2013

Development and Implementation of a Simplified Residential Energy Asset Rating Model

Daire Reilly
Technological University Dublin, dairereilly@gmail.com

Aidan Duffy
Technological University Dublin, aidan.duffy@tudublin.ie

David Willis
E.S.B. Electric Ireland, david.willis@electricireland.ie

See next page for additional authors

Recommended Citation

Reilly, D., Duffy, A., Conlon, M., Willis, D.:A (2013) Development and Implementation of a Simplified Residential Energy Asset Rating Model. *Energy and Buildings*, Volume 65, October 2013. ,pp. 159–166. doi:10.1016/j.enbuild.2013.04.023

Funder: IRCSET/E.S.B - Electric Ireland

Authors
Daire Reilly, Aidan Duffy, David Willis, and Michael Conlon

AUTHOR QUERY FORM

ELSEVIER	**Journal:** ENB **Article Number:** 4270	**Please e-mail or fax your responses and any corrections to:** **E-mail:** corrections.esch@elsevier.thomsondigital.com **Fax:** +353 6170 9272

Dear Author,

Please check your proof carefully and mark all corrections at the appropriate place in the proof (e.g., by using on-screen annotation in the PDF file) or compile them in a separate list. Note: if you opt to annotate the file with software other than Adobe Reader then please also highlight the appropriate place in the PDF file. To ensure fast publication of your paper please return your corrections within 48 hours.

For correction or revision of any artwork, please consult http://www.elsevier.com/artworkinstructions.

Any queries or remarks that have arisen during the processing of your manuscript are listed below and highlighted by flags in the proof. Click on the 'Q' link to go to the location in the proof.

Location in article	**Query / Remark: click on the Q link to go** **Please insert your reply or correction at the corresponding line in the proof**
Q1	Please confirm that given names and surnames have been identified correctly. Please check this box or indicate your approval if you have no corrections to make to the PDF file ☐

Thank you for your assistance.

G Model
ARTICLE IN PRESS

Energy and Buildings xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Highlights

Energy and Buildings xxx (2013) xxx–xxx

Development and implementation of a simplified residential energy asset rating model

Daire Reilly, Aidan Duffy*, David Willis, Michael Conlon

- We examine the effect of reducing the amount of input fields to the asset rating methodology for the Irish housing stock.
- One generic and four reduced input asset rating tools are created.
- Sensitivity analysis and stochastic modelling are used to analyse the models.
- We report a high correlation between the original and some of the simplified tools

Energy and Buildings xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Development and implementation of a simplified residential energy asset rating model

Daire Reilly[a,b], Aidan Duffy[a,b,*], David Willis[c], Michael Conlon[a,d]

[a] Dublin Energy Lab, Dublin Institute of Technology, Ireland
[b] School of Civil and Building Services Engineering, Dublin Institute of Technology, Ireland
[c] Electric Ireland, Dublin, Ireland
[d] School of Electrical Systems Engineering, Dublin Institute of Technology, Ireland

A R T I C L E I N F O

Article history:
Received 15 January 2013
Received in revised form 19 April 2013
Accepted 25 April 2013

Keywords:
Energy efficiency
Residential energy demand
Asset rating
Energy Performance of Buildings Directive
Sensitivity analysis

A B S T R A C T

Recent European legislation (Energy Efficiency Directive) has allocated some responsibility for residential end use energy efficiency to energy supply companies. In order to overcome data and modelling limitations associated with statistical and engineering modelling approaches to energy efficiency and renewable energy retrofit measures, energy suppliers and policy-makers often use simplified methods with limited data requirements to assess dwellings. One approach employed is an asset rating method (ARM); a standardised approach to residential energy demand estimation which is outlined in ISO EN 13790 (Energy Performance of Buildings Directive). Although it is a simplified method which industry is well-equipped to deliver, it is time-consuming to apply ARMs to the large domestic customer bases of energy suppliers. A small per-dwelling time saving will result in significant overall efficiencies for these users. This study examines the effect that reducing input data requirements of the ARM has on the accuracy of the methodology and comments on the trade-off between model simplification and accuracy. We find that it is possible to maintain a high degree of accuracy (~95%) with 20 fewer variables than the baseline model. This is equivalent to almost 40% fewer variables than in the full model and represents a significant saving in effort

1. Introduction

The recent European Energy Efficiency Directive (2012/27/EU) requires national governments introduce a range of measures to ensure that energy is used more efficiently across their economies. Energy suppliers are targeted by the Directive through 'Energy Obligation Schemes' requiring them to reduce the energy consumed by their consumers through the promotion of energy efficiency technologies. National targets are monitored and should accumulate between 2014 and 2020 [1]. Consequently, energy suppliers need to identify the most cost-effective energy saving measures to implement in their customer-base, while individual customers need to be able to assess the cost-effectiveness of any proposed measures at a household level.

