Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Using building performance simulation to save residential space heating energy: A pilot testing

Shen Wei[1], Xiaoxin Wang[2], Rory Jones[1] and Pieter de Wilde[1]

1 Building Performance Analysis Group, Plymouth University, Plymouth, UK, shen.wei@plymouth.ac.uk.
2 DesignBuilder Software Limited, Stroud, Gloucestershire, UK.

Abstract

This paper describes a pilot study testing the applicability of using building performance simulation (BPS) to quantify the impact of 28 energy saving behaviour changes on the residential space heating demand, based on a mid-terraced house located in the southwest of England.

The 28 behaviour change options were collected based on a combination of literature review and expert knowledge. DesignBuilder V3.2, whose thermal dynamic simulation engine is Energyplus 7.2, was used to predict the impact of each behaviour change option on the space heating demand of the case study house. The study shows that the predicted energy saving potentials of all 28 options are consistent with general expectations, and so BPS can be used to quantify the impact of energy saving behaviour changes. However, using this methodology in real applications to help occupants save energy still needs more efforts.

Keywords: Building performance simulation, Occupant behaviour, Residential building, Behaviour change, Energy saving

1 Introduction

In the UK, residential buildings are responsible for a significant part of the nation's greenhouse gas emissions (DEFRA, 2006). Therefore, reducing their energy consumption is essential for achieving the UK government's 2050 target for CO_2 emission reduction. In residential buildings, occupants can have a significant influence on the actual building energy consumption, caused by their operation of the building or the building systems (Morley and Hazas, 2011, Guerra-Santin and Itard, 2010, Haas et al., 1998).

In the past several decades, better understanding occupant behaviour in buildings has been the aim of numerous researchers (Wei et al., 2014, Fabi et al., 2012, Roetzel et al., 2010). To enhance building energy efficiency, building performance simulation (BPS) has been adopted as a useful tool in some studies to predict the impact of changing behaviour on building energy consumption (de Wilde et al., 2013, Kim and Altan, 2013, Love, 2012, Shorrock and Dunster, 1997), by comparing the energy consumption before and after the behaviour change. In these studies, however, researchers typically only explore a limited set of behaviour change options: de Wilde et al.(2013) carried out an initial study exploring the impact of changing door and curtain operations; Kim and Altan (2013) focused on the change of heating operation, heating system and building external insulation; Love (2012) was interested in heating operation and building efficiency; Shorrock and Dunster (1997) used a physically-based model, BREHOMES, to predict the energy saving potential by improving the building construction and systems. However, occupants' behaviours that will affect building energy consumption have a much wider range than the ones that have been studied thus far (Gunay et al., 2013). Therefore, this paper first establishes a comprehensive classification of possible behaviour change options that can be applied in a UK residential building to reduce the building space heating demand, based on a combination of literature review and expert knowledge. Then the applicability of using building performance simulation to quantify the impact of these options on residential space heating consumption is examined. Some challenges of using building performance simulation to help real building occupants make behaviour change decisions are discussed in the paper as well.

The study introduced in this paper was carried out in the context of a currently running UK research project, eViz (Energy Visualisation for Carbon Reduction), which aims to change occupant behaviour in buildings through visualisations. In eViz, the usefulness of using BPS as a tool to help occupants reduce their energy demand is being explored, and this paper introduces some preliminary results of it.

2 Classification of behaviour change options

In general occupant behaviour relating to save building energy consumption can be classified into two classes, either curtailment or investment behaviour (Gardner and Stern, 2002). The curtailment behaviours refer to "using equipment or systems less frequently or intensively" (Gardner and Stern, 2008), so it is related to changing occupants' operation or control of the building or the building systems. The investment behaviours include "adopting more energy-efficient equipment or installing or maintaining efficiency-boosting modifications to existing energy equipment" (Gardner and Stern, 2008), and so it is about upgrading/retrofitting the building construction or the building systems. For both change classes, there would be a number of behaviour change options that can help to reduce residential space heating demand.

