Understanding the Influence of Occupants' Behaviour on the Hygrothermal Performance of Insulated Solid Walls

Daniel Herrera Gutiérrez-Avellanosa
Scott Sutherland School of Architecture & Built Environment, Robert Gordon University, Aberdeen, UK. e-mail: d.herrera-gutierrez-avellanosa@rgu.ac.uk

Amar Bennadji
Scott Sutherland School of Architecture & Built Environment, Robert Gordon University, Aberdeen, UK.

Abstract

Residential buildings in the UK consume around 28% of total final energy use. Therefore, in order to achieve the CO_2 and fuel poverty reduction targets set by the Scottish government, it will be necessary to improve the energy efficiency of the existing housing stock. This research explores the improvement of the envelope's performance in traditionally constructed buildings (which represent 20% of the total stock) so as to reduce the space heating energy demand. Current studies show a great level of uncertainty regarding the long term effects of energy retrofit on moisture migration in traditional fabrics. Evaluation of risks, prior to any alteration on building's physics, is critical to avoid any future damage on the envelope's performance or occupants' health and well being.

Moisture dynamics in buildings' envelopes are affected by the geometry of the enclosure, material properties and external and internal boundary conditions. Within the internal boundary there are several user related factors determining the environmental conditions like hours of heating use, number of rooms heated, temperature settings, ventilation patterns or cooking and dry clothing habits. However, due to the difficulty to obtain and model this information, internal climate is often neglected or extremely simplified.

This research will explore the influence of user's behaviour on the risk of condensation in solid walls in order to predict the actual effects of retrofit measures. Specifically, it will focus on the users' influence on the hygrothermal performance of granite solid walls in Scottish tenement buildings after the insulation of the cavity between inner face of the masonry and the original lining. This research project intends to use Heat, Air and Moisture (HAM) numerical simulation to examine the impact of different behavioural patterns on the insulated walls. These patterns will be previously identified and analysed by means of long term environmental monitoring and occupants' in-depth interviews. The results of this research may be used to advice owners and practitioners about the feasibility of different retrofit measures and the behavioural aspects that need to be monitored after its implementation.

Keywords: traditional buildings, energy retrofit, moisture dynamics, occupants' behaviour

Introduction

Since the elaboration of the Leipzig Charter on Sustainable European Cities in 2007, energy retrofit has become one of the priorities for the European Union. Governmental policies and scientific research have set the improvement of the energy efficiency of existing buildings as one of the main goals for the following years (Nemry et al. 2008, Sullivan 2007, RICS 2008). But, why is so important to improve the energy performance of the existing built stock? And, why traditional and historic buildings in particular?

1. To reduce our green house gas emissions and mitigate the climate change

The Scottish government is aiming to reduce the net Scottish greenhouse gas emissions by 80%, respect 1990 levels, for 2050 (Scottish Parliament 2009). To achieve this ambitious target it is essential to reduce the CO_2 emissions of traditionally constructed buildings since 45% of total CO_2 emissions in the UK are due to the built environment (RAENG 2010), and 19% of this built stock can be considered “traditional” (Curtis 2010). Furthermore, due to the low rate of renovation in the European countries (between 1.2% and 1.4% per year (Dyrbøl, Thomsen, et al. 2010)), existing buildings will still represent around 80-85% of the total stock in 2050 (RAENG 2010, Palmer et al. 2006).

2. To reduce fuel consumption and ensure energy affordability

Buildings are responsible for 40% of the final energy consumption in the EU (Ferreira, Duarte Pinheiro and de Brito 2013). Most of this energy is dedicated to the operational stage, including usage, maintenance and repair (Forster et al. 2011). Of all uses involved in building operation, space heating is especially important as it accounts for 55% of the total energy consumption (DECC 2012). Furthermore, according to the House Condition Surveys Team’s report, every 5% increase in average annual fuel prices would result in 30,000 more households in risk of fuel poverty (Cormack et al. 2004).

3. To ensure the preservation of the built heritage

As stated by ICOMOS (1999), *“due to homogenisation of culture and of global socio-economic transformation, vernacular structure all around the world are extremely vulnerable, facing serious problems of obsolescence, internal equilibrium and integration”*. Adapting the existing stock of traditional buildings to the current needs and standards of comfort is probably the most effective approach to prevent neglect and deterioration and therefore the best solution to ensure their preservation.

Rationale for research

Following, the rationale for this research is presented. Further clarification of these concepts will be provided throughout the next sections of this paper.

i. There is a need to improve the thermal performance of the traditional built stock in the UK.
ii. Solid masonry walls are “hard to treat” and the insulation of the cavity between the masonry and the lath and plaster may offer a compromised solution between efficiency, conservation and effectiveness.
iii. There is still a high level of uncertainty regarding the long term effect of insulation on the conservation of the fabric because of the changes caused to the internal moisture migration.
iv. Moisture dynamics in building envelopes are determined by the enclosure properties and boundary conditions although indoor climate is often neglected in favour of external conditions and material characterization.
v. Internal boundary conditions after the insulation of the envelope are difficult to predict because of the strong dependence on occupants’ behaviour.
vi. Monitoring of combined effect of insulation and occupants’ behaviour has a limited capability to evaluate the feasibility of this measure due to the wide range of user related patterns involved and the long period of time required to achieve the moisture balance in the envelope.

Aims and Objectives

The aim of this research is to *understand the influence of occupants' behaviour on the hygrothermal performance of insulated solid walls.* Therefore, the following objectives and research question are defined:

Objective 1. *To review the existing knowledge on the effect of retrofit measures on traditional building physics.*

- Q1. What are the current technologies for retrofitting solid masonry walls?
- Q2. How are the envelope's moisture dynamics affected by these measures?
- Q3. What factors are influencing the risk of condensation after the improvement of the envelope?

Objective 2. *To investigate the relationship between the adoption of retrofit measures and energy consumption patterns.*

- Q4. What are the driving factors for decision makers when adopting energy efficient technologies in traditional buildings?
- Q5. How are occupants' behaviour and needs considered when adopting energy efficient technologies in traditional buildings?

Objective 3. *To study the influence of occupants' behaviour on the internal climate of traditional buildings.*

- Q6. What parameters of occupants' behaviour are affecting the internal environment conditions?
- Q7. How does occupants' behaviour change after the improvement of the envelope?

Objective 4. *To explore the effect of internal boundary conditions on the performance of insulated solid walls.*

- Q8. To what extent are indoor climate conditions affecting the moisture dynamics of insulated solid walls?
- Q9. Do insulated traditional buildings require any particular behavioural response?

State of the Art

The literature review has been organized in four different categories based on the main threads of this research: traditional buildings, energy retrofit, moisture dynamics and occupants' behaviour. In the following, the *"state of the art"* in each category is briefly presented.

Traditionally constructed buildings

According to the first section of the Charter on the Built Vernacular Heritage (ICOMOS 1999:1), traditional architecture may be recognised by "*a manner of building shared by the community*" or *"a recognisable local or regional character responsive to the environment"*. It is evident that the term vernacular includes not only listed or historic buildings, but all traditionally constructed buildings. In the Scottish context, traditional buildings can be defined by the following characteristics (Urquhart 2007, Historic Scotland 2012, Wood, Brocklebank and Pickles 2010, Buda, Taylor and Bennadji 2013):

1. Use of load bearing masonry walls
2. Use of pitched roofs covered with slates or any other natural material
3. Use of permeable materials that both absorbs and releases moisture
4. Use of timber sash and case windows

Traditional buildings are often considered as "hard-to-treat" (Beaumont 2013) because conventional retrofit measures for cavity insulation, loft insulation or air tightness are often not compatible with these characteristics. In the UK, those are the characteristics of the majority of buildings built before 1919 and most of those built until 1945 (Wood, Brocklebank and Pickles 2010:17).

