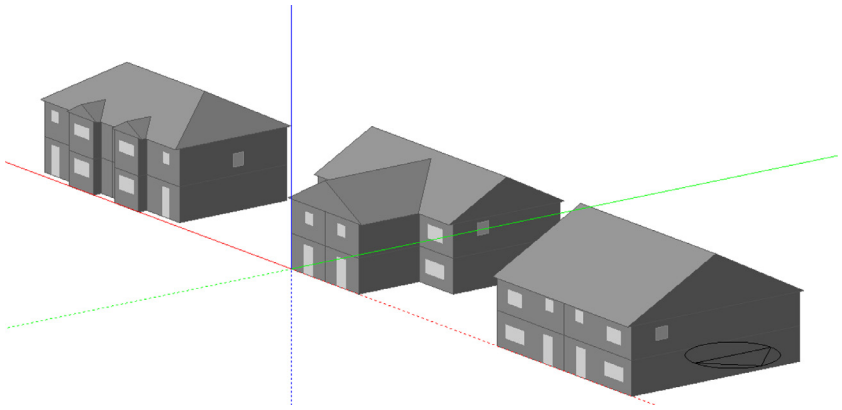

Fig. 8. Left to right: the reference house for identifying the best zoning strategy, the reference house for verifying the enhanced geometry and the resulting RdDEM model.

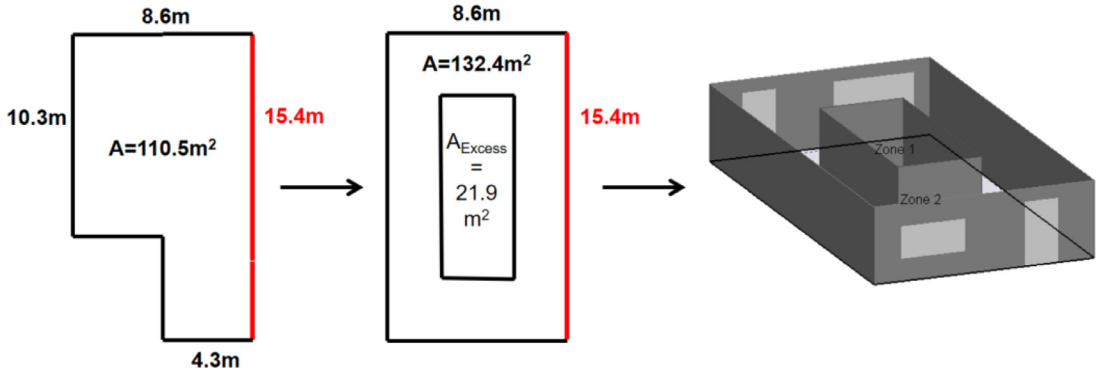

Fig. 9. An example of how the RdDEM transforms the L-shaped reference geometry model to the rectangular prism model.