To provide a comprehensive list of behaviour change options, the method used here is based on a combination of literature review and expert knowledge. The reviewed papers were collected from (1) SCI impact journals, such as Energy and Buildings, Building and Environment, (2) key conferences, such as the IBPSA building simulation conference, and (3) government's official reports, using key words such as 'energy efficient', 'behaviour change', 'intervention' and 'building retrofit'. The expert knowledge gathering was carried out among built environment professionals in the environmental building group of Plymouth University. From the literature review and the expert knowledge, available behaviour change options within a UK house are collect and listed in Tables 1 and 2, for investment and curtailment behaviours respectively.

Table 1. Options of investment behaviour.

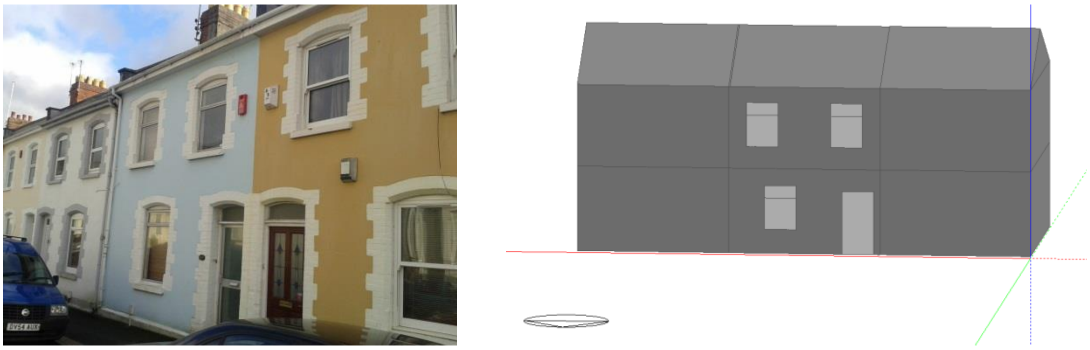
Behaviour items	Options of investment behaviour
Upgrading façade insulation	(1) Adding external wall insulation; (2) Adding ground floor insulation; (3) Adding ceiling insulation; (4) Adding roof insulation.
Improving building air tightness	(1) Adding membranes; (2) Adding weather-stripe/draft excluders for windows/doors.
Upgrading external windows	(1) Adding window layers; (2) Changing filling materials.
Upgrading external doors	(1) Adding door layers; (2) Improving door insulation.
Upgrading the heating system	(1) Installing energy-efficient heating systems; (2) Installing smart control strategies for the heating system.
Upgrading curtains/blinds	(1) Fitting heavier blinds/curtains.

Table 2. Options of curtailment behaviour.

Behaviour items	Options of curtailment behaviour
Window operation behaviour	(1) Reducing window opening time when at home but not sleeping; (2) Closing all windows when leaving home; (3) Closing all windows before sleeping at night; (4) Closing all windows in unused rooms.
Door operation behaviour	(1) Reducing back door opening time when at home but not sleeping; (2) Closing the back door when the adjacent room is not used.
Blind/curtain operation behaviour	(1) Shutting off all blinds/curtains during night-time; (2) Opening the south-facing blinds/curtains when it is sunny outside.
Thermostat operation behaviour	(1) Lowering the thermostat settings; (2) Turning down thermostat settings when leaving home; (3) Turning down thermostat settings before sleeping at night.
TRV operation	(1) Setting different temperatures for different rooms; (2) Lowering the TRV settings; (3) Turning down the TRV settings when leaving homes; (4) Turning down the TRV settings before sleeping at night.
Boiler operation	(1) Turn off boiler when leaving homes.

3 Methodology

The building simulation model was developed in DesignBuilder V3.2, by which dynamic thermal simulations were performed hourly to predict the building energy performance during the winter period. DesignBuilder is the first comprehensive user interface of EnergyPlus (DesignBuilder, 2014), and DesignBuilder V3.2 adopts EnergyPlus 7.2 as the engine for dynamic thermal simulations. The energy saving potential of each behaviour change option was calculated as the difference between the energy consumption before the behaviour change and that after the change. The model was established according to a typical UK mid-terraced house located in an urban area in the Southwest of England (Figure 1a). The house is over 100 years old so its energy condition needs to be improved (the current Energy Efficiency Rating (EER) is D). The house has two floors and the front faces north. On the ground floor, there is a living room and kitchen, and on the first floor there are two bedrooms and a bathroom. There is a back door in the kitchen, linking the house and the garden. Figure 1b shows the simulation model of the case study house. For each casement window in the house, there is an outward opening top light, and the remaining part is fixed. The approximate opening area of the window is about 10% of the total area of the window.