Energy retrofit technologies

Walls are the main source of heat loss in traditional buildings as they represent the larger area in contact with the external environment. However, traditionally constructed buildings in Scotland were usually built using ashlar masonry (Mcmillan 2006) so external insulation would be inappropriate in most of the cases and internal insulation feasibility shall depend on the existing finishes and available floor space (Currie 2013). In addition to that difficulty of implementation, disruption for occupants, upfront cost or loss of floor space are reasons usually mentioned to avoid the adoption of any of these measures (Gilbertson et al. 2006, Abdel-Wahab, Moore and MacDonald 2011, Mallaband, Haines and Mitchell 2012, Achtnich and Madlener 2014). Insulation materials pumped into the cavity formed between the solid wall and the lath and plaster seems to be a compromised solution (fig. 1). It reduces the heat loss and air leakage through the envelope while preserving the external appearance and internal finishes. Moreover, it minimises the cost of the operation and the disruption caused to the occupants.

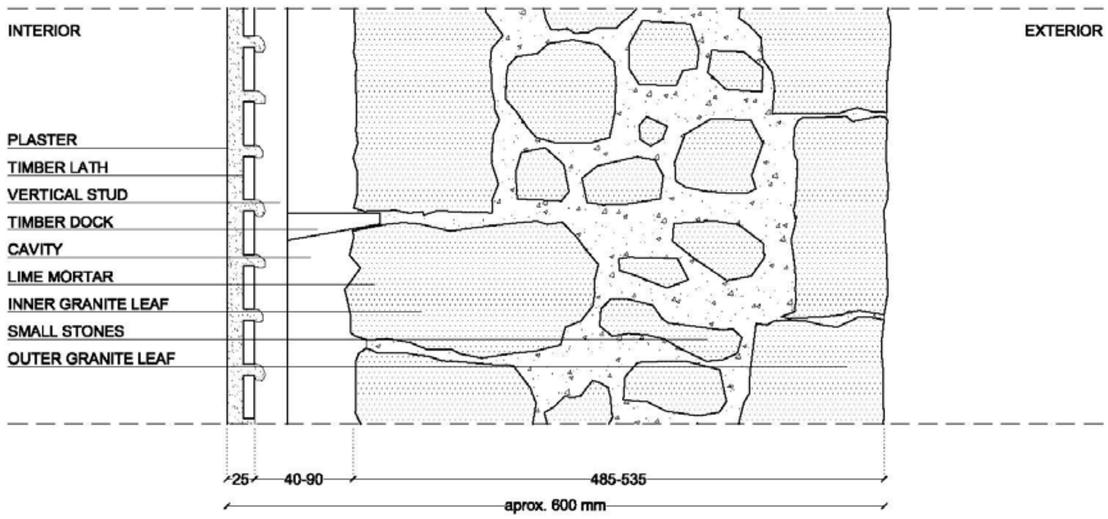

Figure 1. Insulated solid wall section detail (Adapted from Buda, Taylor and Bennadji 2013)

Several experiments carried out in the past years have assessed the feasibility of the implementation of blown insulation in traditional buildings. Different materials have been pumped into the cavity to reduce the thermal conductivity of the envelope: PUR Foam (Abdel-Wahab and Bennadji 2012), Polystyrene beams (Jack and Dudley 2012, Jenkins 2012a, 2012b, 2012c, Changeworks 2012), Cellulose (Curtis 2012, Jenkins 2012c), Aerogel (Curtis 2012), Perlite (Snow 2012) or Mineral wool (Changeworks 2013). However, the level of uncertainty regarding the consequences of blocking the air circulation within the cavity is still fairly high. It is important to investigate the long term effects of these measures since some of the moisture-related pathologies in fabric or occupants become visible only after several years of its application (Ridout 2000)

Moisture dynamics in building envelopes.

Traditional buildings are affected by moisture in a completely different way than modern construction. While impermeable barriers are used to keep humidity out of modern buildings, traditional construction makes use of the porosity and permeability of natural materials to buffer and slowly evaporate the moisture (Hughes 1987, Urquhart 2007). To control internal moisture, traditional construction relies on high rates of air renovation in rooms and unheated cavities (crawl space, loft or wall cavity) in order to avoid condensation and mould growth (Halliday 2009). Therefore, any alteration of the envelope will produce changes in the hygrothermal performance that need to be carefully studied.

Assessment of the hygrothermal performance of buildings is a complex process that requires the evaluation of heat (considering conduction, convection and radiation), air (natural and mechanical airflows) and moisture (including vapour diffusion, convection and liquid transport) (Ramos et al. 2010). For a prediction of the hygrothermal performance it is necessary to establish the geometry of the enclosure, materials' characteristics and boundary conditions. Accordingly, the prediction will be as accurate as the data used when modelling and, as stated by Straube and Burnett (2001:84), *"boundary conditions imposed on a mathematical model are often as critical to its accuracy as the proper modelling of the moisture physics"*.

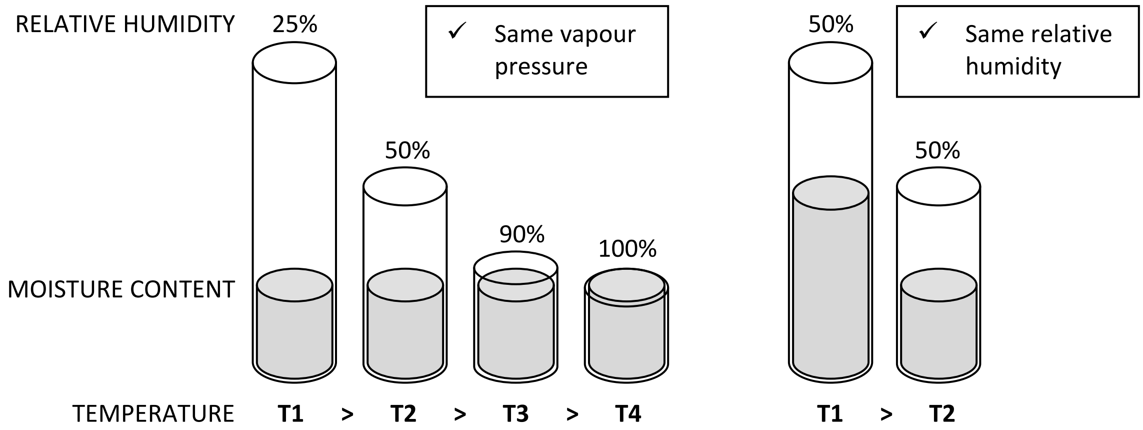

Figure 2. Figurative representation of temperature and humidity interaction (Adapted from Bedoya and Neila 1997)

Interstitial condensation is the result of the difference between vapour pressures of internal and external spaces; therefore moisture generated by the occupant activity is a crucial parameter as it determines the internal vapour pressure. Internal air temperature is also important because warmer air implies higher vapour pressure at the same relative humidity (fig. 2). Moreover, high temperature gradients create stack pressure differences that contribute to greater migration of moist air through the permeable materials (Sanders 2005)

The relevance of the users' role in the evaluation of condensation risk and numerically based simulation has already been acknowledged in previous research (Kavgic et al. 2010, STBA 2012 and Tariku, Kumaran and Fazio 2014). Despite its importance, internal boundary conditions are often neglected in favour of more detailed description of external conditions and material characterization. Previous studies on moisture migration within insulated walls (Morelli and Svendsen 2012, Steskens, Janssen and Rode 2009, Mukhopadhyaya et al., Künzel 2000) have considered indoor environment as a constant boundary with fixed values for temperature and relative humidity (usually 20 °C and 50% RH). However, and as showed in the next section, indoor climate is far from being constant or homogeneous.