The domestic energy improvement measures that can be supported vary between member states but may include:

- upgrading heating and cooling systems;
- retrofitting insulation and windows;
- new hot water devices;
- energy efficient lighting;
- efficient heat recovery, cooking and refrigeration devices; and
- Micro-generation appliances that lead to a reduction in the amount of electricity or fuel purchased.

In accordance with Directive 2006/EC/32 all European member states were required to submit three successive Energy Efficiency Action Plans (EEAPs) outlining energy efficiency measures proposed to reach emissions savings targets set out in the directive. The Irish NEEAP allocates an expenditure of €30m in capital funding to the Better Homes Scheme, aiming to deliver annual energy savings of 250 GWh and CO_2 reductions of 60,000 tonnes through energy efficient retrofit of existing residential dwellings. In Britain household energy demand targeted policies such as carbon reduction targets, energy efficiency commitments and energy supplier

Abbreviations: ARM, Asset rating model; BER, Building energy rating; BREDEM, British Research Establishment Domestic Energy Model; CDF, Cumulative distribution function; CERT, Carbon Emissions Reduction Target; CODEMA, City of Dublin Energy Management Agency; DEAP, Dwelling Energy Assessment Procedure; EE, Energy efficiency; EPBD, Energy Performance of Buildings Directive; MAPE, Mean absolute percentage error; NEEAP, National Energy Efficiency Action Plan; RES, Renewable energy supply; SEAI, Sustainable Energy Authority of Ireland; SAP, Standard Assessment Procedure.

* Corresponding author. Tel.: +353 0 1 402 3940, fax: +353 0 1 402 3720.
E-mail address: aidan.duffy@dit.ie (A. Duffy).

0378-7788/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.enbuild.2013.04.023

obligations are forecasted to achieve annual of savings 56.6 and 76.56 TWh by 2016 and 2020 respectively [2]. In 2011 a working paper presented to the European Commission on the implementation of the NEEAPs by member states showed that over one third of national energy efficiency measures were aimed at improving the energy performance of buildings with residential specific measures making up a significant portion of this [3].

In order to realise national energy savings in a cost-effective manner, Energy suppliers and state agencies need to be able to identify which technologies to promote and which households to target. However, energy suppliers typically do not have the information needed to identify the most cost-effective technology which should be applied to a particular household or customer group. The main information gaps include sufficient data and robust methods for accurately identifying the energy and cost savings for particular technology-household combinations. The data requirements for achieving this aim are significant; not only are historic fuel and electricity consumption data required, but detailed information including dwelling geometry, fabric and condition as well as occupancy levels and patterns are also needed. If these data were available, they could be used to model the effects of energy efficient (EE) and renewable energy supply (RES) retrofit measures. However, data gathering and inputting to models is a complex and time consuming process, particularly for large numbers of dwellings.

A number of different building energy simulation models are presented in literature which can be broadly categorised as either 'statistical' or 'engineering'; these are sometimes combined as hybrid approaches [4–7]. Statistical models are highly data dependent and explain household energy use in terms of dwelling and occupant characteristics. They are sample-specific and cannot be reliably applied to housing populations which are not represented by the sample. Statistical approaches are averaged across household type and cannot be applied to individual dwellings deterministically. Dependent energy variables are typically for large time steps of two months to one year and current relationships do not describe the impact of retrofit measures due to data constraints. Engineering building energy models require a detailed physical description of the building as well as the relationships which describe its material properties, heating and occupancy schedules and appliance data; heat transfer principles and mass flow are used to simulate the energy requirements of the building. The approach allows EE and RES retrofit technologies to be modelled. However, the approach suffers from significant drawbacks for energy suppliers and homeowners [8]. It is expensive since it is labour intensive and uses complex commercial software requiring expert operation. Large amounts of data are required including a detailed geometric representation of the dwelling as well as material properties and climatic conditions. It is computationally intensive.

In order to overcome the data and modelling limitations associated with statistical and engineering approaches, those involved in modelling EE and RES retrofit measures in large samples of dwellings–such as energy suppliers and policymakers–use simplified hybrid methods with limited data requirements. One approach is to employ an asset rating method (ARM). ARMs use heat transfer principles and simple physical dwelling data in conjunction with empirical relationships regarding occupancy, thermal comfort and heating season. The use of average occupancy rates reduces the short-term accuracy of these models since occupancy levels and patterns have been found to affect energy use in a residential dwelling [9–11]. However, the focus on the physical characteristics of a building is well placed since these factors have the greatest impact on energy use [4,12–14]; however, in the long-run, average building occupancy is likely to approach the assumed ARM average occupancy rate. But perhaps the most important reason for the popularity of the ARMs–apart from their simplicity – is the existence of extensive EU and national guidance documents and tools.