(a) Case study home (b) Simulation model

Figure 1. Case study house.

The weather data used in the simulation was collected in 2002, from the main campus of Plymouth University, which is about 1 mile away from the case study house. The simulation period was from 1st October to 31st March. Simulation scenarios, before (base case scenario) and after behaviour change, are concluded in Tables 3 and 4, for investment and curtailment behaviours respectively, according to the behaviour change options defined in Tables 1 and 2.

Table 3. Simulation scenarios for investment behaviour.

Behaviour items	**Base case scenario**	**Behaviour change option**		**After change scenario**
Upgrading façade insulation	U-value = 2.071 (no insulation)	1	Adding external wall insulation	U-value = 0.260
	U-value = 1.463 (no insulation)	2	Adding ground floor insulation	U-value = 0.220
	U-value = 0.388 (75mm insulation)	3	Adding ceiling insulation	U-value = 0.250
	U-value = 2.930 (no insulation)	4	Adding roof insulation	U-value = 0.187
Improving building air tightness	Poor air tightness defined in DesignBuilder[1]	5	Adding membranes or Adding weather-stripe/draft excluder for windows/doors	Good air tightness defined in DesignBuilder
Upgrading external windows	Double clear glazing (3mm) filled with air (6mm)	6	Adding window layers	Triple clear glazing (3mm) filled with air (6mm)
		7	Changing filling materials	Double clear glazing (3mm) filled with argon (6mm)
Upgrading external doors	U-value = 2.251	8	Adding door layers	Adding an unheated porch at the entrance of the house
		9	Improving door insulation	U-value = 0.755
Upgrading the heating system	Efficiency = 60%	10	Installing energy-efficient heating systems	Efficiency = 80%
		11	Installing smart control strategies for the heating system	Lowering thermostat setting automatically to 18°C when the house is unoccupied.
Upgrading curtains/blinds	Drapes open wave (light)	12	Fitting heavier blinds/curtains	Drapes open wave (Medium)

[1] In DesignBuilder, the air tightness level is defined as five levels: excellent, good, medium, poor and very poor. Each air tightness level is defined by a combination of air leakage from Openings (windows, doors, vents), Walls, Floors/ceilings and Roofs.

Table 4. Simulation scenarios for curtailment behaviour.

Behaviour items	Base case scenario	Behaviour change option		After change
Window operation behaviour	All windows are open from 00:00 to 24:00	1	Reducing window opening time when at home but not sleeping	Closed when the house is occupied but not sleeping
		2	Closing all windows when leaving homes	**Weekdays:** closed between 08:00 and 18:00 **Weekends:** no change
		3	Closing all windows before sleeping at night	**Mon to Thur:** closed between 23:00 and 07:00+1 **Fri and Sat:** closed between 23:00 and 08:00+1
		4	Closing all windows in unused rooms	Only leave windows open when the room is occupied
Door operation behaviour	The back door is open when the house is occupied but not sleeping time	5	Reducing back door opening time when at home but not sleeping	Closed when the house is occupied but not sleeping
		6	Closing the back door when the adjacent room (kitchen) is not used	Only open when the kitchen is occupied
Blind/curtain operation behaviour	For weekdays: shut off between 07:00 and 18:00 & open for the rest For weekends: shut off between 08:00 and 18:00 & open for the rest	7	Shutting off all blinds/curtains during the night-time	Shut off always
		8	Opening the south-facing blinds/curtains during the daytime to gain more solar energy	South-facing blinds/curtains always open
Thermostat operation behaviour	22°C always	9	Lowering the thermostat settings	20°C always
		10	Turning down thermostat settings when leaving homes	18°C when the house is not occupied
		11	Turning down thermostat settings before sleeping at night	**Sleeping time:** 18°C **Unsleeping time:** 22°C
TRV operation	all rooms set at 22°C always	12	Setting different temperatures for different rooms	**Living room:** 22°C **Bedroom:** 18°C **Kitchen:** 18°C **Bathroom:** 21°C **Corridor:** 18°C
		13	Lowering the TRV settings	all rooms set at 20°C always
		14	Turning down the TRV settings when leaving homes	**Occupied time:** 22°C **Unoccupied time:** 18°C
		15	Turning down the TRV settings before sleeping at night	**Sleeping time:** 18°C **Unsleeping time:** 22°C
Boiler operation	boiler always on	16	Turning off the boiler when leaving homes	**Weekdays:** Boiler off between 08:00 and 18:00 **Weekends:** No change