Occupants' behaviour in retrofitted buildings

A wide range of different indoor climates have been measured (Oreszczyn et al. 2006, Love 2012, Andersen 2012) proving the strong correlation between internal boundary conditions and occupants' behaviour. Behavioural aspects are often studied in the context of energy consumption reduction and therefore most the investigations are usually focused on the identification of the driving factors for space heating demand. According to Wei (2014), those factors can be classified as environmental, building and system related, occupant related or others. Some of the most relevant drivers are summarised in Table 1.

Table 1. Driving factors for occupants' heating behaviour (Adapted from Wei, Jones, deWilde 2014)

CATEGORY	DRIVER	EFFECT	REFERENCES
Environmental	Internal Relative Humidity	Changes in the relative humidity lead to more frequent setting adjustment	*Fabi 2013*
Building and system related	Building age	No effect	*Vine 1987*
		Older homes tend to be colder	*Hunt 1982, French 2007, Guerra-Santin 2009*
	Room type	Living rooms are heated up to higher temperature and for longer periods	*Hunt 1982, Summerfield 2007, Conner 1990, Oreszczyn 2006, French 2007, Isaacs 2010, Guerra-Santin 2009, Yohanis 2010*
	Heating system	No clear correlation	*Hunt 1982, Andersen 2009, Kavgic 2012*
	Level of insulation	Lower temperature in insulated buildings	*Verhallen 1984*
		Higher temperatures in living room and bedroom when insulated	*Pimbert 1981, Haas 1998, Shipworth 2009*
User related	House ownership	No relationship	*Vine 1987*
		Higher demand in rented housing than in any other tenure groups	*Rehdanz 2007, Andersen 2009, DEFRA 2009*
	Household income	No relationship	*Vine 1987, French 2007, Guerra-Santin 2010, Isaacs 2010*
		Less energy spent for space heating in families with lower income	*Newman 1975, Hunt 1982, Day 2009, Weihl 1990, Vringer 2007*

Besides the energy use drivers, it is also necessary to identify and investigate how the occupants' behaviour changes after the improvement of the envelope. Changes in energy consumption have already been investigated in several studies (Milne and Boardman 2000, BRE 2005, Martin and Watson 2006 and Hong 2001) and it has been shown that energy demand reduction is not directly proportional to the improvement of the envelope as several other factors are involved in the final energy use. Both Weihl and Gladhart (1983) and Shipworth et al. (2009) identified higher set-point temperatures in energy efficient homes while Verhallen and Van Raaij (1984) found lower thermostat settings in dwellings with higher levels of insulation. However, this variable should be used with caution since set-point temperatures do not necessarily mean equal internal temperatures.

Research on heating periods (number of hours of active heating) is still very limited. Griffiths (1987) and Martin and Watson (2006) monitored use of heating before and after the refurbishment, however results of these longitudinal studies have not been made available. Only Shipworth et al. (2009) and Love (2013) have published some data reporting the changes that occurred after the improvement of the envelope but just for small samples and acknowledging many limitations to the results. Regarding the number of rooms heated before and after the insulation, only qualitative data has been collected (Gilbertson et al. 2006). According to this study, more rooms are used after the refurbishment and in consequence more rooms are heated.

Changes in the internal temperature have been documented in several studies (Verhallen and Van Raaij 1984, Haas, Auer and Biermayr 1998, Oreszczyn et al. 2006, Martin and Watson 2006, Hong 2011, Love 2013), however it is difficult to come to any valid conclusion as the variation in temperature differs greatly from one example to the other. It is not possible to explain these results without considering sociological aspects as previously described (family income, thermal sensation or occupant age, gender and culture). It is necessary to highlight that in a study carried out by Critchley et al. in 2007 to investigate the explanatory factors for persistent cold temperatures, pre-1930 properties were the predominant type of homes that remained cold after the improvement.

Measurements of the variation in the internal relative humidity have only been done by Love (2013). According to these results, internal humidity will decrease around 10-20% after the insulation. Verhallen and Van Raaij (1984) also noticed changes in the ventilation behaviour of users with more airing out of rooms in highly insulated buildings but no record of humidity is provided.

All these studies have their focus on existing buildings, but, as acknowledge by the STBA (2012:30), at the moment "*there is no work on user behaviour focused specifically on traditional buildings, neither on whether the behaviour of users of traditional buildings might be any different to that of occupants of any other types of building stock, nor, indeed, whether a retrofitted traditional building determines or requires particular behavioural responses*".

Lastly it is important to emphasise the role that modelled behavioural profiles play in the study of users' effect on the energy demand. According to Verhallen and Van Raaij (1984:148): "*a segmentation approach based on behavioural patterns provides better insights in the interaction of energy behaviour, attitudes, house characteristics and sociodemographics*". This approach is also used by Love (2012), STBA (2014) and Fabi, Andersen and Corgnati (2013) in their respective studies.

Research Design

This research can be broken down into four steps (Table 2) according to the main stages of data collection established to address the research questions.

Table 2. Research design summary

RESEARCH STAGE			RESEARCH QUESTIONS	
1. Literature review				
	Task 1.1	Traditional buildings	Q1	*What are the current technologies for retrofitting solid masonry walls?*
	Task 1.2	Energy retrofit		
	Task 1.3	Moisture dynamics	Q2	*How are the envelope's moisture dynamics affected by...?*
	Task 1.4	Occupants behaviour	Q3	*What factors are influencing the risk of condensation after...?*
2. Decision making analysis				
	Task 2.1	DMs interviews	Q4	*What are the driving factors for decision makers when...?*
3. Occupants' behaviour survey				
	Task 3.1	Occupants interviews	Q5	*How are occupants' behaviour and needs considered...?*
			Q6	*How does occupants' behaviour change after the...?*
	Task 3.2	Environ. monitoring	Q7	*What parameters of occupants' behaviour are affecting...?*
4. Numerical simulation				
	Task 4.1	Scenarios modelling	Q8	*To what extent are indoor climate conditions affecting the moisture dynamics of insulated...?*
	Task 4.2	Simulations		
	Task 4.3	Sensitivity analysis	Q9	*Do insulated traditional buildings require any particular...?*

Stage 1. Literature review

Literature has been reviewed to identify the existing options for retrofitting traditional buildings and the relationship between moisture dynamics in the envelope and influence of occupants' behaviour on the internal climate. The findings shaped the hypotheses to be tested in the following steps of the research. The literature review has been organised using the same four categories defined in the previous "state of the art" section.

Stage 2. Decision making analysis

In-depth interviews with home owners and stakeholders has been the first method used for collecting data in the research. Qualitative methods were used to identify the different variables influencing the approach taken by owners and stakeholders when refurbishing an old house (Townsend 2010).

- *Data collection*

The semi-structured interviews followed a predesigned outline to ensure that all the relevant topics were addressed but, at the same time, giving some freedom to the interviewees to choose the order and depth for each subject to be discussed. Up to now, 11 interviews have been conducted. Each interview, including a site visit, lasted between 60 and 100 minutes. Participants have been selected among those who own a traditional building and have done, or are planning to do, some refurbishment work in order to improve their energy efficiency.

Participants' recruitment for the interviews was done using different approaches. Private owners were first contacted at energy-related events (e.g. All-Energy conference) and then word of mouth from participants themselves (also known as snowball sampling, Marshall and Rossman 1999) allowed contacting new owners of the same area. In order to contact other types of decision makers, invitation letters were sent to a total of 26 organisations, including rural landlords, housing associations, property developers and estates department. A reminder letter was sent a few weeks later to those who did not reply to the first one. Positive answers were received from all the groups with the exception of property developers that refused to participate.

A formal pilot study has not been undertaken. Instead, a complete evaluation of the process and results was carried out after the first 3 interviews. This process allowed the identification of weaknesses in the structure of the interview, recording methods or data analysis. Data obtained in these first interviews can still be used since "*contamination is less of a concern in qualitative research, where researchers often use some or all of their pilot data as part of the main study*" (van Teijlingen and Hundley 2001:3).