The Energy Performance of Buildings Directive (EPBD) [15] requires EU-27 member states to adopt a certification system in order to rate the energy efficiency of individual residential dwellings; the information thus provided allows buyers to factor energy costs into their purchasing decisions. Such a rating is required for new dwellings prior to occupation and for existing buildings which are for resale or rent [16]. The methodology guidance allows for some flexibility in the choice of rating technique for the certification system; a calculated rating, measured rating or a combination of both may be used. In Ireland the certificate is issued upon completion of a rating exercise is called a Building Energy Rating (BER) while the UK uses a method called the Standard Assessment Procedure (SAP); both of which are calculated ratings. These assessment procedures are now widely deployed in EU-27 countries and calculated ratings are in use in Austria, Czech Republic, Denmark, The Netherlands, Poland, Portugal and Spain among others.

The ARM derives occupancy numbers from the total floor area of the dwelling under scrutiny and assumes that all dwellings in the housing stock are heated to the same level during the heating season in both zones considered; the living room area and rest of house. The heating season duration and heating system schedule is fixed for all dwellings. Hot water demand is drawn from the simulated occupancy with standard consumptions patterns. The rating allows dwellings to be compared against one another on a national scale despite differing occupancy and heating schedules.

Widespread standardisation and availability of training courses for ARM-type energy efficiency measurement tools means that they are now used for applications beyond their initial purpose. Policy makers use them for assessing the benefits of energy efficiency and emission reduction policies. For example, in the UK the Carbon Emissions Reduction Target (CERT) addresses the energy efficient refurbishing of existing dwellings. It requires energy providers to actively reduce the demand of their customers. Aggregated fuel savings from proposed measures implemented across their customer base are estimated using the British Research Establishment Domestic Energy Model (BREDEM), which uses a calculated rating methodology and provides the basis for SAP. Other policy informing calculated rating models are documented in literature. The impact of Irish building regulations on new building stock as proposed by Dineen and Ó Gallachóir uses a calculated rating to estimate future energy use [17]. Impacts of national energy efficiency upgrade programmes are also predicted by similar models for Ireland [18], Scotland [19], Belgium [20]. In Italy Ballarini (2009) also concluded that the heat loss coefficient, derived as part of the ARM procedure, is a good indicator of the energy performance of a building [14].

Despite their simplicity relative to other building energy models, ARMs require an in situ survey and analysis of the dwelling which must be performed by trained specialists. A survey of 5 consultancies performing BERs in Ireland revealed that undertaking the dwelling survey could take between 40 min and 4 h depending on the experience of the surveyor, the techniques employed by the company and the complexity of the dwelling being surveyed. Following the survey, data input to the DEAP (Dwelling Energy Assessment Procedure) software was reported to take 40 min to 3 h. SEAI, who administer the BER process in Ireland, advised that the survey could take as little as an hour but this time increased with the complexity of the house being surveyed and the level of inexperience of the surveyor and could potentially take up to 1 day. Similarly, SEAI advised that the data input to DEAP software could take as little as an hour but the time required was liable to escalate for the same reasons; with the proficiency of the assessor with the computer programme also referenced as a factor.

ARM approaches therefore offer the simplest and quickest method for estimating a standardised energy profile for a dwelling.

It is a standardised approach which industry is well-equipped to deliver. Nevertheless, it is time-consuming to apply ARMs to the large domestic customer bases of energy suppliers where even a small per-dwelling time saving will result in significant overall efficiencies. There is therefore a need to identify the most cost-effective approach to fulfil both consumer and industry needs. This paper investigates the possibility of developing a simplified calculation procedure based on the ARM approach. We ask whether an ARM can be simplified while maintaining outputs suitable for energy supply companies' implementation of energy saving programmes involving estimating the energy performance of residential dwellings when retrofitted with energy efficient and renewable energy supply technologies. Therefore, this study examines the effect that reducing input data requirements has on the accuracy of ARM and comments on the trade-off between model simplification and accuracy.

2. Methodology

A generic ARM model was first developed based on the Irish DEAP method. This is similar to the UK's SAP both of which are calculated (asset) ratings. Similar calculated ratings are also employed throughout the EU-27 region. Sensitivity analysis using data ranges from a detailed survey of Irish dwellings was used to rank the sensitivity of the model to input variables. Monte Carlo analysis was used to model the output distribution of energy ratings for a sample of the Irish housing stock. The least sensitive variables were parameterised using median values and new output distributions were estimated for models with 10, 20, 30 and 40 parameterised variables. The effect of increasing parameterisation on output distributions was quantified by comparing them to the original distribution in order to identify the trade-off between effort and accuracy.

2.1. Household database

A survey performed by the City of Dublin Energy Management Agency (CODEMA) provided the main data set for this work. A set of 159 dwellings were comprehensively surveyed by trained energy assessors for the study which was conducted in 2006. The dwellings surveyed in the study were chosen using a stratified sampling process, guaranteeing the sample's statistical significance for construction year, dwelling type and tenure type for the Irish housing stock. The study was performed to compare theoretical and actual energy use and to test a method for conducting building energy ratings prior to the introduction of the DEAP method. The data set contains all the variables necessary for the analysis of the Irish housing stock using ARM tools. The variables that were collected in this survey are included in Table 2 for reference.