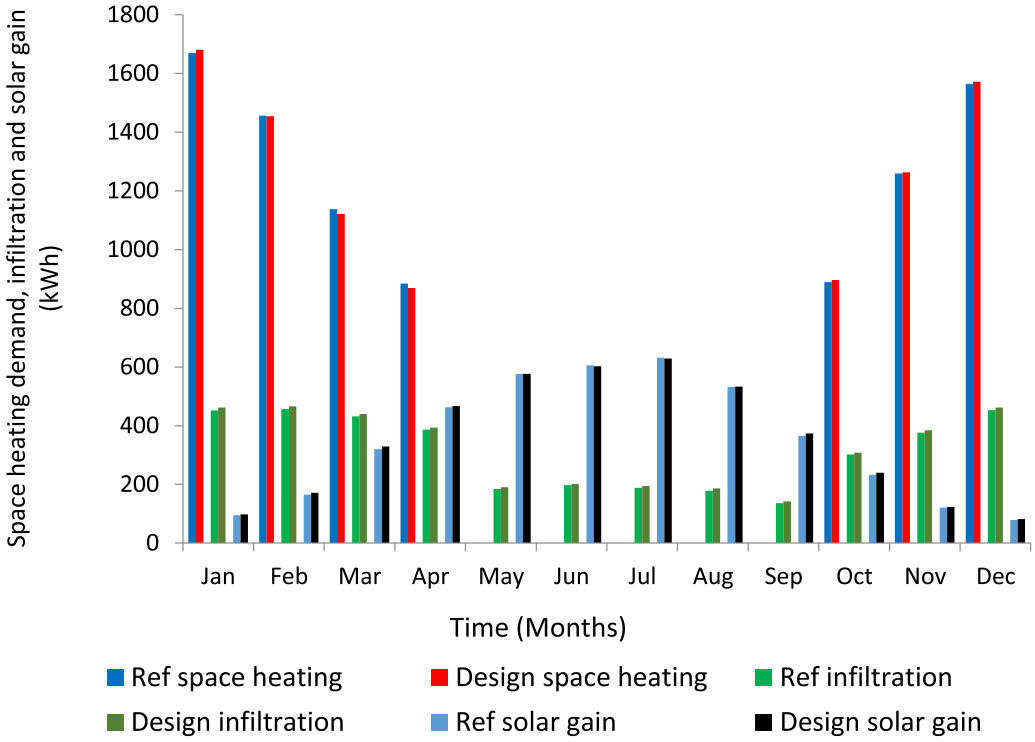

Fig. 10. Monthly averaged space heating demand, external infiltration and solar gain predictions of RdDEM compared to the reference geometry model.

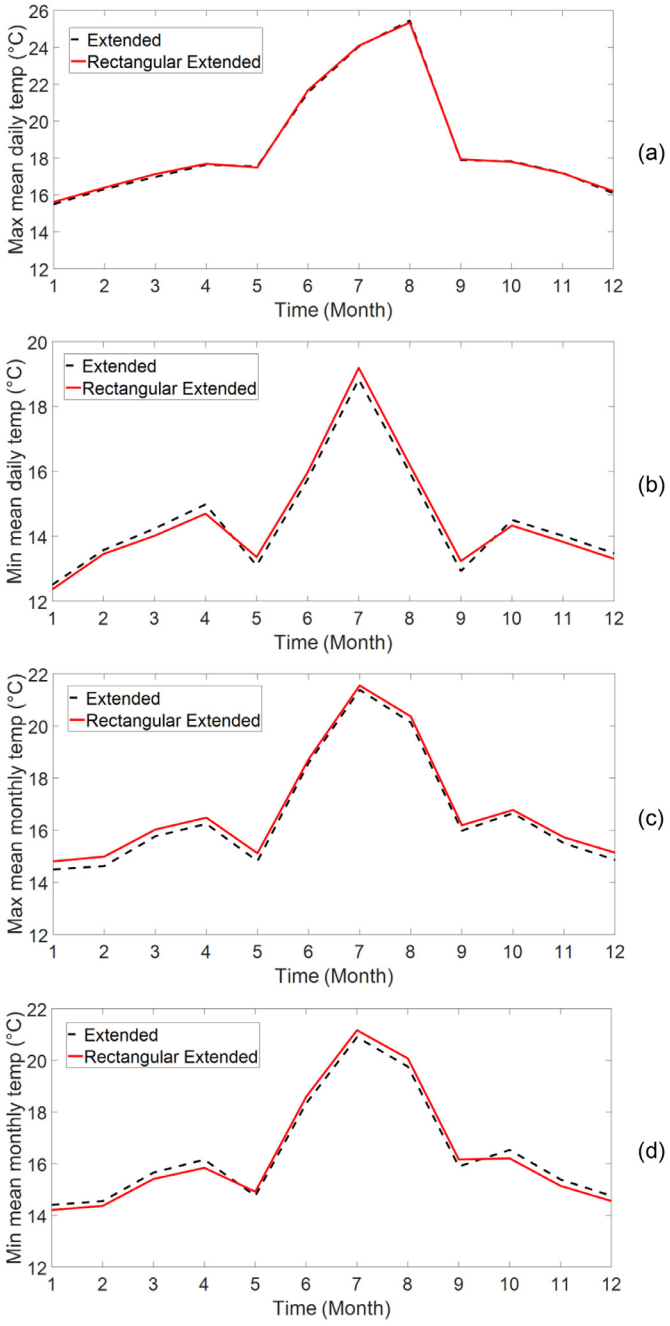

Fig. 11. Internal temperatures of the reference geometry model and the design geometry model.

Table 6
Summary of construction elements of the reference house and approximate U-values.