- *Data analysis and interpretation*

The first step of an interview analysis is the full transcription of the audio recordings to facilitate the identification of relevant topics. Transcript labelling facilitates the identification and interpretation of the underlying patterns. Topics may be relevant due to the repetition during the interview, because is explicitly said by the interviewee or because its connection with a certain theory or other participants' answers.

The interim analysis of the interviews allowed the identification of a purchase process similar to the model created by Oates et al. (2008) to investigate consumers' use of information sources when purchasing sustainable technological products. Use of a similar template (fig. 3) for the analysis will facilitate the identification of "strong and weak filters" arisen during the decision making process.

Due to small sample size, demographic information will not be statistically relevant. Questionnaires results will be only used to re-evaluate the findings of the qualitative analysis of the interviews trying to find the relation, if exists, between the demographic characteristics and the responses.

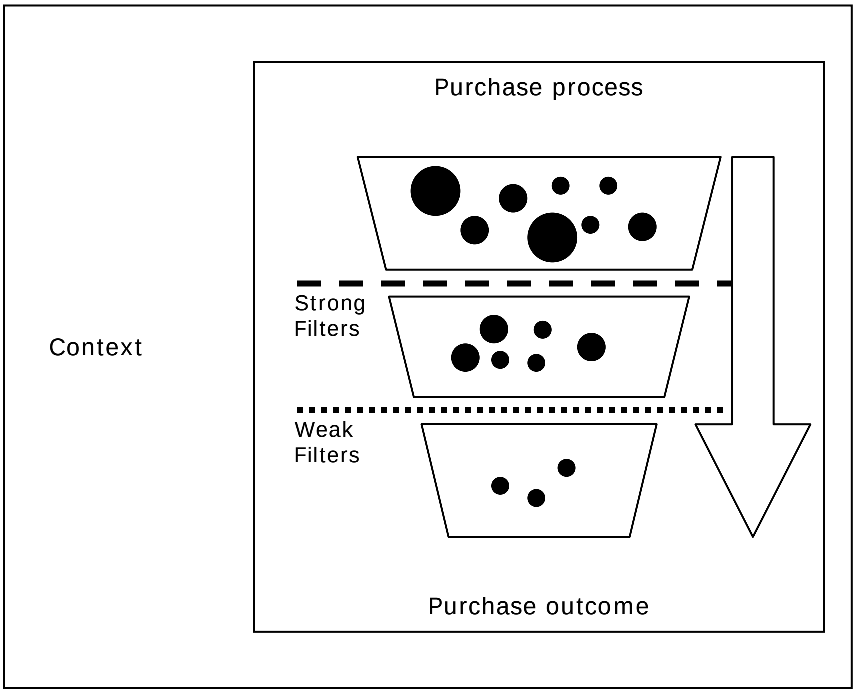

Figure 3. Purchase process analysis template (Adapted from Oates et al. 2008)

Stage 3. Occupants' behaviour survey

To minimise the uncertainty associated with the indoor climate, this research aims to use real data collected from traditional buildings in order to model accurate retrofit scenarios.

- *Data collection*

Each case study will provide two different types of data, quantitative data from the environmental monitoring and qualitative information of occupants' considerations derived from in-depth interviews. As decision maker' interviews, questions to the occupants will follow a predefined semi-structured outline to ensure the acquisition of all the relevant data while allowing autonomy to the users to speak freely about their experience inhabiting the building.

The environmental monitoring consists of the acquisition of temperature and humidity data from the living room and main bedroom of solid wall residential buildings over a period of twelve months. Data is recorded using Lascar EL-USB-2 (fig. 4) stand alone data-loggers. The sensors are placed away from direct heating sources and occupants' reach in order to reduce both disruption and variability in the measurements. Longitudinal monitoring of internal spaces (Summerfield et al. 2007) requires owners' consent and the engagement of the occupants during long periods of time and accordingly sample selection is laborious. For a consistent sample and an easier comprehension of the results, participants should belong to similar demographic groups and occupy comparable type of buildings.

The sample selected is formed by two homogeneous groups. The first one comprises nine un-insulated flats located in a granite tenement in Aberdeen. The building belongs to a Housing Association, previously interviewed, which ensures a demographically homogeneous sample and allows the comparison of the results obtained from interviews with both decision makers and users. The second set of households included in the sample belongs to rural estates. This second sample is formed by recently insulated properties rented under the scheme of "affordable housing" providing a comparable set of data for a cross-sectional study (Hong, Oreszczyn and Ridely 2006).

Figure 4. Lascar EL-USB-2 data logger

- *Data analysis and interpretation*

Again, full transcription of the audio recordings will be the first step for data analysis in order to identify relevant and recurrent topics. Occupants' interviews will be analysed from two different perspectives, first results will be studied together with the monitoring data to find the relationship between the recorded measures and the users' opinions. Secondly the results will be compared to the selection criteria identified in the interviews with the decision makers to address research question number 5 *"How are occupants' behaviour and needs considered when adopting energy efficient technologies in traditional buildings?"*

The environmental data gathered from un-insulated buildings, together with the findings from literature, will be analysed and synthesised to create different user profiles. Number and characteristics of these profiles will be determined after data analysis but it is likely that they will be similar to those created by Verhallen and Van Raaij (1984) (conservers, cool, average, warm and spenders) or Fabi, Andersen and Corgnati (2013) (passive, medium, active). Post-retrofit scenarios will be defined by the improvement of the envelope and the changes in the internal climate due to the users' behaviour (fig. 5). Like in the un-insulated scenarios, different profiles of users' conduct will be proposed. The magnitude of these changes will be determined after the analysis of the insulated properties monitoring and review of previous cross-sectional studies.

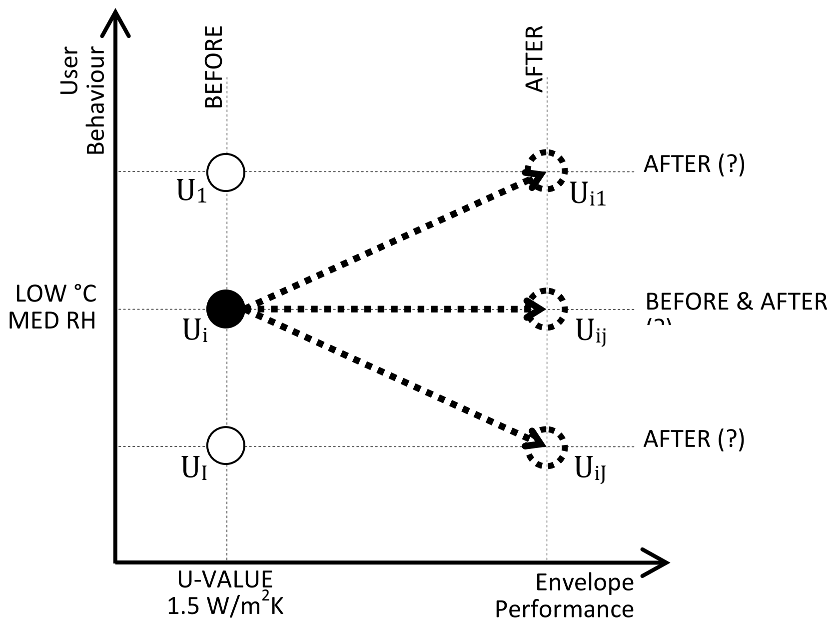

Figure 5. Illustrating the pre and post-retrofit scenarios

Stage 4. Numerical simulation

To develop a numerical simulation of the moisture dynamics in the envelope this research project will make use of Heat, Air and Moisture (HAM) software. The simulation will examine the impact that a range of different behavioural patterns (heating, ventilation, etc.) have on moisture migration in granite solid walls with different types of insulation "pumped" into the cavity between inner face of the granite and the lath and plaster lining (fig. 1).