2.2. Asset rating model

A spreadsheet-based ARM was first developed in Microsoft Excel; using guidance provided for DEAP and SAP and in conjunction with 'EN ISO 13790:2008: Energy performance of buildings–Calculation of energy requirements for space heating and cooling' [21]. The input fields and calculation procedure included in the model reflect what are captured in DEAP and SAP so that the outputs are consistent with what is being used in the industry. The dependent variable is primary energy delivered per meter squared per annum (kWh m^{-2} a^{-1}). The total number of independent variables incorporated in the method developed for this study is 50, which is not as exhaustive as some other national methodologies. The study was limited to the availability of data and input variable parameter distributions for the Irish housing stock, as given by CODEMA. Table 2 (Appendix A) indicates the variables included and those omitted. The initial ARM model developed which includes all variables is called the 'Zero' model.

2.3. Sensitivity analysis

The energy rating for a 'typical' Irish dwelling was estimated by selecting median values from the CODEMA dataset to give a baseline value. Minimum and maximum values for each input variable were then established and used to perform a sensitivity analysis using the ARM. This was achieved by individually inputting the minimum and maximum value for each variable while keeping all other variables at the median values. In instances where the independent variable required a binary answer the more frequently occurring selection in the dataset was chosen for the base case simulation. The magnitude of change of the dependent variable across the range of an independent variable is used as the measure of sensitivity. The sensitivity is measured as percentage change above and below the baseline value and recorded as an absolute percentage. Results were used to rank the influence of each input (independent) variable on the primary energy delivered (dependent) variable.

2.4. Reduced input models

The distributions of the input variables with the smallest effect on the ARM (identified above) were parameterised by removing and replacing them with their median values, thus reducing the number of variables in the model. Four new 'reduced input models' were created, each with 10, 20, 30 and 40 less variables than the original ARM, referred to as the −10, −20, −30 and −40 models respectively; consequently, there were five versions of the ARM model, including the original Zero model with all variables.

2.5. Monte Carlo analysis

A Monte Carlo analysis was conducted for all versions of the ARM model in order to estimate the effect of eliminating variables on total primary energy delivered. Input distributions were derived from the CODEMA database and distributions for each variable were created directly from the data. Although the sample was representative of house type, year and tenure; houses with very large floor areas were unrepresented. A Weibull distribution was therefore fitted to the data to better represent larger house types. A continuous standard distribution was fitted to the data histogram using distribution fitting EasyFit software.

It was necessary to consider the relationship between correlated variables to ensure that the characteristics of the simulated

Table 1
statistical parameters of the distributions for the 'Zero', '−10', '−20', '−30' and '−40' ARM models (all kWh m^{-2} a^{-1} except "r^2" and MAPE).

	Zero	−10	−20	−30	−40
Min	93.22	90.06	97.39	87.86	82.95
Mean	291.08	287.24	295.86	301.54	285.18
Max	2245	2225	2200	2079	1421
Standard deviation	119.24	117.49	119.10	123.52	109.87
r^2	1	0.99747	0.98507	0.95924	0.84833
Mean absolute percentage error (%)	0.00	1.48	3.91	7.22	11.04

Please cite this article in press as: D. Reilly, et al., Development and implementation of a simplified residential energy asset rating model, Energy Buildings (2013), http://dx.doi.org/10.1016/j.enbuild.2013.04.023