Element	Description	U-value (W/m^{2}K)
External walls	Brick cavity (un-insulated)	1.6
Floor	Solid (concrete slab)	0.7
Roof	Pitched roof covered with clay tiles	2.3
Windows	Single glazing with wooden frame	4.8
Entrance door	Wooden	3.0
Party wall	Brick cavity	1.6
Internal partitions	Solid brick covered with plaster	2.1

The heating system in the reference house was a low-pressure hot water central heating system with a condensing boiler and radiators. The heating system was ON from 07:00 to 09:00 and 16:00 to 23:00 for the heating season: 1st October to 31st May. The heating set point temperatures were 21 °C for living room and dining room, 18 °C for bedrooms and kitchen, and 22 °C for bathroom. The reference house had an overall infiltration rate of 0.7 ACH with roof infiltration rate of 2 ACH.

4.1. Identifying the best zoning strategy

While RdSAP models each house as two zones ('living area' and 'rest of dwelling') Energy Plus can model as many thermal zones as required. Three potential zoning strategies were identified:

i Single zone strategy: where a single zone was assigned to the whole house;
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.

Results from simulation of the reference house using each zoning strategy in turn were compared to the detailed model, where every habitable room in the house was modelled as an individual thermal zone. During the summer, all three zoning strategies under-predicted maximum mean daily internal temperature by about 1 °C in comparison with the detailed model (Fig. 5(a)). Minimum mean daily internal temperature (Fig. 5(b)), was over-predicted by all three zoning strategies with 'Floor' zoning showing the better result. Monthly mean internal temperature graphs (Fig. 5(c) and (d)) show a similar trend to the daily graphs with all zoning strategies predicting higher maximum monthly temperatures and lower minimum temperatures compared to the detailed model. 'Floor' zoning produced monthly temperature predictions that were closest to the detailed model.

During the winter (Fig. 6) there were larger differences between predictions. All three zoning strategies predicted lower maximum mean daily temperatures in the winter (Fig. 6(a)) with 'SAP' zoning giving closer predictions to the detailed model. All three zoning strategies predicted higher minimum mean daily temperatures compared to the detailed model (Fig. 6(b)). The maximum and minimum mean monthly temperatures had a similar trend to mean daily maximum and minimum values (Fig. 6(c) and (d)).

Overall, the 'Single' zone strategy showed poorest temperature predictions, 'Floor' zoning gave better predictions of internal temperatures in summer condition and 'SAP' zoning was better under winter conditions.

Considering the prediction of monthly space heating demand (Fig. 7), 'SAP' zoning predicted the highest space heating demand each month while the results from 'Floor' zoning were closer to the detailed model. A similar trend was observed in the annual space heating demand predictions where 'SAP' zoning showed the biggest difference to the detailed model (4%) and 'Floor' zoning had the closest result (0.1%). The 'Single' zone strategy had a 1.9% difference.

Based on this assessment, 'Floor' zoning was chosen as the most suitable zoning strategy for the RdDEM as, overall, it gave results closest to a detailed model.

4.2. Verifying the enhanced geometry simplification

The lack of detailed geometry in datasets is one of the main issues raised by previous dynamic energy modelling studies [5-7] and each study dealt with this issue in a different way. Swan et al. [6] assumed a rectangular geometry layout and developed an

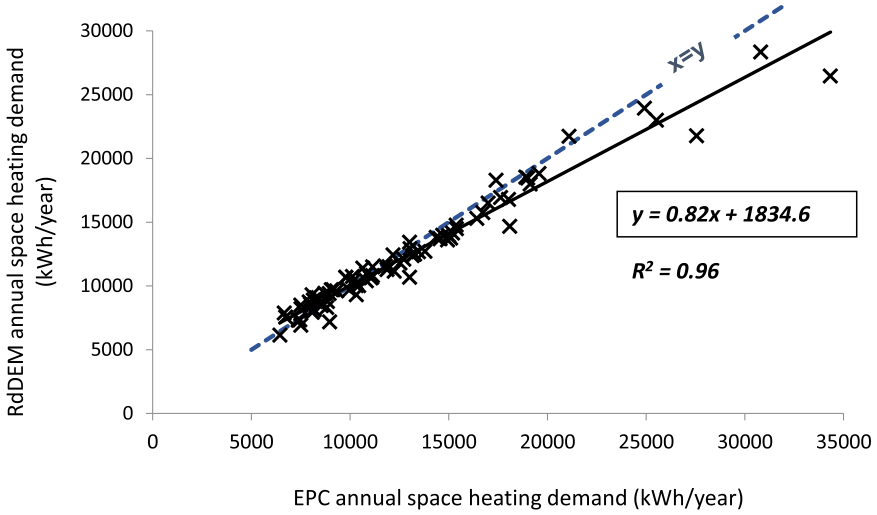

Fig. 12. Comparison of space heating demand predictions of the RdDEM with those from RdSAP calculation for the batch of 83 semi-detached houses.