- *Data collection*

Previous research has shown that it can take up to 20 years to reach moisture balance in insulated walls, although in most cases the balance is evident after 5 to 10 years of insulation (Browne 2012:68). Hence, the use of numerical simulations is especially appropriate in this case because it helps to simultaneously explore the changes in the wall's performance under different boundary conditions for long periods of time.

After the evaluation of the different HAM software available for commercial and research purposes (Straube and Burnett 2001, Janssens et al. 2008, Hens 2009, Ramos et al. 2010 and Delgado et al. 2013), DELPHIN has been chosen to be used in this stage of the research. DELPHIN is a simulation program developed by The Institute for Building Climatology at Dresden University of Technology. This software has been repeatedly used in previous studies (Häupl, Fechner and Petzold 2004, Scheffler 2008, Morelli and Svendsen 2012) and has been validated conforming to EN 15026:2007.

Modelling of the envelope and the boundary conditions will require several steps and different data inputs. After the definition of the enclosure geometry, it is necessary to define the materials forming the envelope. These data can be obtained from both built-in libraries and previous studies that have already characterized its thermophysical properties (Hens 1991, Kumaran 1996). The next step is the definition of the boundary conditions for external and internal spaces. Exterior conditions will not be affected by the changes in the envelope, so the same conditions can be used for modelling the scenarios before and after the insulation. The external parameters will be obtained from a weather station located on the roof of the first monitored building recording the climatic conditions for a whole year.
Lastly, the internal climate for both un-insulated and insulated walls will be defined by the user profiles elaborated with the results of the previous stage. The profiles will include hourly data of temperature and relative humidity for a twelve months period and will take into account every user related factor identified through the research (heating use, ventilation, cooking, laundry drying, etc.). The following variables will be evaluated:

- Pre-retrofit user behaviour (e.g. passive, medium, active)
- Post-retrofit behavioural change (e.g. favourable, stable, adverse)
- Insulation material (e.g. PUR foam, polystherene beam, cellulose)

All these simulations will be performed in a typical wall section detail (fig. 1), but the most critical scenarios will also be studied in more vulnerable areas such as wall to floor junction, wall to wall junction or gable walls.

- *Data analysis and interpretation*

Finally, a sensitivity analysis will enable the identification of the most influential user related factors. As stated by Hamby (1994:135) "a sensitivity analysis of these [the most influential] parameters is not only critical to model validation but also serves to guide future research efforts". Two types of sensitivity are usually evaluated: individual ones, those exploring the influence of each single input, and total sensitivities, for the estimation of the effect of the uncertainties in all the input data (Lomas and Eppel 1992). According to Lomas, investigating the influence of both individual and total sensitivities has numerous practical benefits:

i. To identify the inputs to which the output are particularly sensitive and those to which they are insensitive.
ii. To identify inputs to which the program is sensitive, but for which adequate data is not yet available.
iii. To establish the resolution of the program (i.e., the maximum accuracy) that can be expected in absolute predictions.
iv. To identify the probability for the distribution of the results.
v. To establish the significance of uncertainties due to technical limitations or modelling assumptions.

Table 3. Appraisal of sensitivity analysis techniques. (Adapted from Lomas and Eppel 1992:40)

Technique	Advantages	Disadvantages
DSA	No code modifications necessary, easy to implement, any parameter, simple post-processing, individual and total uncertainties	Necessary to assume linearity and superposability to calculate **total uncertainties**
MCA	No code modifications necessary, easy to implement, any parameter, simple post-processing, no assumptions necessary about linearity and superposability	Only total uncertainties can be obtained, not **individual uncertainties**

There are several techniques for the application of the sensitivity analysis (Hamby 1995). Two different techniques have been successfully tested in a previous investigation regarding thermal simulation programs, a field comparable to this research project (table 3): differential sensitivity analysis (DSA) and Monte Carlo analysis (MCA). Since the evaluation of individual uncertainty is a crucial aspect in this study, DSA seems to be the most appropriate method to conduct the analysis. This technique requires the alteration of one parameter in each simulation while the rest remain stable at the most common value. An iterative process of parameter input alteration will allow the determination of all the individual effects. Since the internal climate in HAM software is characterised by air temperature and relative humidity or vapour pressure, the analysis should include any parameter affecting these two variables (fig. 6). At present, neither the parameters to be analysed nor the value of the perturbations can be defined and will be determined after the interpretation of interim results.

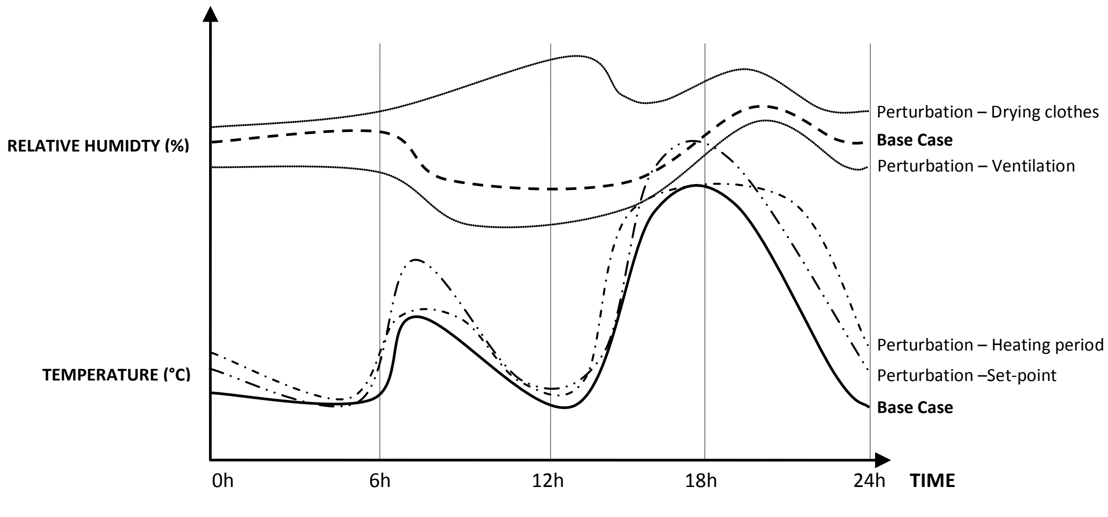

Figure 6. Illustrating the effect of different input perturbation on the internal climate

Due to the repetitive nature of the DSA implementation, in Lomas and Eppel study (1992) the process was automated using a Fortran program. In this case an analogous procedure will be used (fig. 7), but all the processes for selection and perturbation of the parameters and calculation of individual uncertainties will be completed manually.