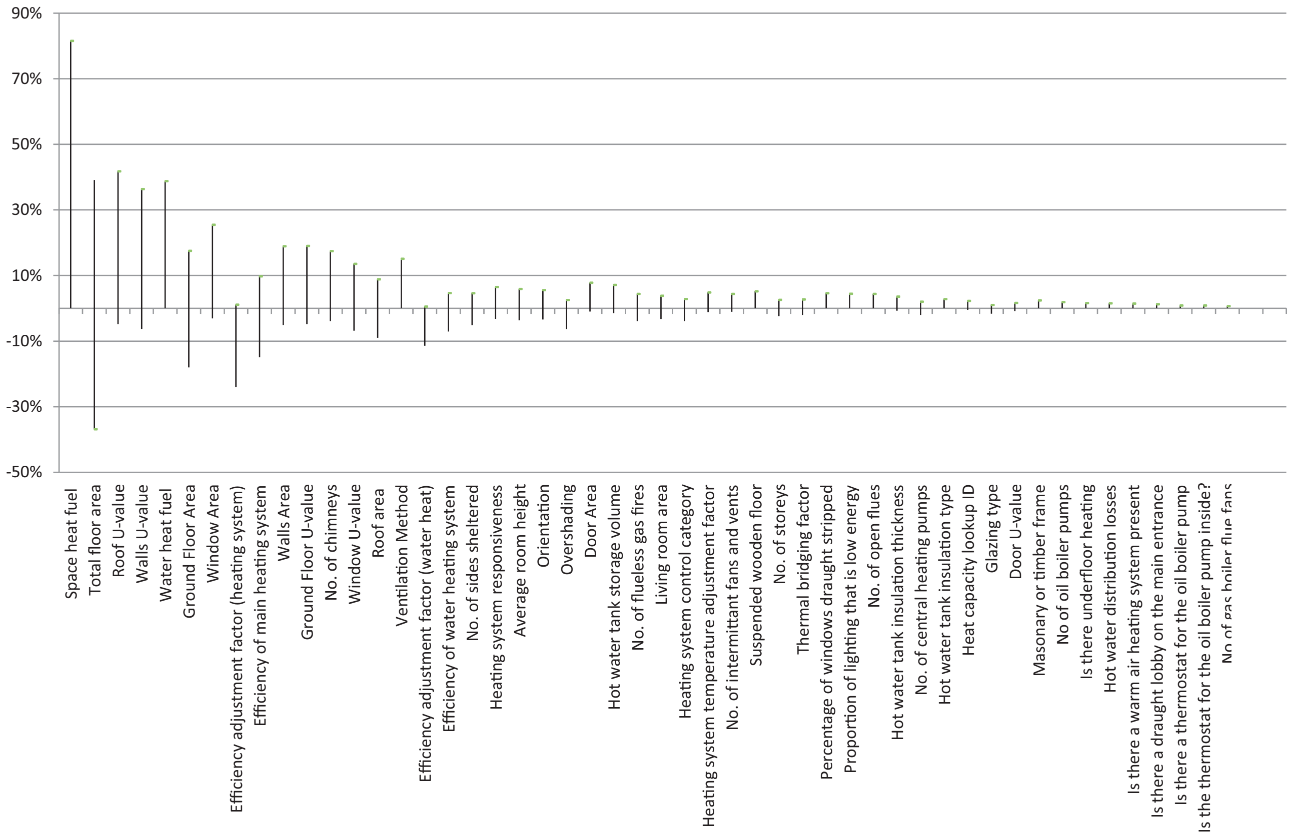

Fig. 1. Sensitivity analysis results. The *y*-axis shows the percentage change in dependent variable of the simulated base case for the range of each of the independent variables (shown on the *x*-axis).

dwellings were physically viable. For example, window area is typically related to wall area of a dwelling so the correlation between wall and window areas was determined from the data and window area expressed as a function of wall area. This approach was applied to window area (function of wall area), wall area (function of total floor area), roof area (function of ground floor area and number of stories)

A random number generator and lookup function produced random input data using the cumulative distribution functions (CDF) for each of the variables' assigned distributions. The analysis involved 10,000 repeated random samples, each of which were used to calculate annual energy consumption, giving the distribution of annual energy consumption for the simulated housing stock. The process was repeated for each of the reduced input ARMs. The distribution of the dependent variable (primary energy delivered per m^2 per annum) across the simulated sample population was recorded for each of the reduced input field scenarios and compared to the original to quantify the divergence between the Zero and reduced input models.

2.6. Comparative analysis

The output distributions from the Zero, −10, −20, −30 and −40 asset models were first compared using standard statistical parameters including mean, range and standard deviation. This measures differences in central values, maxima and minima and the variation in the different models.

The reduced input models were then compared to the Zero model using a goodness of fit test in order to tell how well the reduced input models fit the original Zero distribution. The coefficient of determination and mean absolute percentage error is used to tell how well the reduced input models represent the original.

3. Results and discussion

3.1. Sensitivity analysis

The results of the sensitivity analysis performed on the ARM model are shown in Fig. 1. The graph displays the responsiveness of the dependent variable to the range of each of the independent

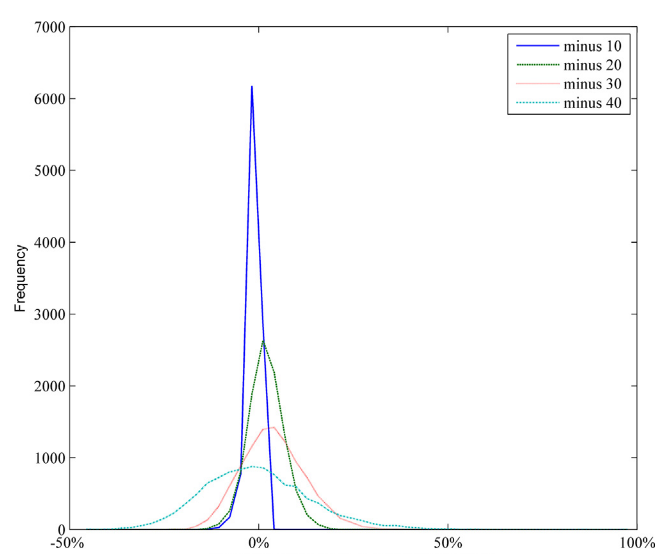

Fig. 2. Distribution of percentage variation between Zero Model and the four reduced versions of the ARM for the dependent variable (Primary energy per m^2 annum).

Table 2
input variables.