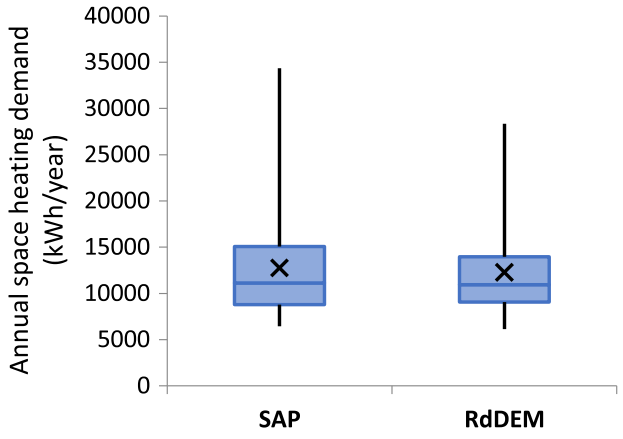

Fig. 13. Comparison of the space heating demand predictions from RdDEM with those from EPC calculation for the batch of 83 semi-detached houses.

average width to length ratio which was applied to all the modelled houses. He et al. [7] considered two geometrical layouts: a rectangular and an L-shaped layout. In this paper the rectangular approach proposed by Swan et al. [6] 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 houses, the RdDEM used the 'Excess Area Block' approach (see Section 3.2.1). This made it possible to model the exact floor area, exposed perimeter, and party wall length as identified in the dataset.

A modified version of the reference house was used to test the impact of modelling an L-shaped layout as a rectangular block (Fig. 8). The geometry reference house had the same width as the reference house but 25% was added to the floor area as an extension and window areas and internal wall areas were also increased by 25%. It was modelled using floor zoning as described above and transformed to an equivalent rectangular prism (Fig. 9). As seen in Fig. 9, converting the L-shaped geometry to a rectangular one while preserving all details results in an excess block (A_{Excess}) which in this case is equal to the extension area.

Predictions from the simplified model were compared with those obtained by using the full geometry of the reference house. There was close agreement between monthly infiltration and solar gains (<2%) while the difference in space heating demand was less than 1% in all months and the annual space heating demand was within 3 kWh/year (Fig. 10). The monthly difference between internal air temperature predictions (Fig. 11) 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.

4.3. Model verification

A lot of effort was put into ensuring that there were no errors in the Energy Plus models. This included modelling houses multiple times and cross-comparison of results. In order to verify zoning strategy (Section 4.1), enhanced geometry (Section 4.2) and equivalent thermal mass (Section 3.2.2) techniques used to develop the RdDEM, the model predictions for three of the houses in the dataset (chosen for model verification) 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 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 demands from the RdDEM and the detailed Energy Plus models were compared. The detailed models of the three test houses predicted lower annual energy demands compared to the RdDEM. The difference between RdDEM and detailed model predictions, which was less than 5% in all the studied houses, verified the data preparation process developed to model geometry, thermal mass and zoning using reduced data.

5. Comparison of the RdDEM results with those from RdSAP

The RdDEM predictions were compared with RdSAP predictions for the batch of 83 semi-detached houses. All the simulations were run in Energy Plus 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 7. The RdSAP methodology from SAP 2012 was used to calculate annual energy demands and mean internal temperatures for each month.