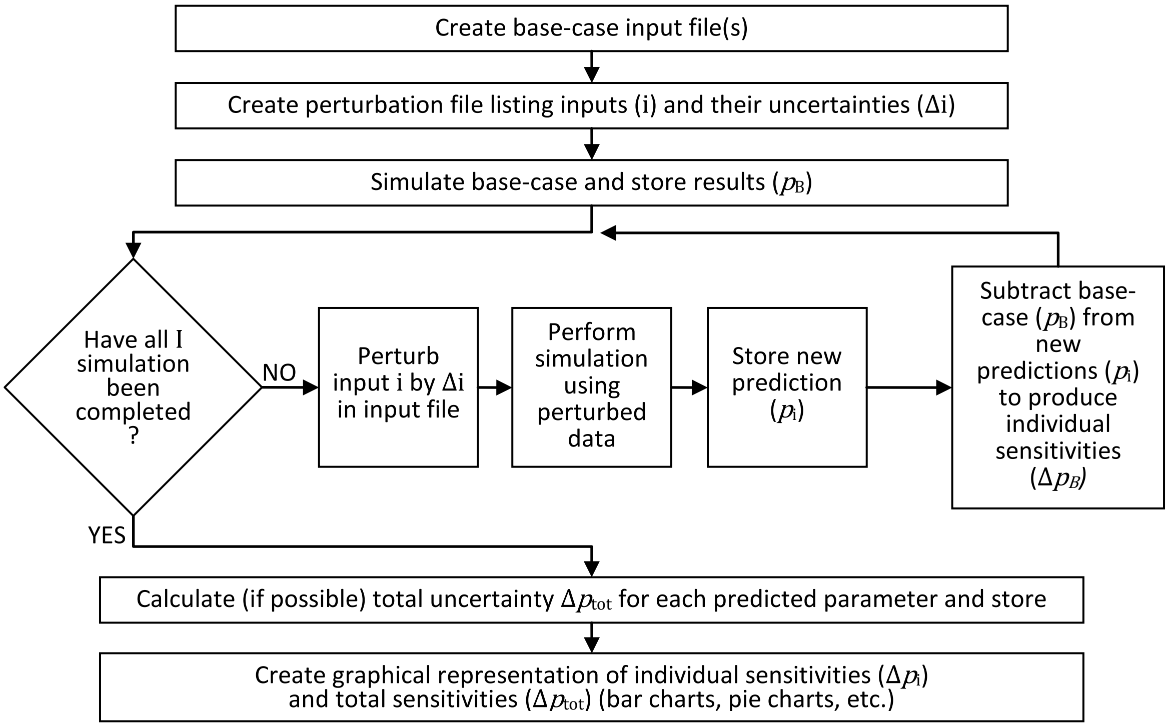

Figure 7. Implementation of the differential sensitivity analysis procedure (Adapted from Lomas and Eppel 1992)

The results obtained with the sensitivity analysis will be compared to the driving factors of decision makers to confirm if their purchase filters are taking the critical aspects of occupants' behaviour into account (fig. 8). Decision makers could then be advised about the measures that can be safely applied and the behavioural aspects that need to be monitored after their implementation.

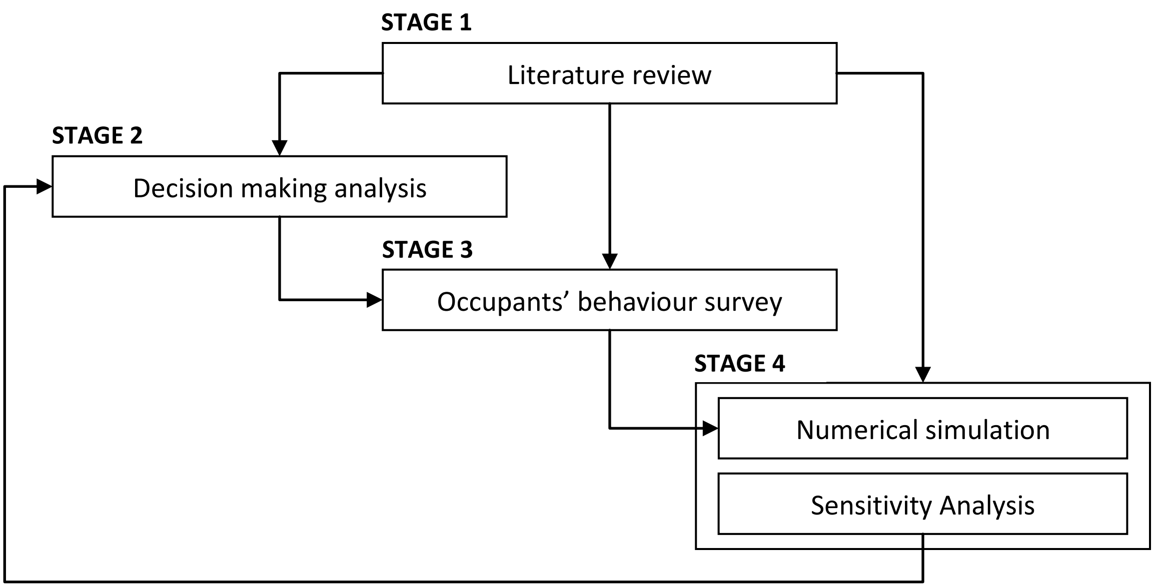

Figure 8. Research methodology overview

Contribution to Knowledge

The contribution of this research to the scientific knowledge can be summarised as follows:

1. Gaining a better understanding of owners and stakeholders perspectives regarding the energy retrofit of traditional buildings.
2. Deepening the knowledge on occupants' behaviour in traditional buildings.
3. A description of different behavioural patterns and its influence on the indoor climate in residential traditional buildings.
4. Identification of critical aspects of users' behaviour that need to be assessed after the insulation of solid walls to ensure their correct performance.
5. Development of a new approach to evaluate the effect of changes in occupants' behavior on the indoor climate.
6. Development of a methodology to evaluate the sensitivity of solid walls to different user related patterns.

References

ABDEL-WAHAB, M. and BENNADJI, A., 2013. Skills development for retrofitting a historic listed building in Scotland. *International Journal of Low-Carbon Technologies,*

ABDEL-WAHAB, M., MOORE, D. and MACDONALD, S., 2011. Exploring the adoption of low carbon technologies by Scottish housing associations. *International Journal of Low-Carbon Technologies,* 6(4), pp. 318-323

ACHTNICHT, M. and MADLENER, R., 2014. Factors influencing German house owners' preferences on energy retrofits. *Energy Policy,*

ANDERSEN, R.K., 2012. The influence of occupants' behaviour on energy consumption investigated in 290 identical dwellings and in 35 apartments. *10th International Conference on Healthy Buildings.*

ANDERSEN, R.V. et al., 2009. Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy and Buildings,* 41(1), pp. 11-16

BAKER, P., 2008. *Thermal performance of traditional windows.* Edinburgh: Historic Scotland, Technical Conservation Group.

BAKER, P., 2011. Technical Paper 10: U-values and traditional buildings-In situ measurements and their comparisons to calculated values.

BAKER, P. et al., 2010. Thermal Performance of Traditional Windows and Low-Cost Energy-Saving Retrofits. *APT Bulletin,* 41(1), pp. 29-34

BEAUMONT, A., 2007. Hart to treat homes in Enlgand. *Sustainable urban areas.* 25-28 June. Rotterdam: European Network for Housing Research.

BEDOYA, C. and NEILA, F.J., 1997. Técnicas arquitectónicas y constructivas de Acondicionamiento ambiental.

BRE, 2005. Energy Use in Homes: A series of reports on domestic energy use in England. 4 Fuel consumption. [online] Available from: http://www.bre.co.uk/filelibrary/pdf/rpts/FuelConsumption.pdf [Accessed 13/03/2014]

BROWNE, D., 2012. The SPAB Research Report 3. The SPAB Hygrothermal Modelling: Interim Report. [online] Available from: http://www.spab.org.uk/downloads/SPAB%20Hygrothermal%20Modelling%20Report%2031.pdf [Accessed 13/03/2014]

BUDA, G., TAYLOR, B. and BENNADJI, A., 2013. The nature of mass masonry granite walling and the potential for retrofit internal wall insulation strategies. *Journal of Building Survey, Appraisal & Valuation,* 2(1), pp. 36-43

CHANGEWORKS, 2008. *Energy Heritage: A guide to improving energy efficiency in traditional and historic homes.* Edinburgh: Changeworks.

CHANGEWORKS, 2012. Solid Wall Insulation in Scotland. [online] Available from: http://www.changeworks.org.uk/uploads/Solid_Wall_Insulation_in_Scotland_Report_Changeworks-June-2012.pdf [Accessed 13/03/2014]

CHANGEWORKS, 2013. Guide to Insulating Hard-to-Treat Cavities (HTTCs). [online] Available from: http://consultancy.changeworks.org.uk/assets/uploads/Guide_to_Insulating_Hard-to-Treat_Cavities_April13.pdf [Accessed 13/03/2014]

CONNER, C. and LUCAS, R., 1990. *Thermostat related behavior and internal temperatures based on measured data in residences,*

CORMACK, D. et al., 2004. Fuel Poverty in Scotland: Further Analysis of the Scottish House Condition Survey. 2004. *Edinburgh, Communities Scotland and Scottish Executive,*

CRITCHLEY, R. et al., 2007. Living in cold homes after heating improvements: Evidence from Warm-Front, England's Home Energy Efficiency Scheme. *Applied Energy,* 84(2), pp. 147-158

CURRIE, J., WILLIAMSON, J.B. and STINSON, J., 2013. *Technical Paper 19: Monitoring thermal upgrades to ten traditional properties.* Edinburgh: Historic Scotland, Technical Conservation Group.