	Included in:					Reason for exclusion	Inputs for sensitivity analysis				Absolute percentage change to dependent variable across range	Sensitivity analysis rank
	'Zero' model	−10	−20	−30	−40		Base	Min	Max	Unit		
First floor area						Only needed to work out total floor area. Total floor area captures necessary information	–	–	–	–	–	–
Second floor area							–	–	–	–	–	–
Other floors							–	–	–	–	–	–
First floor room height						Only needed to work out average room height. Average room height captures necessary information	–	–	–	–	–	–
Second floor room height							–	–	–	–	–	–
Other floors room height							–	–	–	–	–	–
Total floor area	√	√	√	√	√	–	109.2	55	400	m²	76.0%	2
Average room height	√	√	√	√		–	2.45	1.95	3.1	m	9.6%	20
Living room area	√	√	√			–	32.11	11	50	m²	7.1%	26
No. of chimneys	√	√	√	√	√	–	1	0	5		21.4%	12
No. of open flues	√	√				–	1	0	2		4.4%	35
No. of intermittent fans and vents	√	√	√			–	1	0	5		5.4%	29
No. of flue less gas fires	√	√	√			–	1	0	2		8.4%	25
No. of storeys	√	√	√			–	2	1	3		5.0%	31
Masonry or timber frame	√					–	0	0	1		2.4%	42
Suspended wooden floor	√	√	√			–	0	0	1		5.2%	30
Is there a draught lobby on the main entrance	√					–	0	0	1		1.2%	47
Has an air permeability test been carried out						None can be performed on simulated dwellings						
Percentage of windows draught stripped	√	√				–	40	0	100	%	4.6%	33
No. of sides sheltered	√	√	√	√		–	2	0	4		9.8%	18
Ventilation method	√	√	√	√		–	1	1	5		15.1%	15
Door area	√	√	√			–	2.92	1.8	9.2	m²	8.7%	23
Door U-value	√	√				–	3	2.1	4.5	m² K/W	2.5%	41
Window area	√	√	√	√	√	–	20.7	10	60	m²	28.6%	7
Window U-value	√	√	√	√		–	3.22	1.7	5.7	m² K/W	20.4%	13
Floor type	√					U-Value collects all required information						
Ground floor area	√	√	√	√	√	–	54.6	0	98	m²	35.6%	6
Ground floor U-value	√	√	√	√	√	–	0.49	0.1	1.35	m² K/W	23.9%	11
Wall type						U-Value collects all required information						
Walls area	√	√	√	√	√	–	70.5	30	140	m²	24.0%	10
Walls U-value	√	√	√	√	√	–	0.73	0.15	2.25	m² K/W	42.7%	4
Roof type						U-Value collects all required information						
Roof area	√	√	√	√		–	54.6	0	98	m²	17.8%	14
Roof U-value	√	√	√	√	√	–	0.44	0.1	2.6	m² K/W	46.6%	3
Thermal bridging factor	√	√	√			–	0.11	0.08	0.15		4.7%	32
Frame type	√					–	3	1	4		0.0%	52
Glazing type	√	√				–	3	1	7		2.6%	40
Overshading	√	√	√	√		–	3	1	4		8.9%	22
Orientation	√	√	√	√		–	3	1	5		9.0%	21
Roof window						U-Value collects all required information						
Hot water distribution losses	√					–	0	0.15	0		1.5%	45

Table 2 (*Continued*)

	Included in:					Reason for exclusion	Inputs for sensitivity analysis				Absolute percentage change to dependent variable across range	Sensitivity analysis rank
	'Zero' model	−10	−20	−30	−40		Base	Min	Max	Unit		
Are there storage losses						All dwellings in data set have water tanks						
Hot water tank insulation type	√	√				–	0	0	1		2.8%	38
Hot water tank insulation thickness	√	√				–	30	20	145	mm	4.3%	36
Hot water tank storage volume	√	√	√			–	125	75	435	litres	8.7%	24
Is manufacturers loss available						Cannot input to simulation						
Is there solar water heating						No information in data set						
Is supplementary water heating used in summer						operates on same principle as water heating						
Is there a combi boiler						Not available in data set						
Primary circuit loss type						Not available in data set						
Proportion of lighting that is low energy	√	√				–	25	0	100		4.4%	34
Heat capacity lookup ID	√	√				–	3	1	5		2.7%	39
Heating system temperature adjustment factor	√	√	√			–	0.2	−0.2	0.6		6.0%	28
Heating system control category	√	√	√			–	2	0	3		6.8%	27
Heating system responsiveness	√	√	√	√		–	2	1	4		9.7%	19
No. of central heating pumps	√	√				–	1	0	2		4.0%	37
No of oil boiler pumps	√					–	1	0	1		1.9%	43
No of gas boiler flue fans	√					–	0	0	1		0.6%	50
Is there thermostat for the central heating pump	√					–	0	0	1		0.6%	51
Is there a thermostat for the oil boiler pump	√					–	0	0	1		0.9%	48
Is the thermostat for the oil boiler pump inside?	√					–	0	0	1		0.9%	48
Is there a warm air heating system present	√					–	0	0	1		1.4%	46
Is there under floor heating	√					–	0	0	1		1.6%	44
Efficiency of main heating system	√	√	√	√	√	–	75	60	92	%	24.7%	9
Efficiency adjustment factor (heating system)	√	√	√	√	√	–	1	0.7	1.02		25.1%	8
Efficiency of water heating system	√	√	√	√		–	75	60	92	%	11.7%	17
Efficiency adjustment factor (water heat)	√	√	√	√		–	1	0.7	1.02		11.9%	16
Fraction of heat from secondary space heating system						Operates on same principles as primary space heating. Inclusion would just compound results						
Efficiency of secondary space heating system												
Space heat fuel	√	√	√	√	√	–	1	1	2		81.6%	1
Water heat fuel	√	√	√	√	√	–	1	1	2		38.8%	5
Renewable energy produced or saved						Not available in data set						