The base case scenario for the building construction and systems was defined according to the real condition of the building. Due to the lack of data about occupants' real use of the building, the base case scenarios for occupant building operation used the worst case behavioural condition, which is when all behaviour change options are not applied. Although this may not reflect the real operational condition of the case study house, these assumptions are acceptable in this paper as the main purpose here is to test whether BPS can provide consistent predictions of energy saving potential of all behaviour change options listed in Table 1 and 2, when compared with general expectations, not to provide accurate predictions for the case study house. The lack of occupants' real use of the building is an important challenge of using BPS in real applications and this will be discussed in the later discussion section. The occupancy and activities of the house occupant are defined in Table 5 for the simulation work.

Table 5. Definition of occupancy condition and activities.

Weekdays	00:00 – 07:00 Sleeping (Bedroom 1)	07:00 – 08:00 Breakfast (Kitchen)	08:00 – 18:00 Working (Unoccupied)	18:00 – 19:00 Dinner (Kitchen)	19:00 – 23:00 Relaxing (Living room)	23:00 – 24:00 Sleeping (Bedroom 1)
Weekends	00:00 – 08:00 Sleeping (Bedroom 1)	08:00 – 09:00 Breakfast (Kitchen)	09:00 – 18:00 Relaxing (Living room)	18:00 – 19:00 Dinner (Kitchen)	19:00 – 23:00 Relaxing (Living room)	23:00 – 24:00 Sleeping (Bedroom 1)

4 Results

The prediction of the energy saving potential of each behaviour change option was carried out by undertaking dynamic thermal simulations for the base case scenario and for the scenario applying that behaviour change option, and then comparing the energy used for heating the house.

4.1 Model validation

The case study house has an EPC rating of D in 2010, which is an average rating of UK homes. According to the Ofgem (2011), the average UK home consumes about 20,500 kWh per year for space heating. For the case study house, the simulated annual heating energy consumption is 22,562 kWh, about 10% more than the average level. This is reasonable as the occupant's operation of the building was defined using the worst case condition in the simulation, which will result in additional energy consumption. Based on these results, the model developed was considered to be suitable to carry out further simulations.

4.2 Prediction of energy saving potential

Figure 2 shows the prediction results for the 12 investment behaviour options, represented as a percentage of the base case energy consumption. The predictions show the positive impact of all investment behaviour change options on reducing the energy consumption for heating the house, but with varying magnitudes. For the case study house, adding external insulation (Option 1), improving the house air tightness (Option 5), installing energy-efficient heating systems (Option 10) and installing smart heating controls (Option 11) show significant contributions on improving the building energy efficiency. Adding an unheated porch at the entrance of the house (Option 8), separating the indoor environment with the outdoor environment, can also contribute to reducing space heating demand by about 6%. Upgrading the insulation levels of the ceiling and the roof does not play well for the case study house, due to the existing insulation layer of the ceiling, which has separated the ceiling and roof with the indoor environment.

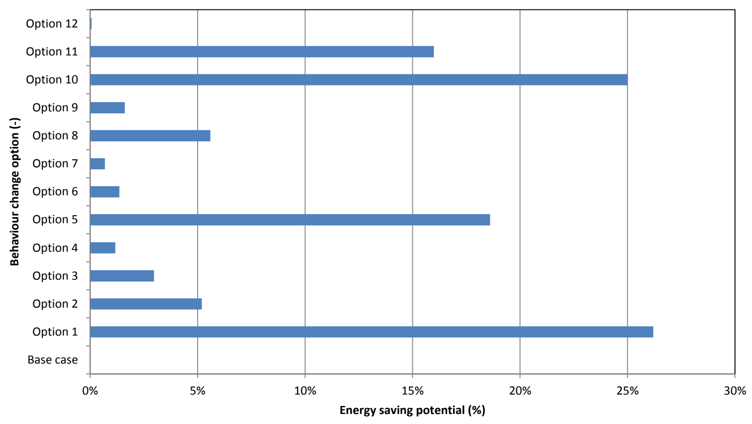


Figure 2. Prediction results for all change options of the investment behaviour.