CURTIS, R., 2010. Climate Change and Traditional Buildings: The Approach Taken by Historic Scotland. *Journal of Architectural Conservation,* 16(3), pp. 7

CURTIS, R., 2012. Historic Scotland Refurbishment Case Study 2 . [online] Available from: http://www.historic-scotland.gov.uk/refurb-case-study-2.pdf [Accessed 13/03/2014]

DAY, R. and HITCHINGS, R., 2009. Older people and their winter warmth behaviours: Understanding the contextual dynamics.

DECC, 2012. *Energy consumption in the united kingdom: 2012. domesic energy consumption in the UK since 1970.* [online] Departmet of Energy and Climate Change, United Kingdom. Available from: http://www.decc.gov.uk/assets/decc/11/stats/publications/energy-consumption/2323-domestic-energy-consumption-factsheet.pdf [Accessed 01/22 2012]

DEFRA, 2009. Public Attitudes and Behaviours Towards the Environment – TrackerSurvey Final Report to the Department for Environment, Food and Rural Affairs. [online] Available from: http://webarchive.nationalarchives.gov.uk/20130123162956/http:/www.defra.gov.uk/statistics/files/report-attitudes-behaviours2009.pdf

DELGADO, J.M. et al., 2013. *Hygrothermal Numerical Simulation Tools Applied to Building Physics.* Springer.

DYRBØL, S., THOMSEN, K.E. and ALBÆK, T., 2010. European Directive on the Energy Performance of Buildings-Energy policies in Europe-Examples of best practices. *2010 ACEEE Summer Study on Energy Efficiency in Buildings.* August 2010. pp. 126-140

EN, B., 2007. 15026: 2007 Hygrothermal performance of building components and building elements—Assessment of moisture transfer by numerical simulation. *German version DIN EN,* 15026

ENGLISH HERITAGE, 2010. *Energy Efficiency In Historic Buildings – Draught-proofing windows and doors.* English Heritage.

Leipzig charter on sustainable European Cities. European Union Bill (Presidency, German;)

FABI, V., ANDERSEN, R.V. and CORGNATI, S.P., 2013. Influence of occupant's heating set-point preferences on indoor environmental quality and heating demand in residential buildings. *HVAC&R Research,* 19(5), pp. 635-645

FERREIRA, J., DUARTE PINHEIRO, M. and DE BRITO, J., 2013. Refurbishment decision support tools: A review from a Portuguese user's perspective. *Construction and Building Materials,* 49(0), pp. 425-447

FORSTER, A.M. et al., 2011. Green maintenance for historic masonry buildings: an emerging concept. *Building Research & Information,* 39(6), pp. 654-664

FRENCH, L.J. et al., 2007. Temperatures and heating energy in New Zealand houses from a nationally representative study—HEEP. *Energy and Buildings,* 39(7), pp. 770-782

GILBERTSON, J. et al., 2006. Home is where the hearth is: grant recipients' views of England's home energy efficiency scheme (Warm Front). *Social science & medicine,* 63(4), pp. 946-956

GRIFFITHS, I., 1987. *Human factors in domestic gas consumption in South-East England 1981-1985.* Colchester, Essex: UK Data Archive.

GUERRA SANTIN, O., ITARD, L. and VISSCHER, H., 2009. The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings,* 41(11), pp. 1223-1232

GUERRA-SANTIN, O. and ITARD, L., 2010. Occupants' behaviour: determinants and effects on residential heating consumption. *Building Research & Information,* 38(3), pp. 318-338

HAAS, R., AUER, H. and BIERMAYR, P., 1998. The impact of consumer behavior on residential energy demand for space heating. *Energy and Buildings,* 27(2), pp. 195-205

HALLIDAY, S., 2009. Technical Paper 6: Indoor air quality and energy efficiency in traditional buildings.

HAMBY, D., 1994. A review of techniques for parameter sensitivity analysis of environmental models. *Environmental monitoring and assessment,* 32(2), pp. 135-154

HAMBY, D.M., 1995. A comparison of sensitivity analysis techniques. *Health physics,* 68(2), pp. 195-204

HÄUPL, P., FECHNER, H. and PETZOLD, H., 2004. Interior retrofit of masonry wall to reduce energy and eliminate moisture damage: Comparison of modeling and field performance. *Proceedings of Buildings IX Conference, Clearwater Beach, FL, USA.*

HENS, H., 1991. IEA Annex 14: Condensation and Energy, vol. 3: Catalogue of Material Properties. *International Energy Agency,*

HENS, H.S., 2009. IEA-ECBCS Annex 41 Whole Building Heat, Air, and Moisture Response. *ASHRAE Transactions,* 115(2),

HISTORIC SCOTLAND, 2012. *Fabric improvements for energy efficiency in traditional buildings.* [online] Historic Scotland. Available from: http://conservation.historic-scotland.gov.uk/fabric-improvements-traditional-buildings.pdf [Accessed 01/22 2013]

HONG, S.H., 2011. *Changes in space heating energy consumption following energy efficient refurbishment in low-income dwellings in England.* [online] PhD thesis, UCL (University College London).

HONG, S.H., ORESZCZYN, T. and RIDLEY, I., 2006. The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. *Energy and Buildings,* 38(10), pp. 1171-1181

HUGHES, P., 1987. *The Need for Old Buildings to Breathe.* Society for the Protection of Ancient Buildings.

HUNT, D.R.G. and GIDMAN, M.I., 1982. A national field survey of house temperatures. *Building and Environment,* 17(2), pp. 107-124

ICOMOS, 1999. *Charter on the built vernacular heritage.* [online] Mexico: ICOMOS. Available from: http://www.icomos.org/charters/vernacular_e.pdf [Accessed 04/08 2013]

ISAACS, N. et al., 2010. Energy in New Zealand houses: comfort, physics and consumption. *Building Research & Information,* 38(5), pp. 470-480

JACK, M. and DUDLEY, A., 2012. Historic Scotland Refurbishment Case Study 1 . [online] Available from: http://www.historic-scotland.gov.uk/refurb-case-study-1.pdf [Accessed 13/03/2014]

JANSSENS, A. et al., 2008. From EMPD to CFD–overview of different approaches for Heat Air and Moisture modeling in IEA Annex 41. *IEA ECBCS Annex 41,* , pp. 9-20

JENKINS, M., 2012a. Historic Scotland Refurbishment Case Study 3. [online] Available from: http://www.historic-scotland.gov.uk/refurb-case-study-3.pdf [Accessed 13/03/2014]

JENKINS, M., 2012b. Historic Scotland Refurbishment Case Study 4 . [online] Available from: http://www.historic-scotland.gov.uk/refurb-case-study-4.pdf [Accessed 13/04/2014]

JENKINS, M., 2012c. Historic Scotland Refurbishment Case Study 8 . [online] Available from: http://www.historic-scotland.gov.uk/refurb-case-study-8-garden-bothy-cumnock.pdf [Accessed 13/03/2014]

KAVGIC, M. et al., 2010. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment,* 45(7), pp. 1683-1697

KAVGIC, M. et al., 2012. Characteristics of indoor temperatures over winter for Belgrade urban dwellings: Indications of thermal comfort and space heating energy demand. *Energy and Buildings,* 47(0), pp. 506-514

KUMARAN, M., 1996. IEA Annex 24 Final Report, Vol. 3, Task 3: Material Properties. *IEA, Acco Leuven, Leuven,*

KÜNZEL, H., 2000. Moisture risk assessment of roof constructions by computer simulation in comparison to the standard Glaser-method. *International Building Physics Conference, Eindhoven.* pp. 225-232

LOMAS, K.J. and EPPEL, H., 1992. Sensitivity analysis techniques for building thermal simulation programs. *Energy and Buildings,* 19(1), pp. 21-44

LOVE, J., 2012. Mapping the impact of changes in occupant heating behaviour on space heating energy use as a result of UK domestic retrofit.