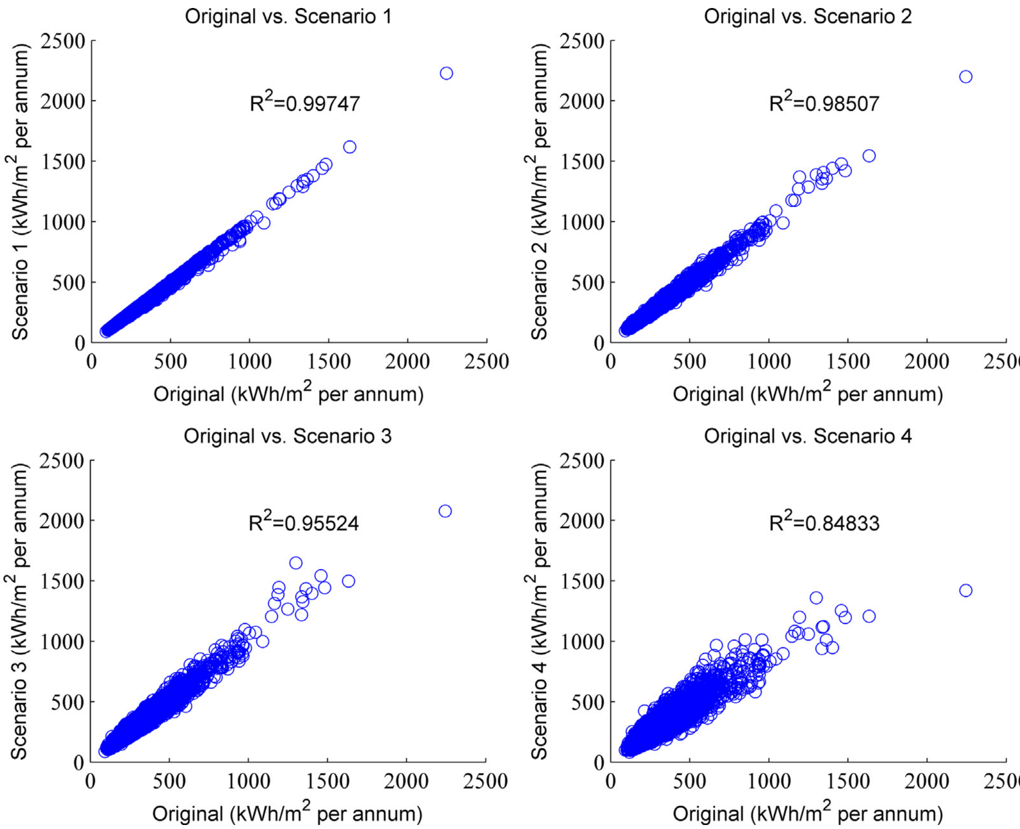

Fig. 3. Scatter plots showing goodness of fit between Zero Model and the four reduced variable versions.

variables; the result is expressed as a percentage deviation from the baseline value. Each variable is ranked by the deviation, from highest to lowest. The 10, 20, 30 and 40 variables with the lowest impact on ARM were parameterised and omitted from the model as shown in Fig. 1 and Table 2

3.2. Monte Carlo simulation

Table 1 summarises the statistical parameters of the distributions for each of the five models created. As the input requirements are removed and parameterised (for the creation of −10, −20, −30, −40 versions) it can be seen that the correlation between that version and the 'Zero' model decreases, while the mean absolute percentage error (MAPE) increases.

Fig. 2 shows the frequency distributions of percentage error in the dependent variable for of each of the reduced input variable models compared to the 'Zero' model. The '−10' model has a tall peak, narrow base and steeply sloped sides close to the 0% mark on the x-axis, thus indicating a high frequency of incidences where the models output is almost identical to the output of the 'Zero' model. This is confirmed by the MAPE (1.48%) and standard deviation (1.67%). In contrast to this the '−40' model has a lower peak and wider base with gentler slopes showing that this version of the model is less accurate (MAPE = 11.00%, standard deviation = 14.02%).