Figure 3 shows the prediction results for the 16 curtailment behaviour options. The results reflect that improving building operation can also contribute to reducing house space heating demand, consistent with general expectations. According to the predictions, changing heating operation (Options 9 to 16) generally has a bigger impact than changing other behaviours, i.e. window operation, door operation and blind/curtain operation. Additionally, keeping the back door open also has a great impact on the house heating energy consumption, as reflected by the predictions for Options 5 and 6, due to the large opening area of the door. In a similar way, because the opening area of the window is small, the contribution of changing window operation (Options 1-4) on reducing the house space heating demand is moderate for the case study house. According to the predictions for Options 7 and 8, it seems that changing blind/curtain operation has little influence on the space heating demand of the case study house.

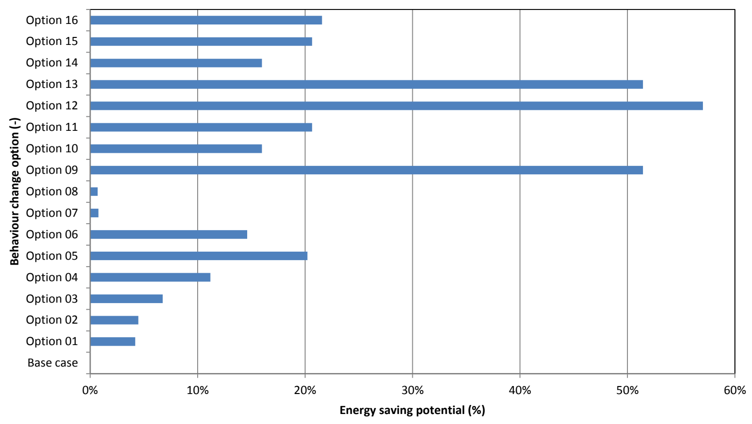


Figure 3. Prediction results for all change options of the curtailment behaviour.

5 Discussions

Reducing residential energy consumption is an important task for the UK government in the next 40 years, to achieve its own 2050 target for CO_2 emission reduction. This can be achieved by both changing occupants' use of the building/building systems and upgrading the building construction/systems. This study has tested the use of building performance simulation to predict the energy saving potential of a number of behaviour change options for a UK residential building. Although the prediction results are consistent with general expectations, meaning that BPS is capable of predicting the impact of changing behaviour on building energy demand, before being used to help real occupants make decisions on saving energy, the methodology still needs to be further improved in future studies, due to several challenges:

1. **Making building occupants enact the results from BPS.** Currently, BPS is mainly used by building designers and researchers to compare building performance between various systems. In real buildings, however, most building users/occupants are not experts in building science and technology, and have little knowledge about BPS. Thus, how to introduce BPS to the general public needs further exploration;

2. **Further capturing occupants' real behaviour on operating the building, so the base case simulation model can be developed as close as possible to real situations.** Due to the stochastic nature of occupants' real use of the building (Nicol and Humphreys, 2004), it is hard to accurately represent it in the building simulation process. Additionally, accurately monitoring occupants' building use is also a complex and expensive task. These issues have been officially raised in the new approved IEA ANNEX 66 project (IEA, 2014) and need to be solved in future studies; and,

3. **Realistically quantifying the behaviour change options.** Real applications are complex and technologies are improving. Therefore, how to provide a quantified and comprehensive list of behaviour change options based on real situations is also important, as this list will be the basis of defining simulation scenarios after behaviour change.

4. **Suitably limiting the behaviour change options.** For the curtailment behaviour, some behaviour change options will influence the indoor thermal environment greatly, such as Options 9-15. Therefore, when performing these options, a balance between building energy consumption and indoor thermal environment should be carefully considered, so as to not sacrifice comfort for saving energy. For the investment behaviour, as most behaviour change options can require significant financial investments, a balance between cost and energy savings becomes important to achieve.

An initial exploration on solving the above challenges is currently on-going by the authors of this paper.