LOVE, J., 2013. The impact of the CESP scheme on a set of case study households. *2013.* [online] Available from: http://www.lolo.ac.uk/projectoutputs/download/idprojects/50/idoutputs/320 [Accessed 13/03/2014]

MALLABAND, B., HAINES, V. and MITCHELL, V., 2012. Barriers to domestic retrofit–learning from past home improvement experiences.

MARSHALL, C. and ROSSMAN, G.B., 1999. *Designing qualitative research.* 3rd ed. Thousand Oaks, CA: Sage.

MARTIN, C. and WATSON, M., 2006. *Measurement of energy savings and comfort levels in houses receiving insulation upgrades.* Energy Saving Trust.

MCMILLAN, A. et al., 2006. *Indigenous stone resources for Scotland's built heritage.*

MILNE, G. and BOARDMAN, B., 2000. Making cold homes warmer: the effect of energy efficiency improvements in low-income homes A report to the Energy Action Grants Agency Charitable Trust. *Energy Policy,* 28(6–7), pp. 411-424

MORELLI, M. and SVENDSEN, S., 2013. Investigation of interior post-insulated masonry walls with wooden beam ends. *Journal of Building Physics,* 36(3), pp. 265-293

MUKHOPADHYAYA, P., KUMARAN, K., NOFAL, M., TARIKU, F. and VAN REENEN, D., Assessment of building retrofit options using hygrothermal analysis tool.

NEMRY, F. et al., 2008. Environmental improvement potentials of residential buildings (IMPRO-building). *European Commission, JRC-IPTS, EUR,* 23493

NEWMAN, D. and DAY, D., 1975. *The American Energy Consumer: A Report to the Energy Policy Project of the Ford Foundation.* Cambridge, Mass: Ballinger Publishing Company.

OATES, C. et al., 2008. Marketing sustainability: Use of information sources and degrees of voluntary simplicity. *Journal of Marketing Communications,* 14(5), pp. 351-365

ORESZCZYN, T. et al., 2006. Determinants of winter indoor temperatures in low income households in England. *Energy and Buildings,* 38(3), pp. 245-252

PALMER, J. et al., 2006. *Reducing the environmental impact of housing.* Environmental Change Institute, University of Oxford.

PIMBERT, S.L. and FISHMAN, D.S., 1981. SOME RECENT RESEARCH INTO HOME HEATING. *Journal of Consumer Studies & Home Economics,* 5(1), pp. 1-12

RAENG, 2010. *Engineering a low carbon built environment: the discipline of building engineering physics.* London: The Royal Academy of Engineering.

RAMOS, N. et al., 2010. Hygrothermal numerical simulation: application in moisture damage prevention. *Numerical simulations-examples and applications in computational fluid dynamics,*

REHDANZ, K., 2007. Determinants of residential space heating expenditures in Germany. *Energy Economics,* 29(2), pp. 167-182

RICS, ROYAL INSTITUTION OF CHARTERED SURVEYORS, 2008. *Towards an Energy Efficient European Building Stock An RICS Status Report on the Implementation of Directive 2002/91on the Energy Performance of Buildings (EPBD) in the EU Member States.* London: The Royal Institution of Chartered Surveyors.

RIDOUT, B., 2000. *Timber decay in buildings: the conservation approach to treatment.* Taylor & Francis.

SANDERS, C., 2005. *Modelling and controlling interstitial condensation in buildings.* Watford: BRE Bookshop.

SCHEFFLER, G.A., 2008. *Validation of hygrothermal material modelling under consideration of the hysteresis of moisture storage,*

SCOTTISH PARLIAMENT. *Climate Change (Scotland) Act 2009 (asp 12).* Edinburgh

SHIPWORTH, M. et al., 2010a. Central heating thermostat settings and timing: building demographics. *Building Research & Information,* 38(1), pp. 50-69

SHIPWORTH, M. et al., 2010b. Central heating thermostat settings and timing: building demographics. *Building Research & Information,* 38(1), pp. 50-69

SNOW, J., 2012. Historic Scotland Refurbishment Case Study 7 . [online] Available from: http://www.historic-scotland.gov.uk/refurb-case-study-7.pdf [Accessed 13/03/2014]

STBA, 2012. *Responsible retrofit of traditional buildings.* [online] London: Sustainable Traditional Buildings Alliance. Available from: http://www.spab.org.uk/downloads/STBA%20RESPONSIBLE-RETROFIT.pdf [Accessed 01/29 2013]

STBA, 2014. *Responsible retrofit guidance wheel.* [online] Sustainable Traditional Buildings Alliance. Available from: http://responsible-retrofit.org/wheel/ [Accessed 03/13 2014]

STESKENS, P.W., JANSSEN, H. and RODE, C., 2009. Influence of the convective surface transfer coefficients on the Heat, Air, and Moisture (HAM) building performance. *Indoor and Built Environment,* 18(3), pp. 245-256

STRAUBE, J. and BURNETT, E., 2001. Overview of hygrothermal (HAM) analysis methods. *ASTM manual,* , pp. 81-89

SULLIVAN, L., 2007. *A low carbon building standards strategy for Scotland.* Livingston: Scottish Building Standards Agency.

SUMMERFIELD, A. et al., 2007. Milton Keynes Energy Park revisited: Changes in internal temperatures and energy usage. *Energy and Buildings,* 39(7), pp. 783-791

TARIKU, F., KUMARAN, K. and FAZIO, P., 2014. Application of a Whole-Building Hygrothermal model in energy, durability, and indoor humidity retrofit design. *Journal of Building Physics,* , pp. 1744259114522400

TOWNSEND, L., 2010. *Home making and identity: a psychology of personality processes in North East Scotland.* [online] PhD thesis, The Robert Gordon University.

URQUHART, D., 2007. *Conversion of traditional buildings: application of The Scottish Building Standards.* Edinburgh: Historic Scotland.

VAN TEIJLINGEN, E. and HUNDLEY, V., 2001. The importance of pilot studies. *Social research update,* (35), pp. 1-4

VERHALLEN, T.M. and RAAIJ, W.V., 1984. Energy conservation through behavioral change: the use of natural gas for home heating. *Journal A. Quarterly Journal of Automatic Control,* 25(3), pp. 144-149

VINE, E.L., 1986. Saving energy the easy way: An analysis of thermostat management. *Energy,* 11(8), pp. 811-820

VRINGER, K., AALBERS, T. and BLOK, K., 2007. Household energy requirement and value patterns. *Energy Policy,* 35(1), pp. 553-566

WEI, S., JONES, R. and DE WILDE, P., 2014. Driving factors for occupant-controlled space heating in residential buildings. *Energy and Buildings,* 70(0), pp. 36-44

WEIHL, J.S. and GLADHART, P.M., 1983. Occupant behavior and successful energy conservation: Findings and implications of behavioral monitoring.

WOOD, C., BORDASS, B. and BAKER, P., 2009. *Researching into the thermal performance of traditional windows: timber sash windows.* English Heritage.

WOOD, C., BROCKLEBANK, I. and PICKLES, D., 2010. *Energy efficiency and historic buildings. Application of part L of the Building Regulations to historic and traditionally constructed buildings.* London: English Heritage.

YOHANIS, Y.G. and MONDOL, J.D., 2010. Annual variations of temperature in a sample of UK dwellings. *Applied Energy,* 87(2), pp. 681-690