The goodness of fit between the original Zero ARM model and the four reduced version models is illustrated in Fig. 3. Each reduced version of the model is plotted, for all 10,000 simulations, against the 'Zero' model. Subplot 1 shows a tightly clustered straight line indicating a strong positive relationship between the models whereas subplot 4 shows a wider spread and implies a less robust correlation.

4. Conclusions

A method for simplifying ARM models by parameterising the least sensitive input variables is presented. The effect of reducing the number of input variables on the dependent variable, Primary Energy Delivered, is quantified using Monte Carlo analysis. The −10 model – where the ten least sensitive variables are parameterised – results in only a small deviation from the baseline Zero model with 53 variables. The −20 model also exhibited small deviations with a correlation coefficient of 0.985 and a MAPE of less than 5%. Errors increased significantly with the −30 and −40 models which exhibited MAPEs of 7.22% and 11.03% and correlation coefficient of 0.959 and 0.848 respectively. It is therefore possible to maintain a high degree of accuracy (~95%) with 20 fewer variables. This is equivalent to almost 40% fewer variables than in the full model and represents a significant saving in effort.

Acknowledgements

This research was co-funded by the Irish Research Council and Electricity Supply Board Electric Ireland and conducted as part of the Dublin Energy Lab at Dublin Institute of Technology.

References

[1] European Union, "Energy efficiency Directive," vol. Directive, Official Journal of the European Union, (2012) pp. 2–55.
[2] UK Energy Efficiency Action Plan, D.f.E.F.a.R. Affairs, Department for Environment, Food and Rural Affairs, (2007).
[3] National Energy Efficiency Action Plans (NEEAPs): update on implementation, European Commission, Brussels, (2011).
[4] M. Caldera, S.P. Corgnati, M. Filippi, Energy demand for space heating through a statistical approach: application to residential buildings, Energy and Buildings 40 (10) (2008) 1972–1983.

Please cite this article in press as: D. Reilly, et al., Development and implementation of a simplified residential energy asset rating model, Energy Buildings (2013), http://dx.doi.org/10.1016/j.enbuild.2013.04.023

[5] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renewable and Sustainable Energy Reviews 13 (8) (2009) 1819–1835.

[6] T. Olofsson, T.M.I. Mahlia, Modeling and simulation of the energy use in an occupied residential building in cold climate, Applied Energy 91 (1) (2012) 432–438.

[7] L. Suganthi, A.A. Samuel, Energy models for demand forecasting: a review, Renewable and Sustainable Energy Reviews 16 (2) (2012) 1223–1240.

[8] M. Kavgic, et al., A review of bottom-up building stock models for energy consumption in the residential sector, Building and Environment 45 (7) (2010) 1683–1697.

[9] O. Guerra Santin, L. Itard, H. Visscher, The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, Energy and Buildings 41 (11) (2009) 1223–1232.

[10] R. Haas, H. Auer, P. Biermayr, The impact of consumer behavior on residential energy demand for space heating, Energy and Buildings 27 (2) (1998) 195–205.

[11] A. Wright, What is the relationship between built form and energy use in dwellings? Energy Policy 36 (12) (2008) 4544–4547.

[12] A.G. Entrop, H.J.H. Brouwers, A.H.M.E. Reinders, Evaluation of energy performance indicators and financial aspects of energy saving techniques in residential real estate, Energy and Buildings 42 (5) (2010) 618–629.

[13] J.U. Sjögren, S. Andersson, T. Olofsson, An approach to evaluate the energy performance of buildings based on incomplete monthly data, Energy and Buildings 39 (8) (2007) 945–953.

[14] I. Ballarini, V. Corrado, Application of energy rating methods to the existing building stock: analysis of some residential buildings in Turin, Energy and Buildings 41 (7) (2009) 790–800.

[15] Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings, T.E.P.A.T.C.O.T.E. Union, (2002).

[16] The Department for the Environment, H.a.L.G., European Communities (Energy Performance of Buildings) Regulations 2006, The Stationary Office, Dublin, (2006).

[17] D. Dineen, B.P. Ó Gallachóir, Modelling the impacts of building regulations and a property bubble on residential space and water heating, Energy and Buildings 43 (1) (2011) 166–178.

[18] J.P. Clinch, J.D. Healy, C. King, Modelling improvements in domestic energy efficiency, Environmental Modelling and Software 16 (1) (2001) 87–106.

[19] J.A. Clarke, et al., The EDEM methodology for housing upgrade analysis, carbon and energy labelling and national policy development, in: 11th International IBPSA Conference, Glasgow, Scotland, 2008.

[20] H. Hens, G. Verbeeck, B. Verdonck, Impact of energy efficiency measures on the CO_2 emissions in the residential sector, a large scale analysis, Energy and Buildings 33 (3) (2001) 275–281.

[21] Standardisation, E.C.f., Energy performance of buildings – calculation of energy use for space heating and cooling (ISO 13790:2008), 2008.

Please cite this article in press as: D. Reilly, et al., Development and implementation of a simplified residential energy asset rating model, Energy Buildings (2013), http://dx.doi.org/10.1016/j.enbuild.2013.04.023