6 Conclusions

Residential buildings contribute significantly to the UK's greenhouse gas emissions. Therefore, reducing residential energy consumption is an important task for the UK government in the next decades. With respect to space heating energy consumption in winter, generally, there are two ways to save energy, either by performing curtailment behaviour or by applying thermal investment updates (investment behaviour). The curtailment behaviour is about changing occupants' use of the building or the building systems, whilst the investment behaviour relates to upgrading/retrofitting the building construction or the building systems. This paper has provided a comprehensive classification of behaviour change options for both curtailment and investment behaviours, and has tested the use of BPS to predict the potential impact of each behaviour change option on the space heating demand of a UK mid-terraced house.

The prediction results have revealed that building performance simulation has a potential of being used to predict the impact of all behaviour change options presented in this paper, as the prediction results are consistent with general expectations, hence could be used to help building occupants make decisions on changing behaviour to save residential energy. However, there are also several challenges for using this methodology in real applications and these challenges need to be sorted out in future studies.

Acknowledgement

The work reported in this paper is funded by the Engineering and Physical Sciences Research Council (EPSRC) under the Transforming Energy Demand in Buildings through Digital Innovation (TEDDI) eViz project (grant reference EP/K002465/1).

References

DE WILDE, P., PAHL, S., HAMZA, N., WEI, S., JONES, R. & ABOHELA, I. 2013. Using building simulation to drive changes in occupant behaviour: A pilot study. *Building Simulation 2013 Conference.* Chambery, France.

DEFRA 2006. Climate Change - The UK Programme 2006. London: Department for Environment, Food and Rural Affairs.

DESIGNBUILDER. 2014. *DesignBuilder website* [Online]. Available: http://www.designbuilder.co.uk/.

FABI, V., ANDERSEN, R. V., CORGNATI, S. & OLESEN, B. W. 2012. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment,* 58**,** 188-198.

GARDNER, G. & STERN, P. 2002. *Environmental problems and human behaviour,* Boston, MA, Pearson Custom Publishing.

GARDNER, G. T. & STERN, P. C. 2008. The Short List: The Most Effective Actions U.S. Households Can Take to Curb Climate Change. *Environment: Science and Policy for Sustainable Development,* 50**,** 12-25.

GUERRA-SANTIN, O. & ITARD, L. 2010. Occupants' behaviour: determinants and effects on residential heating consumption. *Building Research & Information,* 38**,** 318-338.

GUNAY, H. B., O'BRIEN, W. & BEAUSOLEIL-MORRISON, I. 2013. A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices. *Building and Environment,* 70**,** 31-47.

HAAS, R., AUER, H. & BIERMAYR, P. 1998. The impact of consumer behavior on residential energy demand for space heating. *Energy and Buildings*, 27**,** 195-205.

IEA. 2014. *IEA ANNEX 66* [Online]. Available: http://www.annex66.org/.

KIM, Y. K. & ALTAN, H. 2013. Using dynamic simulation for demonstrating the impact of energy consumption by retrofit and behavioural change *Building Simulation 2013 Conference.* Chambery, France.

LOVE, J. 2012. Mapping the impact of changes in occupant heating behaviour on space heating energy use as a result of UK domestic retrofit. *Retrofit 2012.* Manchester, UK, 22-26 January.

MORLEY, J. & HAZAS, M. 2011. The significiance of difference: Understanding variation in household energy consumption. *ECEEE 2011 Summer Study.* . Belambra Presqu'ile de Giens, France, 6-11 June.

NICOL, F. J. & HUMPHREYS, M. A. 2004. A stochastic approach to thermal comfort - Occupant behaviour and energy use in buildings. *ASHRAE Transactions,* 110 (Part I)**,** 554-568.

OFGEM 2011. Typical domestic energy consumption figures.

ROETZEL, A., TSANGRASSOULIS, A., DIETRICH, U. & BUSCHING, S. 2010. A review of occupant control on natural ventilation. *Renewable and Sustainable Energy Reviews,* 14**,** 1001-1013.

SHORROCK, L. D. & DUNSTER, J. E. 1997. The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock. *Energy Policy,* 25**,** 1027-1037.

WEI, S., JONES, R. & DE WILDE, P. 2014. Driving factors for occupant-controlled space heating in residential buildings. *Energy and Buildings,* 70**,** 36-44.