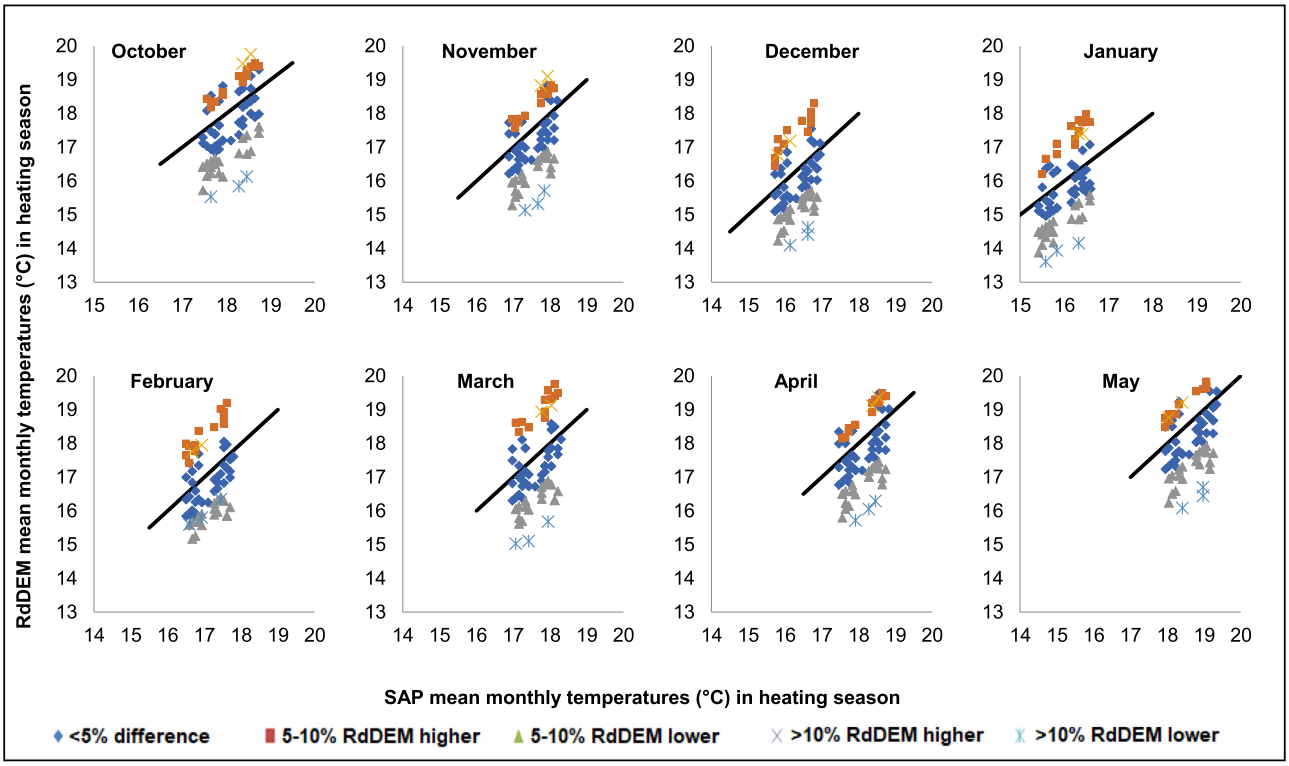

Fig. 14. Comparison of RdDEM monthly average temperature predictions to those from RdSAP for the 83 houses, also indicating the% difference in the monthly energy demand prediction between RdDEM and RdSAP (The black line represents $y = x$).

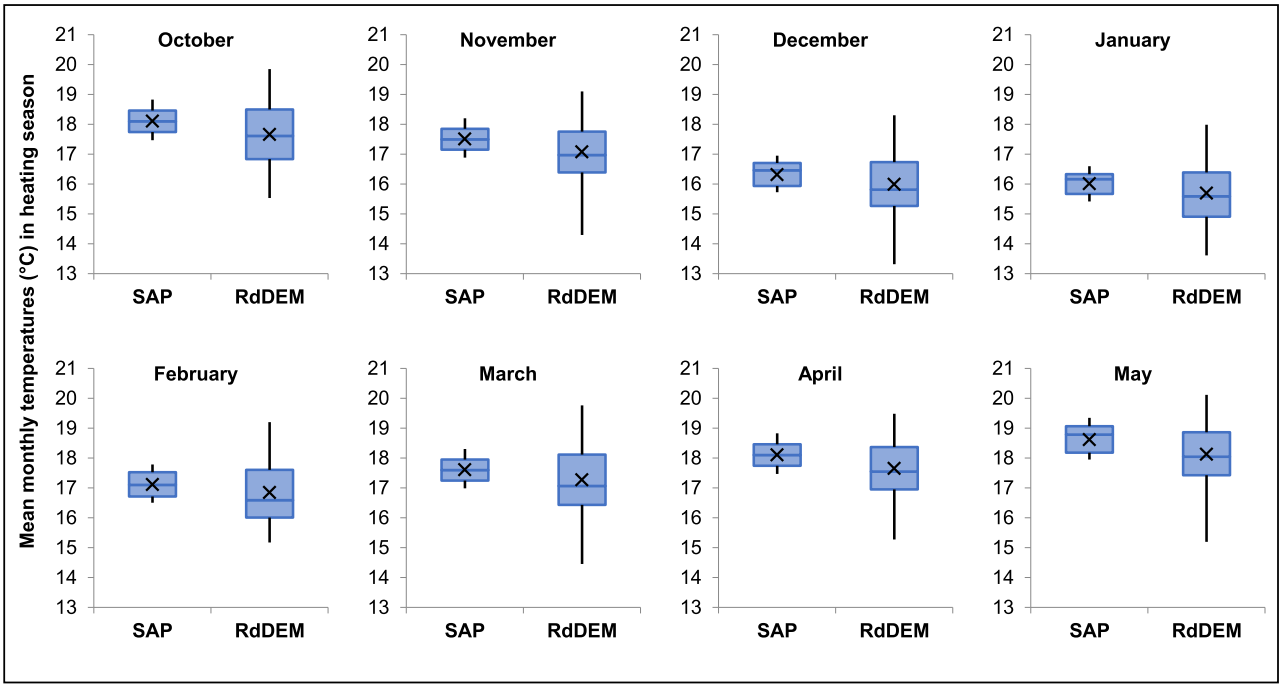

Fig. 15. Comparison of mean monthly internal air temperature distributions between the RdDEM and RdSAP for the 83 houses.

5.1. Space heating demand predictions

For annual space heating demand (Fig. 12), the minimum difference observed between RdDEM and RdSAP 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% (Table 7). 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 (Fig. 13).

Table 7
Comparison of space heating demand predictions between RdDEM and RdSAP for the 83 houses.

	By (%)	Number of houses (%)
RdDEM predicts higher space heating demand than RdSAP	>10%	2 (2%)
	5–10%	9 (11%)
	<5%	12 (14%)
RdDEM predicts lower space heating demand than RdSAP	>10%	3 (4%)
	5–10%	23 (28%)
	<5%	34 (41%)

5.2. Internal temperature predictions

RdDEM generally predicts lower mean monthly internal air temperatures throughout the heating season (Fig. 14). The RdDEM temperature predictions are higher when the energy demand predictions (% difference) are also higher. This trend shows that the difference in space heating demand can mainly be explained by the difference in internal air temperatures. Since other influencing factors (e.g. solar radiation and infiltration) on space heating were similar in the two models, it can be concluded that the temperature differences were the main contributors to varying space heating predictions.

RdDEM gives a wider prediction of internal air temperature than RdSAP in all the heating season months (Fig. 15). The RdDEM tends to predict higher maximum mean monthly temperatures and lower minimums. These distributions suggest that RdSAP constrains the internal temperature predictions more than RdDEM. This trend also suggests RdDEM is more sensitive to external temperatures than RdSAP. The mean, median and first quartile predicted by RdDEM are lower than RdSAP. However, the third quartile is lower in warmer months and higher in colder months. Some of this variation cancels out when the annual energy demand is considered. The average difference between minimum and maximum indoor air temperatures of the houses predicted by RdDEM is 4.6 °C which is considerably larger than the 1.3 °C difference predicted by RdSAP.

6. Discussion

Faced with the lack of available data suitable for running dynamic simulations of UK housing stocks, this paper focused on developing suitable algorithms that use the significant amount of reduced data available in existing EPC datasets. Some key problems had to be overcome. This research investigated different zoning strategies showing that the results of DTS were sensitive to the choices made; evidence on the suitability of alternative floor-by-floor zoning strategies is given (Section 3.2.1 and 4.1). A new method to create detailed geometry from very reduced data (RdSAP geometry) was also tested and found to produce equivalent results for energy and indoor air temperatures when compared to modelling the geometry in full (before reducing the data)(Section 4.2). Methods for creating equivalent constructions, thermal mass and boundary conditions are described for the first time (Section 3.2.2). 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. [5], Swan et al. [6], and He et al. [7] all made assumptions to handle geometrical details missing in the datasets but did not present a sensitivity analysis of the assumptions made. Consequently, the uncertainty added to model outputs in these studies was not quantified. This research avoided introducing new assumptions to model geometry and dealt with the missing geometry in a novel and efficient way.

The inter-model comparison, with equivalent inputs, showed that, using the RdDEM, the DTS program Energy Plus predicts lower annual space heating demands than RdSAP for majority of the 83 houses studied. The tendency of DTS programs to predict lower space heating demand than BREDEM-based models like RdSAP, has been observed in previous studies. Shorrock et al. [32] modelled the semi-detached house described by Allen and Pinney [29] using the DTS programs ESP-r and SERI-RES, and compared the annual space heating demands to steady-state BREDEM-8 and BREDEM-12 models. Both dynamic energy models underestimated the annual space heating demand compared to both BREDEM-8 and BREDEM-12 by up to 18%. Yilmaz et al. [31] observed that Energy Plus predicted a lower energy demand for a semi-detached house than SAP 2009. The RdDEM predicted annual space heating demand for 94% of the houses, (to within 10% margin of RdSAP predictions). Such small margin for the vast majority of modelled houses shows the power of equivalising inputs as described in this research. The RdDEM method would allow many more comparisons of this nature to be made and will enable comparisons with measured energy demand in future work.

This research addressed limitations of the previous energy models developed for UK houses by introducing a transparent dynamic alternative to traditional steady-state SAP calculations. However, this research had limitations which should be addressed in its development. The RdDEM should be expanded to model more than semi-detached houses and should consider conservatories, room-in-roof, or multiple extensions. The reference model described by Allen and Pinney was poorly insulated and better insulated homes should also be explored. The SAP equivalent weather data was recreated by scaling a typical weather file for the Midlands region of UK; more work is needed to produce compatible bespoke weather files for use in inter-model comparisons. Also, comparisons between RdDEM results and long term in-situ measurements would allow more accurate model calibration. It is noted that not feeding detailed dynamic tools with enough input data could result in loss of precision when it comes to overheating or retrofitting analysis.

The modelling framework presented in this paper offers great flexibility and can be expanded by other modellers to include a wider range of dwelling types, constructions, occupancy patterns and heating systems. Other translators can also be developed to use the same methods to convert reduced data into formats suitable for other DTS tools (ESP-r, IES VE, etc.). Such generalization of the modelling framework would enable cost-efficient dynamic thermal simulation of housing stocks around the world and will offer a comprehensive repository of whole building simulation results to enable inter-model comparisons and model validation.

The methods developed for enhancing geometry data was tested and verified using batch of semi-detached dwellings. These methods can be expanded conveniently to include other UK dwellings types (detached, terraced, etc.) as the construction and layout of different house types in UK are greatly similar. While the geometry simplifications (Fig. 2) can be applied to any dwelling type, inclusion of non-UK housing stocks would require further research as some of the assumptions and modelling choices described in this paper might not be valid for other housing stocks.

7. Conclusion

The critical analysis of existing energy models of UK homes revealed the inability of these models to fully capture the dynamics of temperature response and energy consumption. This paper presented work undertaken to use Dynamic Thermal Simulation (DTS) to overcome the limitations of quasi-steady state models such as RdSAP. The main concern in using DTS to predict energy consumption is the large amount of required input data compared to steady-state models. This research explored the possibility of us-

ing the data collected to produce Energy Performance Certificates (EPCs) as a source of input data for DTS programs. Prior to this research, there was no peer reviewed, published literature to indicate the potential of EPC-like datasets as input to DTS programs.

The RdDEM converts EPC XML files, designed for RdSAP calculations, into Energy Plus IDF files suitable for simulation. The overall three-dimensional geometry of the dwelling was produced from floor areas, wall heights and perimeter lengths. A floor-by-floor zoning strategy was also developed. Boundary conditions, equivalent to those used by RdSAP, represent the weather and occupants.

The new inferences and methodological enhancements were then used to create IDF files for 83 semi-detached houses. The annual energy demands predicted by Energy Plus based on the RdDEM were, for 94% of homes, within 10% of those calculated using RdSAP. The differences are explained by the way that the models calculate that indoor air temperature.

The Reduced data Dynamic Energy Model (RdDEM) is a significant step towards using DTS models to predict the energy demands of, and indoor environment in, our housing stocks, while not increasing data collection overheads. This current proof-of-concept RdDEM is limited to semi-detached houses but solves many of the most challenging issues (zoning configuration and geometry simplification in Section 3.2.1, thermal mass in Section 3.2.2 and equivalent boundary conditions in Section 3.2.3). Ultimately, the techniques developed here can be used to provide new insights into the transient aspects of energy use and indoor air temperatures in housing stocks and therefore has international value as both a policy and a research tool. As a future work, authors are considering the transfer of model to a freely accessible online platform which will enable the research community to use and modify the developed model for further research in the building energy modelling context.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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